

Research and Application of Functional Polymer Materials in Flexible Electronics

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Abstract. Flexible electronics technology has emerged as a transformative technology and is developing rapidly. However, traditional metals and inorganic semiconductors face limitations in flexible devices due to poor stretchability and adaptability. Polymers, with their lightweight, flexible, and multifunctional properties, are considered key materials for the fabrication of flexible electronic devices. Additionally, functional polymer materials offer tunable chemical structures, low cost, and compatibility with solution processing techniques, playing a significant role in enabling lightweight, stretchable, and wearable devices. This paper reviews recent advances in the design, synthesis, and integration of conductive, dielectric, piezoelectric, self-healing, biodegradable, and two-dimensional material-enhanced polymers. Additionally, the applications of functional polymer materials in flexible electronics are discussed. Finally, the challenges faced by functional polymer materials in flexible electronics are analyzed, and feasible future development directions are explored.

Keywords: functional polymer material, flexible electronics, wearable sensor, flexible displays.

1. Introduction

The rapid development of flexible electronics technology is driving a transformation in the design, manufacturing, and application of electronic devices. Traditional rigid electronic devices based on semiconductors, metals, and inorganic materials can no longer meet the new demands for flexibility, scalability, and wearability [1,2]. In contrast, flexible electronic devices offer mechanical conformability, lightweight structures, and the ability to adapt to non-planar surfaces, opening entirely new application prospects for wearable devices, flexible robots, biomedical monitoring, and next-generation display technologies [3]. Among these flexible devices, functional polymer materials offer numerous advantages. First, functional polymers typically have more convenient and cost-effective processing methods compared to traditional electronic component manufacturing. Second, the chemical structure of functional polymers can be designed more rationally to suit various applications. Third, under biological conditions, some polymers exhibit excellent biocompatibility and stability within the human body, enabling them to perform health monitoring

functions [4,5]. As a result, functional polymers have become an indispensable material in the field of flexible electronics.

Currently, the field of flexible electronics has achieved many encouraging results [5]. Figure 1 shows a “flexible electronics ecosystem diagram. “It illustrates the entire chain from materials → manufacturing → structural design → devices → system applications on a circular diagram. The inner circle lists key materials and nanostructures, including graphene, silicon, silver, nanotubes (NTs), and nanowires (NWs), which serve as foundational materials determining the performance of flexible electronics. The outer application layer includes displays, energy storage, electronic textiles, touch feedback, medical and biosensing applications, and flexible computing and circuit modules [6].

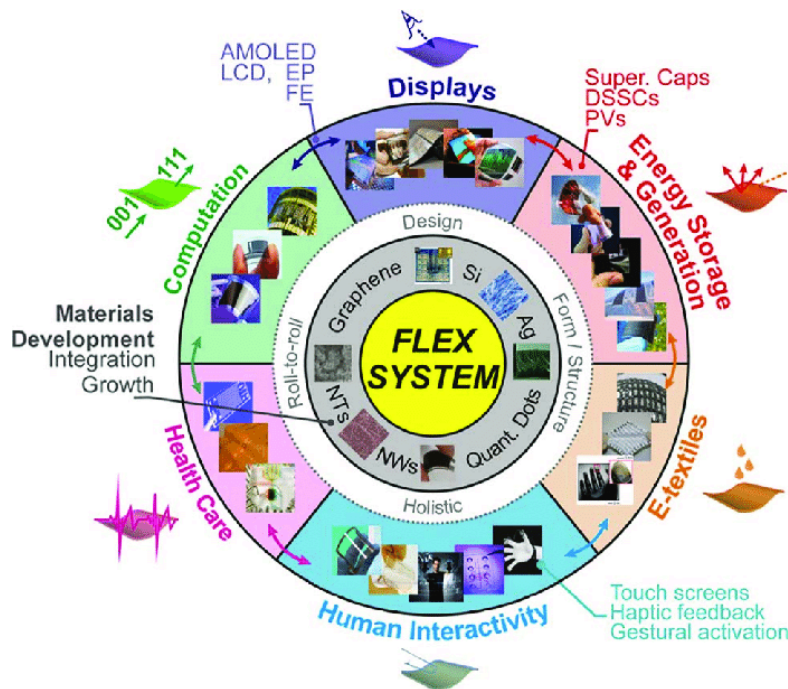


Figure 1. Schematic diagram of next-generation flexible electronic systems and related key areas [6]

