Conductive Fibers

Subjects: Engineering, Electrical & Electronic

Contributor: shuang chen , Xiuhong Li , , Yujie Peng , Zhong Zheng , Jing Li , Fei Zhong

As one of the most impressive materials for wearable sensors, conductive fibers can be made from a variety of raw sources via diverse preparation strategies.

conductive fibers   preparation strategies

1. Introduction

Stretchable wearable devices have attracted extraordinary attention with the upsurge of interest in health monitoring systems and noninvasive human–machine interfaces. As a significant element of wearable electronics, a flexible sensor exhibits an unprecedented potential in human–machine interaction, human healthcare monitoring, electronic skin, artificial intelligence technology, etc. [1], which is capable of detecting and quantifying diverse bioinformation (body temperature, blood pressure, and respiratory patterns) with high specificity and sensitivity [2]. To accommodate the life expectancy of humans, lots of wearable sensors with diverse functions appeared [3]. Likewise, a variety of materials, such as metal sheets, metal wires, foam sheets, and plastic films, are employed to prepare wearable sensors [4][5][6][7][8]. Among them, the most popular and promising materials are conductive fibers owing to their advantages of superior flexibility, conductivity, breathability, durability, washability, biocompatibility, and so on, [3][9][10][11]. With recent advances in materials science and micro/nanofabrication, there has been active research on conductive fibers for wearable sensors.

Conductive fibers have broadly gone through three generations: (1) the first generation is flexible conductive fibers with traditional metals as raw materials, and the metals are designed to be stretchable structures, but with poor wearability, conductive instability, and other problems; (2) the second generation uses polymers as elastic conductive materials. Although their stability and conductivity are not ideal, the preparation process is simple and designable. Moreover, the material sources are wide. (3) The third generation is based on special textile yarns to fabricate composite elastic conductive fibers [1][12][13][14]. Currently, many conductive fibers manufactured by combining textile technology, mechanical technology, materials science, and electronics exhibit several advantages. Firstly, such conductive fibers have good flexibility and large deformation when being subjected to a very small external force, and their Young's modulus ranges from MPa to KPa. Plus, they usually possess a large specific surface area of about $10^{2–3}$ m^2/kg as well as varying degrees of porosity up to 99%, leading to good permeability [15]. In addition, some conductive fibers possess good durability, which can remain stable under stretching, bending, twisting, and shearing at various frequencies for more than 10,000 cycles. Furthermore, other conductive fibers can work not only at room temperature, but also under extreme temperature conditions. For example, some conductive fibers can work normally at low temperatures of −268.15 °C and others can operate at high temperatures of 250 °C [16][17][18]. It is known that the normal working temperature range of the majority of conductive fibers far exceeds the operating temperature range requirements of wearable sensors. Finally, these conductive fibers show good biocompatibility and do no harm to sensitive skin. Therefore, they have been made as artificial organs instead of necrotic organs [19][20][21][22][23]. Based on the building blocks of conductive fibers, they can be classified into three categories: metal-based conductive fibers, carbon-based conductive fibers, and polymer-based conductive fibers. Each conductive fiber has its own advantages: metal-based conductive fibers have relatively high conductivity, carbon-based conductive fibers have relatively low cost, and high fraction-based conductive fibers can be prepared to make more functional sensors.

Due to the excellent features of conductive fibers mentioned above, it is perfect for them to be applied in wearable sensors, which are able to extract various signals and analytes, such as pressure, tension, humidity, temperature, etc., making it possible to monitor human health conditions [12]. Besides, wearable sensors made of conductive fibers are very soft and flexible so that they can be bent, pulled, and folded like textiles. In addition to the soft mechanical properties, the favorable biocompatibility enables them to fit well with human skin, making them particularly comfortable to wear. In terms of the superior advantages of conductive fibers, the wearable sensors made of conductive fibers can be generally divided into three main categories: pressure sensors, strain sensors, and other types of sensors according to the different applications. Pressure sensors, including resistive, capacitive, and piezoelectric, are to convert external mechanical variations to electrical signals, which is mainly used for monitoring human health condition. As one of the next-generation electronics, strain sensors composed of conductive fibers have been widely investigated owing to their excellent mechanical flexibility and stretchability compared to the traditional rigid strain sensors. Nowadays, they can be used in a variety of areas, such as electronic skin, smart textiles, soft robotics, and so on. Meanwhile, other types of sensors consisting of conductive fibers are gas sensors and humidity sensors. They are usually applied to detect toxic gases or control the temperature. All in all, no matter which type of sensors, they take advantage of the conductive fiber’s extraordinary features. Until now, lots of studies have been published to demonstrate the diverse raw materials and wearable sensors used and made for conductive fibers, respectively (as shown in **Figure 1**).

