Available Online: 21 September 2026 DOI: 10.54254/2977-3903/2026.37142

Strain-dependent electrical transport in flexible conductive materials: implications for next-generation electronic devices

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Abstract. Flexible conductive materials possess excellent flexibility, stretchability, and electrical conductivity, enabling them to accommodate complex dynamic deformation modes, stretching, twisting, and wrinkling. This paper systematically reviews the structural characteristics, performance advantages, and fabrication features of the three major material systems, carbon-based materials, polymer composites, and novel flexible conductive materials, elucidates their electrical transport behavior and underlying mechanisms under mechanical deformation and cyclic strain, and compares the application limitations and shortcomings of different materials. Based on this, the paper summarizes current challenges regarding material performance synergy, long-term stability, processing costs, and large-scale fabrication, and analyzes future development directions such as composite structure design, mechanistic research, fabrication processes, and device integration. This paper systematically summarizes the common limitations across various device applications, providing a theoretical reference for the design and engineering applications of high-performance strain sensors and human-computer interaction devices.

Keywords: flexible conductive materials, electrical conductivity, wearable devices, flexible electronic devices

1. Introduction

Driven by the rapid advancement of flexible electronics and wearable devices, flexible conductive materials have emerged as a critical research frontier in materials science.Compared to traditional rigid conductive materials, the most fundamental characteristic of flexible conductive materials is strain-dependent electrical transport, that is, when the material undergoes deformation such as stretching, bending, or twisting under external forces, its electrical conductivity dynamically changes. This property serves as the core foundation for signal sensing and functional control in flexible electronic devices.

Existing research has largely focused on carbon nanotube/polyurethane flexible composite conductive materials, investigating the patterns of electrical transport changes under different strain amplitudes and cyclic deformation conditions, and analyzing the mechanisms of fracture and re of the internal conductive network. This has provided an experimental foundation for optimizing the performance of flexible conductive materials in single-system configurations [1-4]. However, such research remains largely concentrated on investigating the mechanisms and improving the performance of single-material systems, while systematic reviews and cross-comparisons of the strain-dependent electrical transport properties of various flexible conductive materials remain relatively limited [5, 6]. Therefore, this paper systematically reviews the latest research progress on strain-dependent electrical transport behavior in flexible conductive materials, summarizes the performance characteristics and transport mechanisms of different systems, compares the advantages and disadvantages of various materials in applications, analyzes the shortcomings in current research, and outlines the application prospects and development trends for these materials in next-generation flexible electronic devices, thereby providing a reference for future research and industrial applications of flexible conductive materials.

2. Flexible conductive material systems

Strain-dependent electrical transport in flexible conductive materials essentially arises from mechanical deformation-induced changes in the microstructure of the conductive network, which in turn alter electrical parameters such as resistance and conductivity. This process forms the basis for strain sensing and force sensing in flexible devices [6]. Differences in the microstructure and conductive mechanisms of various materials result in variations in their strain response and cycling stability.

2.1. Carbon-based materials

Carbon-based conductive fillers primarily include materials such as graphene, carbon nanotubes, and conductive carbon black [6]. Graphene-based materials exhibit excellent electrical and thermal conductivity as well as mechanical strength, and represent a key class of conductive functional materials [7, 8]. The surface of graphene oxide is rich in oxygen-containing functional groups, which facilitates bonding with substrates; Reduced Graphene Oxide (RGO), obtained through chemical reduction, partially restores the π-conjugated structure of the carbon framework, thereby improving the material's electrical conductivity and interfacial stability [8]. Multi-walled carbon nanotubes possess excellent electrical and thermal conductivity, readily form continuous conductive pathways within polymer matriceswhile acting as nucleation sites for crystallization to improve the mechanical properties of composites [9, 10]. Conductive carbon black can form three-dimensional conductive networks within the system; it is characterized by low cost and ease of processing, making it widely used in conductive composites [11]. Different carbon-based fillers can also be blended to improve the material's electrical conductivity, mechanical properties, and strain response characteristics by constructing multiscale conductive networks [8, 10].