Among the numerous material candidates for these applications, functional polymer materials have garnered significant attention due to their inherent flexibility, chemical tunability, and compatibility with low-temperature, large-area fabrication techniques [7]. These polymers can be engineered to exhibit various properties, including electrical conductivity, dielectric response, piezoelectric effects, self-healing behavior, and environmental degradability [8]. This multifunctionality enables their integration into active and passive components of flexible electronic devices, including stretchable transistors, sensors, biodegradable substrates, and packaging materials. Currently, more than ten companies worldwide have launched foldable screen smartphones or computers, and these electronic products have become highly attractive consumer products once mass-produced [9]. In the field of human interactivity, polymer composite materials have made considerable progress in wearable pressure sensors and are expected to see breakthroughs in applications such as pressure distribution imaging, human motion detection, and medical health [10]. In addition, in the e-textile field, Hansu Kim's team has proposed a scalable continuous capillary-assisted coating (CTAC) process for the preparation of multi-layer conductive tough fibers (CTFs) for washable, wearable electronic textiles [11]. Its Young's modulus is 6.22 MPa; fracture strain: 70%; toughness: $9.40 \times 10^5 \text{ J} \cdot \text{m}^{-3}$; and waterproof rating reaches IPX8. After

being immersed in water for 24 days and washed 100 times, it maintains stable electrical resistance. Compared to control fibers without an EGaln shell layer, it exhibits significantly superior water resistance and electrical resistance retention. By integrating the four requirements of “high conductivity, high toughness, strong water resistance, and washability” into a single fiber and achieving scalable manufacturing, this technology provides a universal interconnection/sensing platform for sustainable e-textiles [11]. Additionally, in the healthcare field, Professor Shuyun Zhuo's team proposed a reusable, free-standing ultra-thin hydrogel electronic tattoo (HET) using a parylene–hydrogel dual-layer structure, which maintains the low interfacial impedance of wet electrodes while offering the ultra-conformability and repositionability of a “sticker-type” tattoo. This simultaneously addresses the pain points of traditional “dry tattoo electrodes” (high impedance/poor motion resistance) and “wet electrodes” (disposable/bulky), providing a material and structural paradigm for long-term, reusable, and low-artifact human electrophysiological monitoring [12].

However, the performance of polymer-based flexible devices is not solely determined by the intrinsic properties of polymers [13]. It is also significantly influenced by material integration strategies and microstructure control techniques. Additionally, hybrid systems composed of nanomaterials and polymers can further enhance their electrical, mechanical, and barrier properties, thereby expanding their application potential [14,15].

In summary, functional polymer materials have been widely applied in various fields of flexible electronics. In light of the significant contributions of functional polymer materials to flexible electronics and the persistent challenges in their implementation, a systematic examination of their progress in this domain becomes imperative. To provide a reference for researchers in related fields, this paper extensively discusses conductive/semiconductive polymers, dielectric-piezoelectric polymers, self-healing polymers, ionic conductors, natural and biodegradable polymers, polymer-two-dimensional materials, and their important research directions. Additionally, this paper outlines the influence of material integration and microstructure control on the performance of polymer-based flexible devices, as well as the application of functional polymers in devices and systems, including sensors and smart skin, flexible displays, energy storage, and multifunctional integration. Finally, this paper identifies the current issues and challenges facing functional polymers in the field of flexible electronics and proposes potential solutions.

