Applied Science and Innovative Research
ISSN 2474-4972 (Print) ISSN 2474-4980 (Online)
Vol. 9, No. 2, 2025
www.scholink.org/ojs/index.php/asir

Original Paper

Synthesis and Performance Study of Conductive Polymers for Flexible Electronic Devices

Yanyu Wang

School of Materials Science and Engineering, Xihua University, Chengdu, Sichuan, 610039, China

Abstract

With the rapid development of wearable devices, flexible sensors, and flexible displays, higher performance requirements are being placed on conductive materials used in flexible electronic devices. Conductive polymers, known for their excellent flexibility, good conductivity, and tunable molecular structures, have become a research hotspot in the field of flexible electronics. This paper systematically summarizes the design and synthesis strategies of conductive polymers for flexible electronic devices, with a focus on the synthesis methods and structural regulation techniques of typical conductive polymers such as polyaniline (PANI), polypyrrole (PPy), and poly(3,4-ethylenedioxythiophene) (PEDOT). It further analyzes their electrical properties, mechanical performance, and environmental stability in flexible electronics. Finally, the paper discusses future development trends and challenges of conductive polymers in flexible devices, aiming to provide a theoretical foundation and technical support for the research of high-performance flexible electronic materials.

Keywords

Conductive polymers, Flexible electronics, Polyaniline, Polypyrrole, PEDOT, Performance study

1. Introduction

1.1 Research Background

With the rapid advancement of information technology, electronic products are evolving toward being lighter, more flexible, intelligent, and wearable. As a key representative of the new generation of electronic technologies, flexible electronic devices are widely used in smart wearables, flexible displays, electronic skins, biosensors, and other fields. However, traditional conductive materials used in electronics, such as copper, silver, and indium tin oxide (ITO), although possessing excellent conductivity, suffer from drawbacks such as brittleness, lack of flexibility, and high manufacturing costs. These issues make them unsuitable for complex mechanical deformation requirements like bending and stretching in flexible electronics. Therefore, identifying new conductive materials that simultaneously offer good conductivity, mechanical flexibility, low cost, and suitability for large-scale manufacturing has become a research focus. Conductive polymer materials, as an important branch of organic electronic materials,

are gradually replacing traditional inorganic conductors due to their unique structures and properties, becoming key materials in flexible electronics.

1.2 Advantages of Conductive Polymers

Conductive polymers are functional materials that combine the plasticity of polymers with the conductivity of metals. Their unique π-conjugated structures allow for effective delocalized electron transport along the polymer backbone, enabling excellent charge transport performance. Compared with traditional metal materials, conductive polymers have several significant advantages:

Firstly, they possess good flexibility and stretchability, capable of withstanding multiple bending cycles without breaking, making them suitable for flexible and wearable devices.

Secondly, these materials can be synthesized via chemical or solution processing methods at low cost, and are compatible with large-scale manufacturing techniques such as roll-to-roll printing.

Thirdly, their molecular structures are highly tunable. Researchers can modify their conductivity, optical properties, and mechanical strength by introducing functional groups or through doping strategies to meet various application needs.

Therefore, conductive polymers not only serve as a material foundation for structural innovation in flexible electronics but also play a crucial role in driving the commercialization of these technologies.

1.3 Research Status at Home and Abroad

The development of conductive polymers can be traced back to the 1970s. In 1977, Japanese scientist Hideki Shirakawa, together with Alan MacDiarmid and Alan Heeger from the United States, discovered that doping polyacetylene could significantly enhance its conductivity. This groundbreaking discovery initiated the study of conductive polymers and earned the trio the Nobel Prize in Chemistry in 2000. Subsequently, a variety of conductive polymers such as polypyrrole (PPy), polythiophene (PT), and polyaniline (PANI) were developed and widely investigated in electronic devices, sensors, and electrochemical applications.

In recent years, poly(3,4-ethylenedioxythiophene)/polystyrene sulfonate (PEDOT:PSS) has been commercialized in flexible electronics, touchscreens, and electroluminescent devices due to its water dispersibility, excellent optical transparency, and high conductivity.

Domestically, institutions such as Tsinghua University, the Institute of Chemistry at the Chinese Academy of Sciences, and Fudan University have made internationally influential progress in the synthesis, structural design, and device integration of conductive polymers. With the continuous advancement of materials science, nanotechnology, and organic synthesis methods, the performance of conductive polymers continues to improve, and their applications in flexible electronics are steadily moving from the laboratory toward large-scale implementation.