The strain-dependent electrical transport properties of carbon-based materials are closely related to the continuity of the microscopic conductive network [8-10]. Under unstressed conditions, stable conductive pathways are established between graphene flakes, carbon nanotubes, and carbon black particles; upon tensile or bending deformation, the fillers undergo slippage, orientation changes, and variations in spacing, altering the number of conductive pathways and contact states, which in turn causes changes in electrical resistance [9, 12]. At low strains, changes in the conductive network are minimal; as strain increases, the distance between fillers increases, contact points decrease, and some conductive pathways break, causing the material's resistance to rise; under high strains, the conductive network may suffer irreversible damage, leading to a decline in electrical performance [9, 12]. Under long-term cyclic strain, carbon-based materials may also experience issues such as flake fragmentation, carbon nanotube breakage, and particle detachment, causing gradual damage to the conductive network and manifesting as resistance drift and reduced sensitivity [4, 6].

2.2. Polymer composites

Polymer composites typically consist of a flexible polymer matrix and functional conductive fillers as the reinforcing phase. They integrate the flexibility, stretchability, and processability of the polymer matrix with the electrical conductivity imparted by the fillers, rendering them critical for flexible electronics [2-4]. Polymer matrix materials primarily include Polyurethane (PU), Polydimethylsiloxane (PDMS), Polyvinyl Alcohol (PVA), and natural rubber [4, 11]. Among these, PU and PDMS possess good mechanical toughness and fatigue resistance, making them suitable for dynamic cyclic deformation. PVA-based hydrogels offer excellent biocompatibility and mechanical compatibility with human skin, and are thus widely employed in flexible medical monitoring devices [11].

Conductive fillers are the core components that impart electrical conductivity to materials. In addition to traditional carbon-based fillers such as carbon black, graphene, and carbon nanotubes, they also include metallic fillers such as silver nanowires and gold nanoparticles, as well as conductive polymer fillers [7, 10]. Various fillers endow composites with distinct electrical conductivity and strain response; metal fillers offer higher electrical conductivity, while carbon-based fillers are characterized by lower cost and better stability [1]. Compared to single-component conductors, conductive polymeric composites offer greater performance tunability; by adjusting the filler loading , dispersion state, and interfacial bonding mechanisms, they can be tailored to device applications requiring different strain ranges and sensitivity levels [1].

Currently, common modification methods include physical and chemical modifications. Physical modifications, such as ultrasonic dispersion and mechanical stirring, can address filler agglomeration and optimize the uniformity of the conductive network; chemical modifications, such as surface functionalization, crosslinking polymerization, and interfacial compatibilization, can strengthen the interfacial bonding between fillers and the matrix, reduce interfacial delamination and slippage during deformation, and improve the material's cycling stability and mechanical durability [2, 4].

2.3. Novel flexible materials

Liquid metals and two-dimensional layered functional materials (MXene, MoS_2) have emerged as key research areas in flexible conductive materials in recent years, capable of meeting the application demands of high-end flexible smart devices, high-precision sensing, and applications requiring extremely large deformations [5, 13]. Liquid metals, based on a gallium-indium-tin eutectic alloy, remain liquid at room temperature and combine the ultra-high electrical conductivity of metals with the exceptional flexibility of fluids; they can adapt to large deformations through their own flow and self-reconfiguration [13]. These materials accommodate extreme deformations via self-reconfiguration and can sustain tensile strains $> 400\%$ while maintaining conductive pathways, rendering them ideal for highly deformable devices, flexible electrodes, and medical applications. However, liquid metals also face application bottlenecks such as difficult encapsulation, susceptibility to leakage, high costs, and challenges in patterning [13].

MXene, as a novel two-dimensional transition metal carbide/nitride material, features ultra-high electrical conductivity, excellent hydrophilicity, and a tunable interlayer structure, which confers extremely high sensitivity to minute strains [12]. Its layered structure enables the formation of dense, continuous conductive pathways, rendering it promising for microstrain and high-precision sensing; however, the layers tend to stack on top of one another, and the material has poor oxidation resistance. Prolonged cyclic deformation can lead to interlayer delamination, resulting in performance degradation [5].