2. Fundamentals of polymer material systems

2.1. Conductive/semiconductive polymers

Conductive/semiconductor polymers are organic materials with a conjugated main chain as the charge-carrying framework and the ability to conduct electricity. Through π – π interactions in the main chain and doping regulation, they can serve as both intrinsic conductors and semiconductors for ion electrolyte control devices. Based on this property, conjugated polymers can act as plastic equivalents to metal wires and silicon channels. Their intrinsic flexibility allows them to retain high levels of electrical conductivity even when bent or folded, which is crucial for applications such as wearable displays or flexible sensor arrays. To balance electrical performance with mechanical robustness, these polymers are often optimized through strategies such as doping or blending. One widely studied example is poly (3,4-ethylenedioxythiophene) : poly (styrene sulfonate) (PEDOT: PSS), which can reach conductivities exceeding $3 \text{ kS}\cdot\text{cm}^{-1}$ without becoming brittle, owing to solvent- or acid-driven phase ordering that reduces insulating voids [16,17]. As illustrated in Figure 2, PEDOT: PSS offers a versatile processing toolbox—chemical / interfacial / electrochemical /

photo / enzymatic routes and aqueous dispersion—yielding films, hydrogels, sponges, elastomeric composites, aerogels, fibers, and powders that enable morphology/phase-ordering control to couple high conductivity with mechanical compliance. Parallel studies on organic thin-film transistors (OTFTs) have shown that improving the planarity of the polymer backbone and fine-tuning the doping level can steadily enhance charge mobility [2].

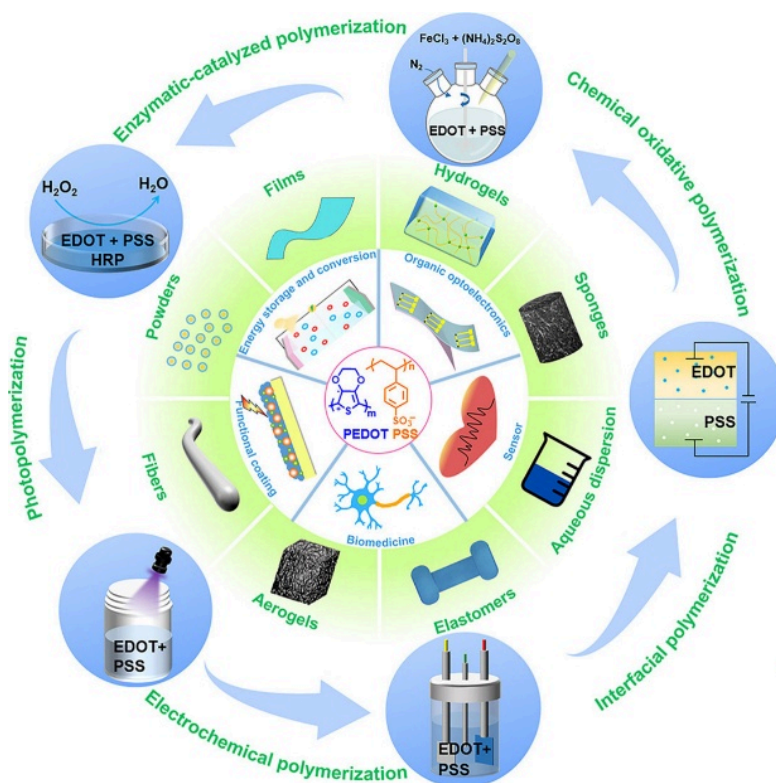


Figure 2. Schematic overview of the PEDOT: PSS ecosystem [16]

2.2. Dielectric-piezoelectric polymers

These polymer materials, which possess both dielectric and piezoelectric properties, undergo electrical polarization when subjected to mechanical stress and can also deform under the influence of an external electric field. As dielectric materials, they serve as insulators, charge storage media, and electric field modulators in capacitors, sensors, and transistor gates; as piezoelectric materials, they can convert energy between mechanical stress and electric polarization, enabling applications such as self-powered sensing, tactile feedback, and energy harvesting. Compared to inorganic oxides, polymers offer low modulus, high flexibility, and low-temperature processing characteristics—key factors for achieving large-area, wearable structures.

A representative material, poly (vinylidene fluoride) (PVDF), particularly in its β -phase, demonstrates flexible ferroelectric properties when the polymer chains predominantly adopt a fully trans (all-trans) conformation. This molecular ordering can be promoted through processing methods such as uniaxial stretching or shear-induced crystallization during melt processing. A similar effect—enhanced dipole alignment—can also be achieved by incorporating polar nanoparticles into the polymer matrix, offering a less mechanically aggressive but effective alternative [18].