1.4 Significance of the Research

This study aims to systematically summarize the synthesis methods of conductive polymers, including oxidative polymerization, electrochemical polymerization, template-assisted synthesis, and solution processing technologies. It also provides an in-depth analysis of how structural regulation affects their

performance, such as conductivity, flexibility, and stability. The study highlights specific application cases of these materials in flexible electronic devices, including flexible electrodes, sensors, and field-effect transistors.

By comparing the effects of different synthesis techniques on the microstructure of materials, this research explores how molecular design and process optimization can synergistically enhance material properties. Moreover, from the perspectives of device reliability, environmental adaptability, and cost control, the paper proposes future development directions and challenges for conductive polymers.

This study not only provides theoretical support and technical references for designing high-performance flexible electronic devices but also offers experimental guidance for developing new conductive polymers. It has significant scientific and practical value in promoting the advancement of emerging industries such as smart wearables and flexible displays.

2. Fundamental Principles and Development History of Conductive Polymers

2.1 Conductive Mechanisms

Conductive polymers are a class of organic polymers with π-conjugated structures, where alternating single and double bonds in the backbone create a system that allows for electron delocalization. This delocalization enables π-electrons to move freely along the polymer chains, endowing the material with a certain level of electrical conductivity. However, undoped conductive polymers typically behave as semiconductors or insulators. Therefore, doping is the key to achieving high conductivity. Doping methods are generally classified into two types: oxidative doping (p-type) and reductive doping (n-type). These processes introduce positive or negative charges into the polymer chains, forming polaronic or bipolaronic species along with counter ions to significantly increase the density of free charge carriers.

Two widely accepted models explain the charge transport in conductive polymers: the *hopping model*, which describes charge carriers thermally hopping between polymer segments (suitable for amorphous or low-order materials); and the *band model*, which is applied to systems with high crystallinity and strong inter-chain coupling, positing the existence of conduction and valence bands similar to inorganic semiconductors. In practice, the electrical behavior of conductive polymers is influenced by various factors including molecular structure, aggregation state, doping level, and processing conditions. The conduction mechanism is often a composite effect involving multiple coexisting models. A deep understanding of these mechanisms is crucial for optimizing material properties and guiding device design.

2.2 Development History

Research on conductive polymers began in the 1970s. In 1977, Japanese scientist Hideki Shirakawa and American scientists Alan MacDiarmid and Alan Heeger discovered that the conductivity of polyacetylene increased by several orders of magnitude after iodine doping. This groundbreaking discovery marked the formal beginning of conductive polymer research and earned the trio the Nobel Prize in Chemistry in 2000.

During the 1980s, polymers such as polyaniline (PANI), polypyrrole (PPy), and polythiophene (PT) were developed, offering advantages over polyacetylene in terms of synthesis conditions, environmental stability, and processability. In the 1990s, poly(3,4-ethylenedioxythiophene) (PEDOT) and its water-dispersible complex with polystyrene sulfonate (PEDOT:PSS) became the focus of attention. Due to their high transparency, excellent conductivity, and mechanical flexibility, PEDOT:PSS found commercial applications in organic solar cells, flexible displays, and e-paper.

In the 21st century, conductive polymers began to integrate with nanotechnology, functional group modification, and composite material technologies, leading to the development of multifunctional, high-performance composites. For instance, combining conductive polymers with carbon nanotubes, graphene, or MXene can significantly enhance both conductivity and mechanical properties, expanding their use in wearable devices, bioelectronics, and smart sensors. Overall, research has evolved from basic material synthesis to structural design, device integration, and commercialization, making conductive polymers a critical component in flexible electronics.

3. Synthesis Methods and Structural Characteristics of Common Conductive Polymers

3.1 Polyaniline (PANI)

Polyaniline (PANI) is one of the earliest and most extensively studied conductive polymers. It features a simple synthesis process, low cost, and good environmental stability, making it widely used in sensors, energy storage devices, and electrochromic devices. PANI is mainly synthesized via two methods: chemical oxidative polymerization and electrochemical polymerization.