Molybdenum Disulfide (MoS_2) is a graphene-like two-dimensional layered semiconductor with excellent flexibility and strain sensitivity, making it suitable for detecting minute deformations and flexible sensing [6]. Its unique interlayer slip mechanism induces changes in electrical resistance, making it well-suited for high-precision monitoring of minute deformations.However, its electrical conductivity is lower than that of graphene and MXene, and its layered structure is prone to disruption under large strains, limiting its service conditions [6]. Overall, traditional materials focus on general-purpose and large-scale applications, whereas emerging materials target high-precision, ultra-large-strain, and specialized operating conditions. Together, these materials form a complementary application system capable of meeting the needs of flexible electronic devices at various levels.

3. Applications of strain-dependent electrical transport properties in flexible electronic devices

Leveraging their distinct strain-electric transport mechanisms, various flexible conductive materials have been widely adopted in multiple next-generation electronic fields, including wearable smart devices, flexible sensing, bionic robotics, and medical monitoring.

3.1. Applications of flexible strain sensors and wearable devices

Flexible strain sensors and wearable devices utilize changes in electrical resistance caused by material deformation to capture and convert human motion signals and mechanical strain signals. Different materials exhibit distinct strain-responsive behavior, thereby enabling tailored motion monitoring applications. Carbon-based flexible materials, which offer cost-effectiveness and excellent stability, can be used to monitor large-amplitude movements such as finger bending, wrist swinging, and limb stretching [7, 10]. MXene and MoS_2 exhibit high strain sensitivity, enabling the detection of minute muscle vibrations and subtle limb deformations [6]. Liquid-metal-based devices exhibit good adaptability to large deformations and can be used for dynamic monitoring of joint bending and repetitive stretching [14]. Currently, such flexible strain sensors have been applied in scenarios such as motion posture recognition, step counting, joint deformation monitoring, and human-computer interaction [15].

3.2. Applications in flexible displays and bionic robot skin devices

In the field of flexible displays, flexible conductive materials must maintain stable conductive pathways during deformation processes such as bending, folding, and stretching to ensure circuit continuity and signal transmission [5]. Carbon-based composite films and flexible polymer conductive materials possess good flexibility and deformation adaptability, making them suitable for use as electrodes and conductive layers in flexible display devices. During repeated folding and curved surface deformation, a stable conductive network helps reduce the risk of electrode failure and improves the device's bending endurance and operational stability [12].

In the field of bionic robotic skin, leveraging the strain-responsive properties of flexible materials, it is possible to fabricate highly flexible, highly sensitive bionic sensing skin that mimics the tactile, pressure, and deformation sensing functions of human skin [6, 14]. Through analysis of electrical responses across diverse strain ranges, these systems enable precise identification of contact pressure, strain magnitude, and force localization in robotic applications. This endows soft robots with intelligent capabilities such as flexible grasping, adaptive environmental sensing, and obstacle avoidance, significantly enhancing the environmental adaptability and operational precision of biomimetic robots. These technologies hold broad application prospects in the fields of soft intelligent robots and intelligent robotic arms [5].

3.3. Flexible medical monitoring devices

Leveraging the excellent biocompatibility, conformability to curved surfaces, and sensitivity to minute strains of the materials, flexible medical monitoring devices can conform to the skin and the curved surfaces of human organs, thereby enabling non-invasive, high-precision, and continuous physiological monitoring. Conductive composite materials made of polymer hydrogels and ultra-thin carbon-based flexible materials can adapt to the flexible deformation of human skin, accurately capturing faint physiological signals such as pulse fluctuations, respiratory variations, and subtle muscle tremors, and are used for cardiovascular health monitoring, respiratory status detection, and sports rehabilitation assessment [11]. Flexible liquid-metal electrodes possess excellent deformability, allowing them to conform to the complex curves of the human body and even integrate with implantable flexible medical devices, enabling long-term, stable monitoring of physiological signals within the body. They feature minimal irritation, excellent adaptability, and extended operational lifespan [13]. Such devices provide innovative technical solutions for smart healthcare, home health monitoring, and postoperative rehabilitation assessment.

4. Challenges and future directions for flexible conductive materials

4.1. Challenges

Although flexible conductive materials and related devices have been applied in multiple fields, numerous common bottlenecks still exist at this stage. Despite their use in wearable devices, flexible sensing, and medical monitoring, challenges remain in areas such as material mechanisms, performance synergy, long-term stability, and fabrication and integration.