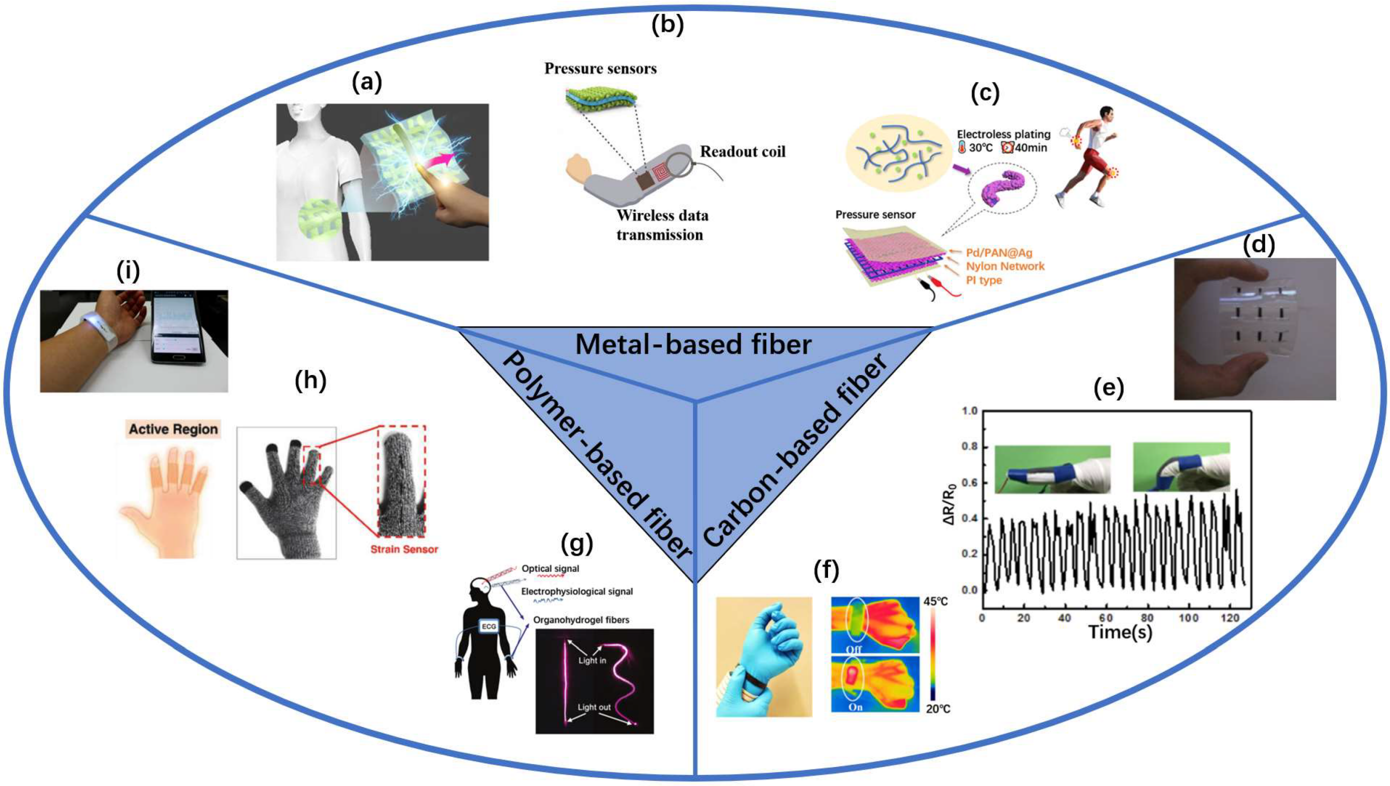

Figure 1. Various wearable sensors prepared from three types of conductive fibers used to detect various parameters of the human body: (**a**) capacitive sensors used in clothing [21], (**b**) an all-fabric pressure sensor with a wireless battery-free monitoring system [22], (**c**) piezoresistive sensor for monitoring human movement [23], (**d**) 3 × 3 flexible strain sensing array [24], (**e**) strain sensor monitors human movement [25], (**f**) a sensor that can be heated and monitored [26], (**g**) smart wireless blood pressure sensor [10], (**h**) a strain sensor applied to gloves [27], (**i**) capacitive sensor made into keyboard [28].