Chemical oxidative polymerization, widely used in both laboratory and industrial settings, typically employs ammonium persulfate (APS) as an oxidant to polymerize aniline monomers in an acidic medium. This method is easy to operate and offers high yield, though controlling polymerization degree and molecular weight distribution can be challenging. Electrochemical polymerization, on the other hand, forms PANI films by applying voltage to conductive electrodes, allowing uniform film formation with controllable thickness—ideal for device integration.

Structurally, PANI exists in three reversible oxidation states: leucoemeraldine (fully reduced), emeraldine (half-oxidized), and pernigraniline (fully oxidized). Among them, the emeraldine salt form exhibits the highest conductivity. PANI's electrical properties are closely tied to its oxidation state, which can be tuned by adjusting dopant type (e.g., HCl, CSA, DBSA), doping level, polymerization temperature, and time. Moreover, the color of PANI changes significantly with its oxidation state, a property leveraged in electrochromic applications. To enhance mechanical flexibility and processability, PANI is often blended with flexible polymers (e.g., polyvinyl alcohol, polylactic acid) or nanomaterials (e.g., graphene, carbon nanotubes), thereby extending its potential in flexible electronics.

3.2 Polypyrrole (PPy)

Polypyrrole (PPy) is another high-performance conductive polymer. Its synthesis methods are similar to those of PANI, primarily including chemical oxidative polymerization and electrochemical deposition.

Chemical synthesis commonly uses oxidants such as ferric chloride ($FeCl_3$) or persulfates to initiate polymerization of pyrrole monomers in aqueous solution. While simple and effective, this method is less suited for forming uniform thin films. Electrochemical deposition, by anodic polymerization on conductive electrode surfaces, enables strong adhesion and adjustable film thickness, ideal for complex structures or flexible substrates and beneficial for practical device fabrication.

Structurally, PPy is a nitrogen-containing five-membered ring conjugated polymer. Its conductivity arises from π-electron delocalization and the formation of charge carriers such as polarons and bipolarons during doping. Dopants (e.g., Cl^-, p-TSA, DBSA) enter the polymer matrix to introduce electron defect states, thus increasing the density of free carriers and enhancing conductivity. PPy exhibits good conductivity, thermal stability, and environmental resistance, with strong performance in supercapacitors, biosensors, and electromagnetic shielding materials.

However, the intrinsic rigidity of PPy limits its stretchability and flexibility, posing challenges for flexible electronics. To overcome this, researchers often composite PPy with flexible substrates (e.g., PDMS, polyurethane films) or modify it with flexible monomers or side chains. Recent advances in combining nano-PPy with carbon-based materials or metal nanoparticles have significantly improved its performance, broadening its application scope.

3.3 PEDOT and PEDOT:PSS

Poly(3,4-ethylenedioxythiophene) (PEDOT) is one of the most widely used conductive polymers today, especially in its composite form with polystyrene sulfonate (PEDOT:PSS). This composite offers excellent optical transparency, electrical conductivity, and flexibility. Coupled with its water dispersibility and strong compatibility with various processing techniques, PEDOT:PSS is widely applied in flexible electrodes, organic optoelectronic devices, and conductive coatings.

PEDOT is typically synthesized via oxidative polymerization using oxidants such as Fe(III)-p-TSA in water or organic solvents, yielding a poorly soluble blue-black solid. To improve processability, PEDOT is blended with PSS to form a stable aqueous dispersion—PEDOT:PSS—suitable for film fabrication via spraying, printing, or spin-coating. In this composite, PSS serves both as a dopant to stabilize PEDOT cations and as a dispersant forming a network structure, ensuring excellent performance in large-area flexible devices.

Key advantages include:

1. High optical transparency, with transmittance over 80% in the visible range;
2. Excellent flexibility, maintaining conductivity under low strain;
3. Good stability, with long-term durability under ambient conditions.

However, untreated PEDOT:PSS typically exhibits moderate conductivity (10^{-1} to 10^3 S/cm). To enhance performance, researchers are exploring PSS-free PEDOT systems, introducing nano-enhancers (e.g., MXene, carbon dots), or employing molecular engineering to optimize both conductivity and mechanical properties.

3.4 Other Emerging Conductive Polymers

In recent years, beyond traditional systems like PANI, PPy, and PEDOT, many novel conductive polymers have emerged, enriching the family of flexible electronic materials. These materials often feature unique conductive mechanisms and exhibit new properties such as photoresponsiveness, biocompatibility, and self-healing ability.

