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Conductive Polymers: Applications, Limitations, and Prospects in Flexible Wearable Devices

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Abstract. This paper focuses on the application of conductive polymer in flexible wearable devices. At the start, the importance of flexible wearable devices in daily healthcare and the strengths of flexible wearable devices over traditional wearable devices are introduced. The material to build a flexible wearable device is special; it needs to acquire High Flexibility, High Conductivity, and Biocompatibility. In this case, the paper introduces conductive polymers, and it also lists three kinds of conductive polymers that are mainly applied in flexible devices. Polystyrene Sulfonate (PEDOT: PSS), Polyaniline (PANI), and Polypyrrole (PPy). The properties and strengths of three kinds of materials are introduced, and their applications are also listed. Practical applications include PANI-based electrochemical sensors for real-time sweat pH monitoring (aiding in detecting diabetes, etc.) and PEDOT: PSS-based flexible EEG devices, which replace rigid electrodes and conductive gels to enhance comfort. The paper also mentions the drawbacks of conductive polymers and states the future development of conductive polymers.

Keywords: Flexible Wearable Device, conductive Polymers, PEDOT: PSS, conductivity, Biocompatibility

1. Introduction

In 2024, the World Health Organization published an astonishing article. They claimed that 1/8 of the people in the world were living in obesity. To prove it, they established the data they collected in 2022. It showed that 2.5 billion adults were overweight, and 890 million of them were living in obesity. 390 million children and adolescents were also overweight, and in the latest collection in 2024, there were also 35 children less than 5 years old who were overweight [1]. Obesity is a severe risk to the human body. Diseases like heart attack and type 2 diabetes can all be caused by it [2]. Fortunately, this problem can be prevented by monitoring the patient's metabolic and hemodynamic parameters, which can all be tracked by a wearable device.

Wearable devices are devices that were designed to be worn on the human body (such as a watch or clothing) that can directly contact the skin and collect data about the human body. The most significant example is the Apple Watch, established by the company Apple. The first Apple Watch purchased on April 24, 2015, has already carried a heart sensor and an accelerometer that could track people’s fitness. Nowadays, the Apple Watch features simple ECGs and other technologies that support real-time monitoring of heart rate, sleep status, and various bodily data points. The most

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important advantage of wearable devices in healthcare detection is convenience [3]. Wearable devices enable people to monitor their health status at any time; if any anomalous data is detected, they can adjust their habits and customs or seek medical attention for the first time. This increases the efficiency of health tracking and decreases the risk of diseases.

2. Dilemmas and solutions of flexible wearable devices

Although wearable devices are essential for health tracking, they still have limitations. The most significant drawback is limited comfort and Biocompatibility for the human body. For example, the traditional Wearable Electroencephalogram (EEG) device uses Silver or Silver Chloride as an electrode, and it also contains a conductive gel to reduce skin electrode impedance. But neither material are designed for comfort for the human body. The user may feel itchy and uncomfortable using the product because the gel and electrode will bump their head and scratch their hair. Furthermore, traditional wearable devices can't directly contact the skin, so the efficiency of the device is insufficient. Lastly, traditional wearable devices have low environmental stability, as they may lose their function when the users are doing sports.

The main solution is to replace traditional wearable devices with flexible wearable devices. A Flexible Wearable device is an electronic device designed to be worn on the body that incorporates flexible or stretchable materials—such as flexible circuits, sensors, and substrates—so it can bend, twist, or stretch without losing functionality. Address the three major drawbacks of traditional devices—comfort, contact efficiency, and stability—flexible wearable devices need to focus on materials with 'high flexibility, high conductivity, and biocompatibility as the core breakthrough point. Conductive polymers precisely meet these combined requirements, making them a key solution [4].

3. Conductive polymers

Conductive polymers are a class of organic polymers that can conduct electricity, combining the electrical properties of metals or semiconductors with the mechanical flexibility and processability of plastics. The conductivity of conductive polymer arises from a conjugated molecular structure—alternating single and double bonds along the polymer backbone—that allows electrons or charge carriers to move through the material. The conductivity can be tuned or enhanced through doping (adding or removing electrons via chemical or electrochemical methods) [5]. Nowadays, the main conductive polymer applied in flexible technologies is PEDOT: PSS, PANI, and PPy.

3.1. PEDOT: PSS

PEDOT: PSS is a polymer made from two components. PEDOT is the conductive polymer that provides high electrical conductivity and optical transparency. PSS is a polyelectrolyte that makes PEDOT dispersible in water, improving processability and film formation. PEDOT has high conductivity because it contains a conjugated polymer backbone with an extended π-conjugation (alternating single and double bonds), which allows the delocalization of electrons along the polymer chain, enabling charge transport. PSS acts as a polyanion dopant, stabilizing PEDOT in its conductive oxidized state. PEDOT: PSS also exhibits high flexibility, as both PEDOT and PSS are long-chain polymers that can be processed into ultra-thin, conformable coatings that bend easily while maintaining conductivity. Apart from that, PEDOT: PSS also has good biocompatibility as its structure is mechanically matched to biological tissue. The function of PEDOT: PSS is usually

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performed by combining it with other materials. For example, PEDOT: PSS can combine with graphene, which could tremendously increase the electrical conductivity and mechanical properties of the material. Scientists apply this technology to flexible strain sensors through direct inkjet printing. When subjected to a bending angle of 80°, the sensors exhibited a maximum resistance variation rate of 3.414, demonstrating strong application potential.