2. Metal-Based Conductive Fiber

Metals, as the most common conductive materials in life, show high mechanical strength, thermal conductivity, and electrical conductivity of about 5 × 10^5 S cm^{-1} [29]. For example, EGaIn, silver, aluminum, copper, nickel, and others are very suitable for making conductive layers of metal-based conductive fibers, and they have been successfully prepared as various conductive fibers with superior electrical conductivity [30][31][32]. Among them, liquid metal (EGaIn) has become a popular material to prepare metal-based conductive fibers due to its low melting point (29.8 °C), low viscosity, high surface tension, high electrical conductivity (3.4 × 10^4 S cm^{-1}), and good thermal conductivity [25][33][34]. It can be well combined with various elastomers, such as PDMS and PU, which can be manufactured as a flexible resistive strain sensor, followed by capacitive pressure sensors and piezoelectric pressure sensors [35][36][37][38]. Though the cost of EGaIn is very high, it is still highly favored by researchers. In a study, Liu et al. [39] injected EGaIn into hollow PDMS fibers to prepare a liquid-metal-based conductive fiber with high conductivity and excellent tensile properties. This conductive fiber was used to develop a resistive strain sensor. Silver is also often prepared as a metal-based conductive fiber by depositing silver nanowires or nanoparticles onto elastic fibers (e.g., nylon, PU fibers), which is mainly in the form of silver nanowires or silver nanoparticles [40]. Yan et al. [41] integrated AgNWs on top of PU fibers to form a conductive fiber with high conductivity and good stability. The conductive fiber was successfully prepared as a resistive strain sensor with high sensitivity. During the preparation process, the most important thing is to ensure that the coating is uniform, continuous, and thin, maintaining good electrical conductivity. The silver-based conductive fibers are generally prepared as a resistive strain sensor. Plus, there are also metals such as aluminum, copper, and nickel that have been applied as raw materials for the metal-based conductive fiber [42][43][44]. Those metals are mainly employed as plating layers combined with various elastomers, whose cost is relatively low compared to EGaIn and silver. However, copper and nickel would reduce the conductivity of the obtained metal-based conductive fibers due to oxidation, affecting the performance of the corresponding wearable sensors. In general, metal-based conductive fibers exhibit good electrical conductivity, durability, thermal conductivity, and high mechanical strength, which are suitable for manufacturing into functional wearable sensors, such as resistive strain sensors, resistive pressure sensors, piezoelectric pressure sensors, capacitive pressure sensors, etc. [45][46][47][48].

3. Carbon-Based Conductive Fiber

The development of carbon-based materials has attracted much attention in recent years due to their potential applications in a wide range of fields, such as energy storage devices, fuel cells, sensors, and electromagnetic shielding. Carbon and its derivatives are used in the manufacture of conductive fibers because of their remarkable characteristics, such as low cost, high electrical conductivity, large specific surface area, excellent chemical stability, and good mechanical durability [49]. The most commonly used carbon and its derivatives are graphene (G), graphene oxide (GO), reduced graphene oxide (rGO), CNTs, activated carbon (AC), and CB [50]. Among them, CB is in the form of black powder, with particle diameters ranging from 10 to 100 nm [51]. Compared with other types of carbon materials, CB is often employed for preparing carbon-based conductive fibers due to its wide sources. In the preparation process of carbon-based conductive fibers, CB is mainly dispersed uniformly in a solution and then coated on the surface of elastomers or it is mixed with the elastomer to form a solution or melt which is then cured into carbon-based conductive fibers. For example, Souri et al. [52] prepared a conductive ink using CB as the main raw material and applied it to elastic cotton fabric to produce conductive fibers. Such conductive fibers are usually made as resistive strain sensors and resistive pressure sensors [53]. CNTs are allotropes of carbon, which are also often used to fabricate carbon-based conductive fibers. However, CNTs have certain toxicity, which is super harmful to humans. Thus, safety precautions need to be taken when using CNTs to manufacture carbon-based conductive fibers [54]. Usually, CNTs are connected with the surface of the fiber to obtain conductive fibers [11]. Sometimes, CNTs as conductive fillers are put into hollow elastic fibers to prepare carbon-based conductive fibers [55]. In a study, Zhou and his colleagues prepared a highly stretchable conductive fiber by uniformly filling CNTs inside thermoplastic elastomer (TPE) tubes [42]. Similarly, G, GO, rGO, AC, etc., are used in a comparable way to prepare carbon-based conductive fibers [56][57][58][59]. For example, Souri et al. [60] fabricated a type of carbon-based conductive fiber by mixing G nanosheets into conductive inks and then coating the mixer onto cotton fabrics. In terms of safety, G nanomaterials are safer compared with CNTs [55]. In addition, it possesses better mechanical flexibility than metal nanomaterials [10]. In general, carbon-based conductive fibers possess superior advantages of electrical conductivity, chemical and mechanical durability, and low cost, which can be applied to make resistive strain sensors, resistive pressure sensors, humidity sensors, etc. They play a key role in the conductive fibers, resulting in significant parts in the field of functional wearable sensors.