For example, polythiophene derivatives (e.g., PT, P3HT, PBTI) allow precise tuning of solubility and band structure through side-chain engineering, finding widespread use in organic field-effect transistors and organic photovoltaics. Rigid-backbone polymers like polycarbazoles and polyacetylenes show promise in thermoelectric and energy storage applications due to their stability and conductivity.

Moreover, conjugated polypeptides that combine π-conjugated structures with biological activity are forming ordered conductive networks via molecular self-assembly, showing potential in bioelectronic interfaces and neural modulation. These emerging materials often integrate molecular engineering, computational modeling, and green chemistry strategies, aiming to enhance conductivity while ensuring environmental sustainability—marking a key direction for future development in conductive polymers.

4. Performance Study of Conductive Polymers

Conductive polymers, due to their unique electronic structures and excellent tunable properties, play critical roles in cutting-edge fields such as flexible electronics, sensors, and biomedicine. However, their practical applications are limited by the comprehensive performance of the materials themselves, including conductivity, mechanical flexibility, and environmental stability. Therefore, a systematic study of their physical, chemical, and mechanical properties is essential for enabling their integration into devices, engineering applications, and commercialization.

4.1 Conductivity Analysis

Conductivity is one of the core indicators for evaluating the performance of conductive polymers. Theoretically, their conductivity originates from the number and mobility of free charge carriers within the π-conjugated electronic system. However, actual conductivity is significantly influenced by factors such as the type of dopant, polymerization conditions, and post-treatment methods.

First, the choice and level of dopants directly determine the concentration of free charge carriers. Taking polyaniline (PANI) as an example, different doping acids (e.g., HCl, CSA, DBSA) induce varying degrees of protonation between molecules, allowing the conductivity to range from 10^{-6} to 10^{2} S/cm. In the PEDOT:PSS system, PSS acts as a fixed anion to stabilize the positively charged PEDOT chains. Its ratio is especially crucial—excessive PSS may hinder π–π stacking between PEDOT chains, reducing carrier mobility.

Second, polymerization conditions—including temperature, duration, monomer concentration, and oxidant ratio—affect the polymer's degree of polymerization, crystallinity, and chain conformation. For instance, polymerization at lower temperatures tends to produce more ordered chain structures conducive to electron delocalization, while higher temperatures may cause more structural defects and act as

scattering centers that lower conductivity.

Moreover, post-treatment methods are essential for enhancing conductivity. In PEDOT:PSS films, treating with high-boiling-point polar solvents (such as DMSO or EG) can disrupt the PSS shell structure and reconfigure PEDOT-rich domains, optimizing phase separation and significantly improving charge transport. Acid treatments (e.g., H_2SO_4) can effectively remove insulating PSS, enhancing conductive network throughput and achieving metal-like conductivity at room temperature (>1000 S/cm).

In terms of measurement, commonly used techniques include the four-point probe method and electrochemical impedance spectroscopy (EIS). The four-point probe is a standard non-contact method that avoids contact resistance, suitable for films, bulk samples, and more. EIS is applicable to conductive polymer electrodes and can reveal ion/electron transport mechanisms and charge transfer resistance by analyzing impedance response at different frequencies—crucial for understanding their performance in energy storage devices.

4.2 Flexibility and Mechanical Properties

With the rapid development of flexible electronics and wearable devices, the flexibility and mechanical properties of conductive polymers are gaining increasing attention. Flexibility not only reflects a material's ability to adapt to external forces but also its capacity to maintain electrical performance under repeated strain. Thus, evaluating and enhancing tensile strength, elasticity, and shape recovery has become a research hotspot.

Common experimental evaluations include tensile testing, bending-recovery cycle tests, and fatigue tests. Tensile testing provides stress-strain curves to assess fracture elongation and elastic modulus. Bending-recovery tests involve repeated bending at various curvatures to monitor conductivity decay and evaluate durability and service life. For instance, untreated PEDOT:PSS samples often show conductivity degradation under less than 5% strain, while optimized structures can maintain stable conductivity even at 20–30% strain.