Existing research has largely focused on macroscopic performance characterization, while there remains a lack of in-depth understanding of processes such as the evolution of strain-dependent electrical transport, interfacial failure, and structural degradation at the microscopic scale. The relationship between changes in material structure and macroscopic electrical performance has not yet been fully elucidated, which also limits further control over material performance. Moreover, inherent trade-offs exist among different performance metrics. Achieving mechanical flexibility, conductive stability, sensing sensitivity, cyclic durability, and environmental adaptability within a single material system remains challenging. For example, materials designed for high tensile strain typically require a relatively stable conductive network, whereas highly sensitive materials may be more susceptible to microstructural changes; thus, a trade-off remains between the ability to accommodate large deformations and high-precision signal detection [5]. Long-term cyclic deformation also affects the stability of materials and devices. During repeated stretching and bending, flexible composites undergo conductive network damage, interfacial failure, and structural fatigue, manifested as resistance drift, elevated hysteresis, and sensitivity degradation [2, 4, 6, 14]. These issues further affect the repeatability and long-term reliability of the devices. In terms of device fabrication and integration, novel flexible materials also face challenges related to patterning, encapsulation, and large-scale production. The fabrication processes for some two-dimensional materials and liquid metals remain relatively complex; device consistency and packaging stability need improvement, and fabrication costs also limit their further large-scale application [13].

4.2. Future directions

Considering current research gaps and industry trends, future breakthroughs in this field should focus on the mechanisms of strain-dependent electrical transport, optimization of material structures, fabrication processes, and device integration. Research into microscopic electrical transport mechanisms can leverage in-situ microscopic characterization and numerical simulation techniques to further elucidate the mechanisms of structural evolution and performance degradation under cyclic strain and complex operating conditions, thereby providing a theoretical basis for performance prediction and control [6]. Material design can leverage multiscale composite structure design and synergistic performance modification to construct multi-level composite conductive networks, optimize filler interfacial bonding and dispersion characteristics, and enhance the material's mechanical properties and electrotransport stability [7]. Fabrication processes require further optimization of material preparation, patterning, and encapsulation techniques to improve device stability and consistency, reduce fabrication costs, and advance related technologies toward large-scale production [13]. Device integration should advance toward multifunctionality through the integration of strain sensing, pressure detection, and signal transmission, thereby broadening applications in wearable devices, healthcare monitoring, soft robotics, and flexible sensors [9, 11].

5. Conclusion

This paper systematically reviews the structural characteristics, performance advantages, and fabrication and modification features of three major material systems—carbon-based materials, polymer composites, and novel flexible conductive materials—and conducts a comparative analysis of the strain adaptation characteristics and application suitability of various materials. It provides an in-depth explanation of the distinct strain-electric transport mechanisms between traditional and novel flexible materials, clarifies the evolution patterns of conductive networks during deformation, the mechanisms of performance degradation under cyclic strain, and fundamental optimization strategies, and focuses on analyzing the ultra-high-strain reconstruction mechanism of liquid metals, as well as the core principles and existing bottlenecks of high-precision strain response in two-dimensional materials. Furthermore, the study systematically explores the application value of strain-dependent electrical transport in flexible sensors, wearable devices, flexible displays, bionic robotic skin, and healthcare monitoring devices, identifying common technical challenges and performance limitations across current device applications. Finally, it pointed out the need for further breakthroughs in four major areas: structural modification, in-depth understanding of mechanisms, process optimization, and intelligent integration.

However, this paper does not conduct quantitative performance modeling and analysis for specific materials, nor does it introduce quantitative numerical simulation models to fit and analyze electrical transport curves. Moreover, the evolution and failure mechanisms of electrical transport under complex operating conditions, for example, extreme temperatures, high humidity, and corrosive environments, receive insufficient attention, and scenario-specific research remains limited. Future work could focus on quantitative studies of the mechanisms governing strain-dependent electrical transport at the microscopic scale; conduct targeted research on the in-service performance and failure mechanisms of materials under complex and extreme conditions to expand the engineering application boundaries of devices; and prioritize the development of multi-component composite modification technologies, low-cost large-scale fabrication processes, and high-stability packaging technologies to overcome core bottlenecks in industrialization.

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