4. Polymer-Based Conductive Fiber

Currently, there are many types of polymers, some of which have become the material choices for manufacturing multifunctional fibers or films owing to their high electrical conductivity, good processability, lightweight, high elasticity, and strong corrosion resistance [45][46]. Typical polymers used for conductive fibers are PPy, PANI, polythiophene (PTh), PEDOT: PSS, etc. [61]. Their conductivity is usually between 10^{-8} and 10^{2} S cm^{-1} at room temperature [62]. Commonly, the polymer-based conductive fibers are prepared by solidifying a co-blended solution of polymers and elastomers. Sometimes, the monomers of the conductive polymer are polymerized directly on the surface of the elastomer to form the conductive fiber. A few polymer-based conductive fibers are made via directly coating the conductive polymer on the elastomer surface, as with some metal-based conductive fibers. For example, Tadesse and his colleagues prepared the conductive paste PEDOT: PSS as the main materials. The conductive paste was then added to the appropriate amount of rheology modifier to increase the viscosity of the conductive paste. Finally, the conductive paste is coated on the fiber surface to form a polymer-based conductive fiber [63]. Polymer-based conductive fibers are often fabricated as resistive strain sensors, resistive pressure sensors, capacitive pressure sensors, piezoelectric sensors, etc. In addition, polymers including PPy, PAIN, PTh, etc., show different degrees of sensitivity to various gases (NH_3, N_2, CO, etc.), resulting in being developed as gas sensors. For instance, a polymer-based conductive fiber can be made into a wearable gas detection sensor, which uses PAIN and PAN nanofibers as the main raw materials. It possesses excellent sensitivity, fast response and recovery time, good reproducibility, and stability for NH_3 at 10–2000 ppm at room temperature [64]. In summary, polymer-based conductive fibers are composed of a variety of polymers, which are not only prepared as resistive strain sensors, resistive pressure sensors, and capacitive pressure sensors, but also as diverse gas sensors [65][66]. This is an advantage that metal-based conductive fibers and carbon-based conductive fibers do not have.

References

1. Lan, L.; Jiang, C.; Yao, Y.; Ping, J.; Ying, Y. A stretchable and conductive fiber for multifunctional sensing and energy harvesting. Nano Energy 2021, 84, 105954.
2. Clevenger, M.; Kim, H.; Song, H.W.; No, K.; Lee, S. Binder-free printed PEDOT wearable sensors on everyday fabrics using oxidative chemical vapor deposition. Sci. Adv. 2021, 7, eabj8958.
3. Kaur, P.; Saini, H.S.; Kaur, B. Wearable Sensors for Monitoring Vital Signs of Patients. Int. J. Eng. Technol. 2018, 7, 62–65.
4. Michard, F. Toward Smart Monitoring with Phones, Watches, and Wearable Sensors. Anesthesiol. Clin. 2021, 39, 555–564.