Improvement strategies mainly include composite formation with elastic polymers and molecular modifications through grafting or blending. The former involves incorporating elastic polymers like polyurethane (PU) or polydimethylsiloxane (PDMS) to build soft–hard hybrid structures, embedding the conductive polymer within a deformable matrix to improve stretchability and resilience. The latter entails molecular design, such as introducing flexible side chains or using interfacial grafting to form good molecular-level coupling between conductive segments and the matrix—preventing conductivity failure caused by phase separation or mechanical fracture.

Additionally, self-healing conductive polymers are attracting attention. Researchers have developed structural systems based on reversible bonds such as hydrogen bonding, metal coordination, and Diels-Alder reactions. These systems enable self-repair under external stimuli (e.g., heat, light, humidity) after microcrack formation, further improving mechanical durability.

4.3 Environmental Stability

Due to their organic molecular nature, conductive polymers are prone to structural degradation and

performance decay under environmental conditions like light, humidity, and temperature—posing challenges for long-term operational reliability. Improving environmental stability is thus key to their engineering applications.

Regarding light exposure, UV or strong visible light can trigger photooxidation in conductive polymers, causing backbone cleavage or dopant degradation. This is particularly critical for structures like polypyrrole (PPy) and PANI that contain reactive nitrogen-containing rings. Humidity mainly causes competition between water molecules and dopants or the polymer backbone, disrupting doping equilibrium and reducing charge carrier concentration. Under high temperatures, increased chain mobility may lead to greater structural disorder, damage to the conductive network, or even carbonization.

To enhance stability, researchers have developed various surface coating techniques and crosslinking strategies. Coating conductive polymers with hydrophobic polymers (e.g., PMMA, PVDF) forms a "protective film" that effectively blocks moisture and oxygen. Sol-gel coating methods can also construct inorganic oxide layers (e.g., SiO_2, TiO_2) for stronger physical barriers. Crosslinking strategies include UV-initiated copolymerization, thermal crosslinking, and silane coupling agents to form robust crosslinked networks, improving thermal stability and resistance to swelling.

Furthermore, using more stable polymer units (such as benzothiophene or benzothiadiazole) or forming composites with 2D materials (e.g., graphene, MXene) can also significantly improve durability in harsh environments. For instance, PEDOT:PSS composites with graphene oxide can retain over 80% of initial conductivity in high-humidity, high-temperature environments, demonstrating excellent application potential.

5. Case Studies on Applications in Flexible Electronic Devices

With the rapid development of flexible electronics, traditional rigid materials can no longer meet the demands of emerging intelligent terminals and wearable devices for flexibility, lightness, portability, and foldability. Conductive polymers, due to their excellent electrical conductivity, flexibility, and processability, are increasingly becoming key functional materials for flexible electronic devices. In recent years, their applications have expanded significantly in fields such as flexible sensors, wearable devices, flexible displays, and energy devices, achieving remarkable results.

5.1 Flexible Sensors

As critical interfaces for human–machine interaction and environmental perception, flexible sensors are widely used in health monitoring, artificial skin, and wearable medical devices. Conductive polymers are ideal materials for constructing flexible sensors due to their sensitivity and responsiveness to external stimuli such as pH, temperature, stress, and electric potential.

For example, polyaniline (PANI)-based flexible pH sensors exhibit excellent electrochemical response in acidic and basic environments. The PANI molecular chains exhibit different oxidation states (leucoemeraldine, emeraldine, and pernigraniline) under varying pH levels, accompanied by significant changes in physical properties such as color and conductivity. This enables rapid pH detection. By

incorporating PANI onto flexible substrates (e.g., PDMS or PU films), it is possible to construct wearable pH-sensing interfaces for continuous sweat monitoring, which can be applied in metabolic assessments, exercise load evaluations, and disease warning systems.

Moreover, conductive polymers like PEDOT and PPy, when combined with materials such as carbon nanotubes (CNTs) and MXene, can achieve high-sensitivity detection of various physiological parameters such as body movements, pulse, muscle electrical signals, and potential changes. For instance, PEDOT:PSS–PDMS composite skin patches can detect impedance changes during dynamic bending, enabling the development of electronic skin systems.

Sensor performance depends not only on the intrinsic properties of the materials but also on their microstructural design. Strategies such as 3D porous structures, patterned electrodes, and micro/nanofiber modifications can significantly increase surface area, enhance signal acquisition, and improve stability.