3.2. PANI

PANI is a conductive polymer made by polymerizing aniline monomers, which was discovered in emeraldine salt. It is also conductive as it has a conjugated polymer backbone like PEDOT. But the chain of PANI contains distortion, and it relies on acid protonation for conductivity. This makes the conductivity of PANI not as strong as PEDOT. However, PANI also has advantages. First is low cost, the monomer of PANI, aniline, is inexpensive and can be widely produced in industrial manufacturing. The polymerization of PANI can also be done at room temperature in acidic aqueous solution, which decreases the cost of both material and equipment. PANI also has high environmental stability as its structure is based on benzene rings linked by nitrogen atoms. Aromatic rings are highly stable due to delocalized π-electrons, which makes the polymer backbone resistant to oxidation and thermal degradation compared to many other conductive polymers. In wearable devices, PANI is mainly used as a biosensor as its conductivity would change by biogases and fluids.

3.3. PPy

PPy is a π-conjugated conductive polymer made by the oxidative polymerization of pyrrole monomers. Its conductivity is stronger than PANI but weaker than PEDOT: PSS. The most significant advantage of using PPy in a flexible wearable device is its high biocompatibility. PPy can be synthesized under mild, aqueous conditions without harsh chemicals, reducing contamination that might cause toxicity. PPy's surface is generally hydrophilic to moderately hydrophobic, which can promote protein adsorption — an important factor for cell adhesion and proliferation. PPy is often used as a Protective / Functional layer for flexible wearable devices. It provides antistatic, anticorrosion, or hydrophilic coatings for long-term wearable use.

Herein, the table below shows the conductivity, stability, and flexibility of 4 conductive polymers mentioned.

Table 1. Conductive polymer's physical properties

Material	Conductivity (S/cm)	Stability in Air	Flexibility	Reference
PEDOT:PSS	10^2–10^3 (treated)	High	High	[6]
PANI	1–10^2	High in acid	Low–Moderate	[6]
PPy	1–100	Moderate	Low	[6]

4. Conductive polymers empowering flexible wearable devices

As introduced, there are three kinds of conductive polymers. The first application of conductive polymers used in a wearable device we will mention is a PANI-based wearable electrochemical sensor. Our body (Eccrine Gland) will produce sweat, which is a fluid that contains 98–99% water. The rest of the part is NaCl, fatty acids, lactic acid, citric acid, ascorbic acid, urea, and uric acid [7].

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Detecting the data of human sweat can help discover the health and fitness of the patient. For example, diseases such as diabetes and cystic fibrosis can be detected by measuring the glucose level and the concentration of chloride in sweat. In the process of detecting the pH of sweat, PANI shows important functionality. The reason is that the oxidative polymeric product of aniline is typically formed under acidic conditions to impart specific properties to the polymer. It also performs in 3 different oxidation states: leucoemeraldine, pernigraniline, and emeraldine oxidation forms [8]. Each state has a different color of yellow, green, and dark blue. When PANI undergoes a reversible redox reaction (reaction related to a weak acid/ weak base), the color and the resistivity of the PANI change. For this property, PANI could be made into thin films and electrodes that could be used in a Flexible Electrochemical Sensor to provide real-time monitoring of pH variations [9].

Another example is the Flexible EEG device I mentioned above. As we know, a traditional EEG device uses Ag/AgCl as electrodes and conductive gel to prevent direct skin contact. These electrodes are rather bulky, and it is impossible to sleep on them. However, PEDOT: PSS could address this issue; we could replace the electrode made of silver or silver chloride with a polymer electrode composed of PEDOT. As PEDOT: PSS has excellent biocompatibility, the conductive gel can also be removed. This change could significantly enhance the user's comfort, as well as the device's flexibility and portability.

5. Conclusion

Conductive polymers, with their high flexibility, conductivity, and biocompatibility, are well-suited for flexible wearable devices, addressing key limitations of traditional devices such as poor comfort, inefficient skin contact, and low environmental stability. Their practical applications, including PANI-based electrochemical sensors for sweat pH monitoring and PEDOT: PSS-based flexible EEG devices, highlight their potential in healthcare monitoring. However, they face drawbacks when it is applied in flexible wearable devices. The first drawback is limited Long-Term Stability. A lot of conductive polymers will degrade under environmental conditions (Eg, Oxygen, Sweat, and UV light). This would cause the functionality of the conductive polymer to decrease. Another concern is the conductivity of the conductive polymer. Its conductivity is not as well as metals like silver and copper.

In future developments, more properties of conductive polymers will be discovered, and they will be able to be applied to wearable devices. First is Self-Healing, this property means Conductive polymers can repair mechanical cracks, scratches, or electrical pathway breaks automatically (or with minimal external trigger), restoring both mechanical integrity and electrical conductivity. This could increase the long-term stability of a flexible wearable device, as it makes the conductive polymer able to undergo frequent bending and prevent environmental corrosion, like sweat and dirt. Also, the methods of increasing the conductivity of conductive polymers have been discovered. The primary method is to apply a stronger dopant, which increases the charge carrier density and, consequently, enhances conductivity. In one day, flexible wearable devices with conductive polymers will significantly improve our lives.

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