5. Zhao, H.; Zhou, Y.; Cao, S.; Wang, Y.; Zhang, J.; Feng, S.; Wang, J.; Li, D.; Kong, D. Ultrastretchable and Washable Conductive Microtextiles by Coassembly of Silver Nanowires and Elastomeric Microfibers for Epidermal Human–Machine Interfaces. ACS Mater. Lett. 2021, 3, 912–920.
6. Ouyang, Z.; Xu, D.; Yu, H.; Li, S.; Song, Y.; Tam, K.C. Novel ultrasonic-coating technology to design robust, highly sensitive and wearable textile sensors with conductive nanocelluloses. Chem. Eng. J. 2022, 428, 131289.
7. Yang, Z.; Zhai, Z.; Song, Z.; Wu, Y.; Liang, J.; Shan, Y.; Zheng, J.; Liang, H.; Jiang, H. Conductive and Elastic 3D Helical Fibers for Use in Washable and Wearable Electronics. Adv. Mater. 2020, 32, 1907495.
8. Li, J.; Wu, T.; Jiang, H.; Chen, Y.; Yang, Q. Ultrasensitive Hierarchical Piezoresistive Pressure Sensor for Wide-Range Pressure Detection. Adva. Intel. Syst. 2021, 3, 2100070.
9. Li, H.; Zhang, W.; Ding, Q.; Jin, X.; Ke, Q.; Li, Z.; Wang, D.; Huang, C. Facile Strategy for Fabrication of Flexible, Breathable, and Washable Piezoelectric Sensors via Welding of Nanofibers with Multiwalled Carbon Nanotubes (MWCNTs). ACS Appl. Mater. Interfaces 2019, 11, 38023–38030.
10. Song, J.; Chen, S.; Sun, L.; Guo, Y.; Zhang, L.; Wang, S.; Xuan, H.; Guan, Q.; You, Z. Mechanically and Electronically Robust Transparent Organohydrogel Fibers. Adv. Mater. 2020, 32, 1906994.
11. Zheng, X.; Wang, P.; Zhang, X.; Hu, Q.; Wang, Z.; Nie, W.; Zou, L.; Li, C.; Han, X. Breathable, durable and bark-shaped MXene/textiles for high-performance wearable pressure sensors, EMI shielding and heat physiotherapy. Compos. Part A Appl. Sci. Manuf. 2021, 152, 106700.
12. Li, J.; Yang, Y.; Jiang, H.; Wang, Y.; Chen, Y.; Jiang, S.; Wu, J.M.; Zhang, G. 3D interpenetrating piezoceramic-polymer composites with high damping and piezoelectricity for impact energy-absorbing and perception. Compos. Part B Eng. 2022, 232, 109617.
13. Jo, H.S.; Kwon, H.J.; Kim, T.G.; Park, C.W.; An, S.; Yarin, A.L.; Yoon, S.S. Wearable transparent thermal sensors and heaters based on metal-plated fibers and nanowires. Nanoscale 2018, 10, 19825–19834.
14. Leal-Junior, A.G.; Frizera, A.; Avellar, L.M.; Pontes, M.J. Design considerations, analysis, and application of a low-cost, fully portable, wearable polymer optical fiber curvature sensor. Appl. Opt. 2018, 57, 6927–6936.
15. Zeng, W.; Shu, L.; Li, Q.; Chen, S.; Wang, F.; Tao, X. Fiber-Based Wearable Electronics: A Review of Materials, Fabrication, Devices, and Applications. Adv. Mater. 2014, 26, 5310–5336.
16. Chen, G.; Wang, H.; Guo, R.; Duan, M.; Zhang, Y.; Liu, J. Superelastic EGaIn Composite Fibers Sustaining 500% Tensile Strain with Superior Electrical Conductivity for Wearable Electronics.

ACS Appl. Mater. Interfaces 2020, 12, 6112–6118.