5.2 Wearable Devices

In wearable electronic products like smart bands, electronic textiles, and remote medical monitoring systems, comfort, softness, and durability are key criteria for material selection. Conductive polymers, with their inherent flexibility, can be directly applied or made into conductive composites to form "smart textiles" when integrated with conventional fabrics.

Methods for fabricating conductive textiles include:

- **Spray coating:** Dispersion of conductive polymers sprayed onto fiber surfaces; this method offers convenient processing and adaptability to various substrates.
- **Dip coating:** Immersing textiles in conductive polymer solutions to form coating layers, which enhance the bond between the conductive layer and fabric.
- **In-situ polymerization:** Polymerizing conductive polymers within the fibers to improve interfacial bonding and stability.

For example, researchers have used PEDOT:PSS to dip-coat polyester fabrics, creating conductive textiles with low resistance and high breathability, suitable for making ECG-monitoring T-shirts and temperature-sensing gloves. PANI has also been used to functionalize cotton and nylon fabrics for static shielding and strain sensing applications.

Despite their good initial properties, conductive polymers face durability challenges in wearable environments. Washing, repeated friction, and sweat corrosion can lead to delamination or performance degradation. In response, researchers have developed multilayer coating techniques, hydrophobic surface treatments, and self-healing strategies. For instance, coating conductive fabrics with PU or fluoropolymers can greatly enhance their water resistance and abrasion resistance while maintaining stable electrical performance.

Additionally, conductive polymers can be used to fabricate flexible electrodes, bendable circuits, and embedded sensing modules, realizing an integrated design from "material" to "system," and promoting the practical deployment of wearable electronics.

5.3 Flexible Displays and Energy Devices

Flexible displays and wearable energy modules are foundational components for realizing "self-powered flexible systems." Conductive polymers play important roles in OLEDs (organic light-emitting diodes), OPVs (organic photovoltaics), and supercapacitors, serving as functional layers or transparent electrodes. For example, PEDOT:PSS is widely used in OLEDs and OPVs as an anode buffer layer or transparent conductive film. Compared with traditional ITO (indium tin oxide), PEDOT:PSS offers advantages such as better flexibility, simpler processing, and low-temperature compatibility. Its excellent film-forming capability allows for large-scale, low-cost fabrication through methods such as spraying, doctor-blading, and printing. It is one of the few conductive polymers already commercialized in flexible electronics.

To further improve transparency and conductivity, researchers have treated PEDOT:PSS with polar solvents like DMSO or EG, boosting its conductivity from 1–10 S/cm to over 1000 S/cm while maintaining over 90% optical transparency. This has seen practical application in OLED modules by companies like Samsung and LG.

In flexible energy storage devices, conductive polymers also hold great potential as electrode materials. For example, PPy and PANI can serve as pseudocapacitive materials in supercapacitors, offering high specific capacitance, fast charge transport, and good electrochemical stability. In flexible structures, coating conductive polymers onto carbon cloth, nickel foam, or fiber substrates enables the unification of high capacity and bendability.

Furthermore, composite electrodes made from PANI and MXene, graphene, or carbon nanotubes can significantly improve power density and cycle life, serving as energy-support modules in flexible electronic devices and medical sensors.

6. Current Challenges and Development Trends

Despite significant progress in the application of conductive polymers in flexible electronics, many challenges remain before they can be widely and industrially applied. Systematic solutions to these key issues, along with alignment with the latest advances in materials science and engineering, are essential for enabling breakthroughs in fields such as smart wearables, bioelectronics, and flexible energy systems.

6.1 Major Challenges

(1) Trade-off Between Conductivity and Flexibility

Improving the conductivity of conductive polymers often compromises their softness and stretchability. For instance, PPy and PANI have good electrical conductivity but are prone to cracking or breaking under large strains, limiting their application in stretchable and wearable scenarios. Achieving both high conductivity and mechanical performance remains a long-standing challenge in conductive polymer research.

(2) Poor Stability in Mass Production

The synthesis of many conductive polymers currently relies on laboratory-scale conditions, such as strict temperature control, complex chemical reagents, and precise regulation of reaction times and oxidant

ratios. This results in poor repeatability and stability in industrial-scale production. Moreover, some conductive polymers are sensitive to air, moisture, or light, leading to performance degradation during processing and storage, which severely impacts real-world application.