17. Xu, Z.; Zhang, Y.; Li, P.; Gao, C. Strong, Conductive, Lightweight, Neat Graphene Aerogel Fibers with Aligned Pores. ACS Nano 2012, 6, 7103–7113.
18. Jing, L.; Bao, R.; Tao, J.; Peng, Y.; Pan, C. Recent progress in flexible pressure sensor arrays: From design to applications. J. Mater. Chem. C 2018, 6, 11878–11892.
19. Ning, C.; Dong, K.; Cheng, R.; Yi, J.; Ye, C.; Peng, X.; Sheng, F.; Jiang, Y.; Wang, Z.L. Flexible and Stretchable Fiber-Shaped Triboelectric Nanogenerators for Biomechanical Monitoring and Human-Interactive Sensing. Adv. Funct. Mater. 2021, 31, 2006679.
20. Abdollahiyan, P.; Oroojalian, F.; Mokhtarzadeh, A. The triad of nanotechnology, cell signalling, and scaffold implantation for the successful repair of damaged organs: An overview on soft-tissue engineering. J. Control. Release 2021, 332, 460–492.
21. Quan, S.; Tao, H.; Zhenbang, X.; Junshuo, Z.; Xiwen, F.; Xinglong, G.; Shouhu, X. Non-tensile piezoresistive sensor based on coaxial fiber with magnetoactive shell and conductive flax core. Compos. Part A Appl. Sci. Manuf. 2021, 149, 106548.
22. Ronghui, W.; Liyun, M.; Aniruddha, P.; Chen, H.; Shuihong, Z.; Xuwei, F.; Hezhi, L.; Weidong, Y.; Wenxi, G.; Yang, L.X. All-Textile Electronic Skin Enabled by Highly Elastic Spacer Fabric and Conductive Fibers. ACS Appl. Mater. Interfaces 2019, 11, 33336–33346.
23. Chen, Y.; Wang, Z.; Xu, R.; Wang, W.; Yu, D. A highly sensitive and wearable pressure sensor based on conductive polyacrylonitrile nanofibrous membrane via electroless silver plating. Chem. Eng. J. 2020, 394, 124960.
24. Chang, F.Y.; Wang, R.H.; Yang, H.; Lin, Y.H.; Chen, T.M.; Huang, S.J. Flexible strain sensors fabricated with carbon nano-tube and carbon nano-fiber composite thin films. Thin Solid Films 2010, 518, 7343–7347.
25. Yang, M.; Pan, J.; Xu, A.; Lei, L.; Cheng, D.; Cai, G.; Wang, J.; Tang, B.; Wang, X. Conductive Cotton Fabrics for Motion Sensing and Heating Applications. Polymers 2018, 10, 568.
26. Li, Y.Q.; Zhu, W.B.; Yu, X.G.; Huang, P.; Fu, S.Y.; Hu, N.; Liao, K. Multifunctional Wearable Device Based on Flexible and Conductive Carbon Sponge/Polydimethylsiloxane Composite. ACS Appl. Mater. Interfaces 2016, 8, 33189–33196.
27. He, Y.; Gui, Q.; Wang, Y.; Zhen, W.; Wang, Y. A Polypyrrole Elastomer Based on Confined Polymerization in a Host Polymer Network for Highly Stretchable Temperature and Strain Sensors. Small 2018, 14, 1800394.
28. Young, K.O.; Jin, L.S.; Hak, O.J. Wearable high-performance pressure sensors based on three-dimensional electrospun conductive nanofibers. NPG Asia Mater. 2018, 10, 540–551.

29. Tan, Y.; Yang, K.; Wang, B.; Li, H.; Wang, L.; Wang, C. High-performance textile piezoelectric pressure sensor with novel structural hierarchy based on ZnO nanorods array for wearable application. Nano Res. 2021, 14, 3969–3976.
30. Wang, S.; Shao, H.; Liu, Y.; Tang, C.; Zhao, X.; Ke, K.; Bao, R.; Yang, M.; Yang, W. Boosting piezoelectric response of PVDF-TrFE via MXene for self-powered linear pressure sensor. Compos. Sci. Technol. 2021, 202, 108600.
31. Mokhtari, F.; Spinks, G.M.; Fay, C.; Cheng, Z.; Raad, R.; Xi, J.; Foroughi, J. Wearable Electronic Textiles from Nanostructured Piezoelectric Fibers. Adv. Mater. Technol. 2020, 5, 1900900.
32. Siwal, S.S.; Zhang, Q.; Devi, N.; Thakur, V.K. Carbon-Based Polymer Nanocomposite for High-Performance Energy Storage Applications. Polymers 2020, 12, 505.
33. Khair, N.; Islam, R.; Shahariar, H. Carbon-based electronic textiles: Materials, fabrication processes and applications. J. Mater. Sci. 2019, 54, 10079–10101.
34. Wang, L.; Wang, H.; Li, B.; Guo, Z.; Luo, J.; Huang, X.; Gao, J. Highly electrically conductive polymer composite with a novel fiber-based segregated structure. J. Mater. Sci. 2020, 55, 11727–11738.
35. Haghgoo, M.; Ansari, R.; Hassanzadeh-Aghdam, M.K. Prediction of electrical conductivity of carbon fiber-carbon nanotube-reinforced polymer hybrid composites. Compos. Part B Eng. 2019, 167, 728–735.
36. Zhang, X.; Lu, W.; Zhou, G.; Li, Q. Understanding the Mechanical and Conductive Properties of Carbon Nanotube Fibers for Smart Electronics. Adv. Mater. 2019, 32, 1902028.
37. Hamid, S.; Debes, B. Highly sensitive, stretchable and wearable strain sensors using fragmented conductive cotton fabrics. J. Mater. Chem. C 2018, 6, 10524–10531.
38. Souri, H.; Bhattacharyya, D. Highly Stretchable Multifunctional Wearable Devices Based on Conductive Cotton and Wool Fabrics. ACS Appl. Mater. Interfaces 2018, 10, 20845–20853.
39. Souri, H.; Bhattacharyya, D. Wearable strain sensors based on electrically conductive natural fiber yarns. Mater. Des. 2018, 154, 217–227.
40. Ma, L.; Yang, W.; Wang, Y.; Chen, H.; Xing, Y.; Wang, J. Multi-dimensional strain sensor based on carbon nanotube film with aligned conductive networks. Compos. Sci. Technol. 2018, 165, 190–197.
41. Zhou, J.; Xu, X.; Xin, Y.; Lubineau, G. Coaxial Thermoplastic Elastomer-Wrapped Carbon Nanotube Fibers for Deformable and Wearable Strain Sensors. Adv. Funct. Mater. 2018, 28, 1705591.
42. Liu, H.; Li, Q.; Bu, Y.; Zhang, N.; Shen, C. Stretchable conductive nonwoven fabrics with self-cleaning capability for tunable wearable strain sensor. Nano Energy 2019, 66, 104143.

43. You, X.; Yang, J.; Wang, M.; Hu, J.; Ding, Y.; Zhang, X.; Dong, S. Graphene-based fiber sensors with high stretchability and sensitivity by direct ink extrusion. 2D Mater. 2020, 7, 015025.
44. Zhang, Q.; Yu, Y.; Yang, K.; Zhang, B.; Zhao, K.; Xiong, G.; Zhang, X. Mechanically robust and electrically conductive graphene-paper/glass-fibers/epoxy composites for stimuli-responsive sensors and Joule heating deicers. Carbon 2017, 124, 296–307.
45. Wang, R.; Jiang, N.; Su, J.; Yin, Q.; Zhang, Y.; Liu, Z.; Lin, H.; Moura, F.A.; Yuan, N.; Roth, S.; et al. A Bi-Sheath Fiber Sensor for Giant Tensile and Torsional Displacements. Adv. Funct. Mater. 2017, 27, 1702134.
46. Cao, M.; Wang, M.; Li, L.; Qiu, H.; Padhiar, M.A.; Yang, Z. Wearable rGO-Ag fiber piezoresistive sensor based on the fast charge transport channel provided by Ag nanowire. Nano Energy 2018, 50, 528–535.
47. He, S.; Xin, B.; Chen, Z.; Liu, Y. Flexible and highly conductive Ag/G-coated cotton fabric based on graphene dipping and silver magnetron sputtering. Cellulose 2018, 25, 3691–3701.
48. Xiang, D.; Chen, Q.; Li, Y.; Liu, S. Strain sensing behavior of conductive polymer/carbon nanotube composites coated fiber. AIP Conf. Proc. 2019, 2065, 030028.
49. Yu, Y.; Zhai, Y.; Yun, Z.; Zhai, W.; Wang, X.; Zheng, G.; Yan, C.; Dai, K.; Liu, C.; Shen, C. Ultra-Stretchable Porous Fiber-Shaped Strain Sensor with Exponential Response in Full Sensing Range and Excellent Anti-Interference Ability toward Buckling, Torsion, Temperature, and Humidity. Adv. Electron. Mater. 2019, 5, 1900538.
50. Souri, H.; Bhattacharyya, D. Highly stretchable and wearable strain sensors using conductive wool yarns with controllable sensitivity. Sens. Actuators A Phys. 2019, 285, 142–148.
51. Zheng, Y.; Li, Y.; Dai, K.; Yan, W.; Shen, C. A highly stretchable and stable strain sensor based on hybrid carbon nanofillers/polydimethylsiloxane conductive composites for large human motions monitoring. Compos. Sci. Technol. 2018, 156, 276–286.
52. Zhang, J.; Seyedin, S.; Si, Q.; Lynch, P.A.; Wang, Z.; Yang, W.; Wang, X.; Razal, J. Fast and scalable wet-spinning of highly conductive PEDOT:PSS fibers enables versatile applications. J. Mater. Chem. A 2019, 7, 6401–6410.
53. Yao, Y.; Jin, S.; Zou, H.; Li, L.; Ma, X.; Lv, G.; Gao, F.; Lv, X.; Shu, Q. Polymer-based lightweight materials for electromagnetic interference shielding: A review. J. Mater. Sci. 2021, 56, 6549–6580.
54. Wang, Y.; Ding, Y.; Guo, X.; Yu, G. Conductive polymers for stretchable supercapacitors. Nano Res. 2019, 12, 1978–1987.
55. Wong, Y.C.; Ang, B.C.; Haseeb, A.S.M.A.; Baharuddin, A.A.; Wong, Y.H. Review-Conducting Polymers as Chemiresistive Gas Sensing Materials: A Review. J. Electrochem. Soc. 2019, 167, 37503.