(3) Low Environmental Resistance and Degradability Issues

Conductive polymers are prone to molecular chain breakage, oxidation, and dedoping under high temperature, humidity, or UV exposure, resulting in decreased conductivity or even failure. In wearable and outdoor devices, materials must withstand prolonged exposure to complex environments, which raises the bar for their stability. Additionally, most conductive polymers are difficult to degrade naturally, or their degradation releases harmful byproducts, posing environmental and ecological risks.

6.2 Future Development Trends

(1) Toward Multifunctionality: Conductivity + Self-Healing + Biocompatibility

Future research on conductive polymers will shift from single-function conductivity to multifunctional integration. For example, self-healing capabilities can extend device lifespans by addressing microcrack-induced performance degradation; biocompatibility modifications will expand applications in healthcare, such as electronic skin and implantable devices. Developing responsive, intelligent, and environmentally adaptable conductive polymers will be a major research direction.

(2) Integration with Nanotechnology and Composite Materials

Combining conductive polymers with nanomaterials such as carbon nanotubes, graphene, MXene, and metallic nanowires can overcome limitations of individual materials and synergistically optimize conductivity, flexibility, and mechanical strength. For instance, PEDOT:PSS combined with silver nanowires can enhance transparent electrode performance, while PANI/carbon nanotube composites exhibit higher sensitivity and stability in strain sensing and supercapacitor applications. Nanocomposite strategies will continue to diversify structural design and functional performance.

(3) Green Synthesis and Sustainable Development Strategies

Environmentally friendly and efficient synthesis methods are becoming crucial for the development of conductive polymers. For example, developing aqueous polymerization under ambient conditions can significantly reduce the use of organic solvents and lessen environmental impact. At the same time, research into the degradability and recyclability of conductive polymers will allow chemical or thermal recovery after end-of-life, aligning with low-carbon and sustainable development goals. Through life-cycle material design, it is possible to establish a green and circular flexible electronics industry.

7. Conclusion

This paper systematically reviews and thoroughly analyzes the research progress of conductive polymers in flexible electronic devices, with a particular focus on their synthesis methods, molecular structure design, and performance in terms of conductivity, flexibility, and environmental stability. Using representative conductive polymers such as polyaniline (PANI), polypyrrole (PPy), and poly(3,4-ethylenedioxythiophene)/poly(styrenesulfonate) (PEDOT:PSS) as examples, the paper summarizes their

practical performance in applications including flexible sensors, wearable devices, flexible displays, and energy devices, confirming the immense potential of conductive polymer materials in the realm of lightweight, bendable, and stretchable electronics.

However, current conductive polymers still face key challenges, such as the difficulty in simultaneously improving conductivity and mechanical flexibility, insufficient environmental adaptability, and the limitations of scalable fabrication processes. Therefore, breakthroughs are urgently needed in areas like material structure regulation, functional composites, and green synthesis.

Looking forward, it is essential to strengthen interdisciplinary collaboration across chemistry, materials science, electronic engineering, and biomedical fields to promote the development of novel multifunctional conductive polymers. Furthermore, their integration into emerging fields such as smart wearables, biomedicine, and flexible energy systems should be actively explored. Emphasis should also be placed on eco-friendly concepts, fostering the development of sustainable, low-energy fabrication techniques to achieve cost-effective and industrial-scale production of high-performance conductive polymer materials.

In conclusion, conductive polymers, as key materials for flexible electronic devices, remain in a stage of rapid development with broad prospects, warranting continued attention and in-depth exploration.

References

Bubnova, O., & Crispin, X. (2012). Towards polymer-based organic thermoelectric generators. *Energy & Environmental Science*, *5*(11), 9345-9362.

Chen Chao, & Zhang Li. (2019). Preparation technology and performance optimization of conductive polymer films. *Modern Materials Science and Technology*, *42*(8), 67-73.

Chen Sijia, & Zhou Zhiyong. (2022). Research progress of PEDOT:PSS in flexible electronic devices. *Journal of Materials Science and Engineering*, *40*(5), 609-615.

Chen, S., Zhang, Q., He, Y., et al. (2019). High-performance flexible organic thermoelectric materials enabled by nanoscale synergy. *Nano Energy*, *58*, 659-667.

Fabiano, S., Aernouts, T., Brown, T. M., et al. (2014). *Improved conductivity of PEDOT:PSS films by an unusual acid treatment. Journal of Materials Chemistry C*, *2*(1), 53-59.

Han Xudong, & Zhao Yu. (2021). Research progress of wearable conductive textiles. *Textile Herald*, *2021*(6), 20-24.

Heeger, A. J., MacDiarmid, A. G., & Shirakawa, H. (2001). Nobel Lecture: Semiconducting and metallic polymers: the fourth generation of polymeric materials. *Reviews of Modern Physics*, *73*(3), 681-700.

Jiang, Y., Yu, J., & Fu, Q. (2017). High performance flexible thermoelectric materials and devices: a review. *Journal of Materials Chemistry C*, *5*(26), 6690-6702.

Li Li, & Liu Guozhen. (2021). Current development and trends of flexible electronics technology. *Application of Electronic Technique*, *47*(2), 5-10.

Li, D., & Kaner, R. B. (2008). Graphene-based materials. *Science*, *320*(5880), 1170-1171.

Kim, N., Kee, S., Lee, H. B., et al. (2014). Highly conductive PEDOT:PSS nanofibrils induced by solution-processed crystallization. *Advanced Materials*, *26*(14), 2268-2272.

Liang Wenjie, & Li Jian. (2019). Conductive properties of polypyrrole and its applications in flexible electronics. *Acta Polymerica Sinica*, *50*(4), 421-428.

Liu Feng, & Hu Wenliang. (2019). Structure and performance of conductive polymers. *Materials Review*, *33*(10), 1234-1240.

Liu Hua, & Li Junfeng. (2021). Study on environmental stability of conductive polymers. *Materials Protection*, *54*(7), 45-50.

Liu Qiang, & Sun Lihua. (2021). Application of green synthesis technology in the preparation of conductive polymers. *Chemical Engineering & Equipment*, *48*(2), 112-117.

Liu, J., Yu, C., Chen, S., et al. (2018). Flexible, highly conductive PEDOT:PSS films fabricated by combining chemical treatment and layer-by-layer assembly for flexible electronics. *ACS Applied Materials & Interfaces*, *10*(30), 25245-25253.

Lü Jiayin, & Li Lei. (2018). Conductive mechanism of polyaniline and its composites. *Polymer Materials Science and Engineering*, *34*(11), 12-18.

Shirakawa, H., Louis, E. J., MacDiarmid, A. G., et al. (1977). Synthesis of electrically conducting organic polymers: halogen derivatives of polyacetylene, (CH)x. *Journal of the Chemical Society, Chemical Communications*, *1977*(16), 578-580.

Skotheim, T. A., & Reynolds, J. R. (2007). *Handbook of Conducting Polymers*. CRC Press.

Groenendaal, L., Jonas, F., Freitag, D., et al. (2000). Poly(3,4-ethylenedioxythiophene) and its derivatives: past, present, and future. *Advanced Materials*, *12*(7), 481-494.

Sun Xiaowei, & Zhang Nan. (2022). Application progress of conductive polymers in flexible supercapacitors. *Electrochemistry*, *28*(3), 195-202.

Wang Hongwei, & Zhang Min. (2020). Application progress of conductive polymers in flexible sensors. *Sensors and Microsystems*, *39*(6), 8-12.

Wang Lili, & Xu Ming. (2020). Preparation and performance of conductive polymer composites. *Functional Materials*, *51*(12), 12034-12040.

Wang, S., Wang, T., Li, C., et al. (2020). Advances in flexible and stretchable electronics for smart wearable devices. *Journal of Materials Chemistry C*, *8*(4), 1237-1264.

Wang, Y., Zhang, J., Zhan, Y., et al. (2018). Flexible and stretchable conductors for organic electronics. *Advanced Materials*, *30*(45), 1705045.

Xu, J., Wang, Y., Li, Z., et al. (2019). Flexible and wearable organic optoelectronics for health monitoring. *Advanced Materials*, *31*(38), 1902646.

Zhang Xiaodong, & Zhang Haitao. (2020). Research progress of conductive polymers. *Progress in Chemistry*, 32(3), 445-456.

Zhao Pengfei, & Wang Xiaomin. (2020). Application of nanotechnology in conductive polymer composites. *Materials Review*, *34*(11), 89-95.

Zhao Qianqian, & Wang Yutao. (2021). Current research status and application prospects of conductive polymers. *New Chemical Materials*, *49*(1), 67-70.