56. Singh, M.; Bollella, P.; Gorton, L.; Dey, E.S.; Dicko, C. Conductive and enzyme-like silk fibers for soft sensing application. Biosens. Bioelectron. 2020, 150, 111859.
57. Wang, X.; Meng, S.; Tebyetekerwa, M.; Li, Y.; Pionteck, J.; Sun, B.; Qin, Z.; Zhu, M. Highly sensitive and stretchable piezoresistive strain sensor based on conductive poly(styrene-butadiene-styrene)/few layer graphene composite fiber. Compos. Part A Appl. Sci. Manuf. 2018, 105, 291–299.
58. Wang, D.; Yu, H.; Qi, D.; Ramasamy, M.; Yao, J.; Tang, F.; Tam, K.M.C.; Ni, Q. Supramolecular Self-Assembly of 3D Conductive Cellulose Nanofiber Aerogels for Flexible Supercapacitors and Ultrasensitive Sensors. ACS Appl. Mater. Interfaces 2019, 11, 24435–24446.
59. Tadesse, M.G.; Mengistie, D.A.; Chen, Y.; Wang, L.; Loghin, C.; Nierstrasz, V. Electrically conductive highly elastic polyamide/lycra fabric treated with PEDOT:PSS and polyurethane. J. Mater. Sci. 2019, 54, 9591–9602.
60. Kikuchi, Y.; Pena-Francesch, A.; Vural, M.; Demirel, M.C. Highly Conductive Self-Healing Biocomposites Based on Protein Mediated Self-Assembly of PEDOT:PSS Films. ACS Appl. Bio Mater. 2020, 3, 2507–2515.
61. Tseghai, G.B.; Mengistie, D.A.; Malengier, B.; Fante, K.A.; Van Langenhove, L. PEDOT:PSS-Based Conductive Textiles and Their Applications. Sensors 2020, 20, 1881.
62. Doshi, S.M.; Thostenson, E.T. Thin and Flexible Carbon Nanotube-Based Pressure Sensors with Ultrawide Sensing Range. ACS Sens. 2018, 3, 1276–1282.
63. Ou, J.; Xie, J.; Jia, Y. Structural Design and Electrical Characteristics of Wearable and Flexible Stainless Steel/Polyester Fibre Mixture. Fiber Polym. 2021, 22, 854–861.
64. Wu, S.; Liu, P.; Zhang, Y.; Zhang, H.; Qin, X. Flexible and conductive nanofiber-structured single yarn sensor for smart wearable devices. Sens. Actuators B Chem. 2017, 252, 697–705.
65. Bagchi, S.; Achla, R.; Mondal, S.K. Electrospun polypyrrole-polyethylene oxide coated optical fiber sensor probe for detection of volatile compounds. Sens. Actuators B Chem. 2017, 250, 52–60.
66. Wang, Y.; Liu, A.; Han, Y.; Li, T. Sensors based on conductive polymers and their composites: A review. Polym. Int. 2019, 69, 7–17.