2.3. Self-healing polymers and ionic conductors

Self-healing polymers refer to materials that can restore their mechanical properties after damage under external environmental conditions. Ionic conductors achieve electrical conductivity through ion migration and can be coupled with self-healing chemistry to achieve synchronous “mechanical-electrical” recovery. Both are used in flexible electronics for stretchable electrodes, pressure sensing, skin-adhesive circuits, soft robots, and solid-state electrolytes, significantly improving device lifespan and safety. In conductive composites, movable ionic bonds or recoverable filler-polymer interfaces are utilized to achieve circuit break self-healing, restoring electrical conductivity or capacitive coupling. These materials are characterized by rapid restoration of conductivity after a circuit break, making them suitable for electronic skin and wearable circuits. Additionally, ionic gels and single-ion conductors are employed in solid-state supercapacitors, emphasizing electrochemical windows, dendrite suppression, and cycling stability. Recent studies have highlighted two key and often competing design considerations: dynamic bond exchange rates, which determine the material's self-healing speed; and intrinsic bond strength, which ensures mechanical durability [19]. In optimized systems, such ionic conductive gels can be stretched to over ten times their original length and recover functionality overnight after damage [20].

2.4. Natural and biodegradable polymer

Natural and biodegradable polymers refer to materials derived from biomass or synthesized from renewable monomers. They are attractive in the field of flexible electronics because they are soft, lightweight, typically skin-friendly, and can degrade or be absorbed at the end of their useful life—thereby reducing electronic waste and enabling temporary or biodegradable devices [21]. Due to these advantages, these materials are highly suitable for use as substrates, packaging materials, and simple circuit structures in disposable medical or environmental devices [22].

Biologically derived chain-like structures—such as cellulose fibers, silk proteins, and starch molecules—not only offer mechanical flexibility and clarity but also degrade into non-toxic byproducts. Their physical performance is largely governed by the ratio of crystalline to amorphous regions in the film: a higher content of β -sheet structures or aligned nanofibers improves stiffness but slows down degradation in soil or seawater. For instance, flexible circuits printed on cellulose nanofiber paper exhibit excellent visible light transparency and sheet resistance below $30 \Omega \cdot \text{sq}^{-1}$, while remaining fully biodegradable [23,24].

2.5. Polymer-two-dimensional material

Polymer-2D hybrid materials combine the exceptional electrical properties of fillers with the softness, stretchability, and processability of polymers by embedding atomically thin fillers into a polymer matrix. This creates a tunable platform suitable for flexible conductive materials, dielectric materials, sensors, and thermal barriers.

Thermal management technology demonstrates significant advantages in hybrid filler structures. Combining one-dimensional nanotubes with two-dimensional layered structures forms a three-dimensional thermal conduction network, effectively filling the gaps between layers and suppressing layer re-stacking, thereby reducing interfacial resistance. As shown in Figure 3, data from Professor Shin-Yi Yang's team indicates that, with a fixed total filler content of $\sim 1 \text{ wt}\%$, a single filler system provides only limited performance improvements compared to pure epoxy resin, while a hybrid system ($0.1 \text{ wt}\%$ MWCNTs + $0.9 \text{ wt}\%$ MGPs) exhibits higher thermal conductivity [25]. By

functionalizing the nanotube surfaces (e.g., GD400), interfacial coupling is further enhanced, resulting in optimal performance under cyclic deformation conditions. This highlights the importance of interfacial chemistry and filler geometry in polymer-two-dimensional composite materials.

Interface design plays a pivotal role in determining composite performance. Optimal dispersion of these fillers establishes a low percolation threshold, facilitating high electrical conductivity even at minimal loading concentrations. Simultaneously, robust interfacial adhesion ensures efficient stress transfer and helps prevent mechanical failure under deformation. Recent studies have spotlighted systems such as laser-induced graphene or MXene-seeded PVDF, where tailored interfacial interactions result in flexible, high-output composites with long-term durability [26, 27].

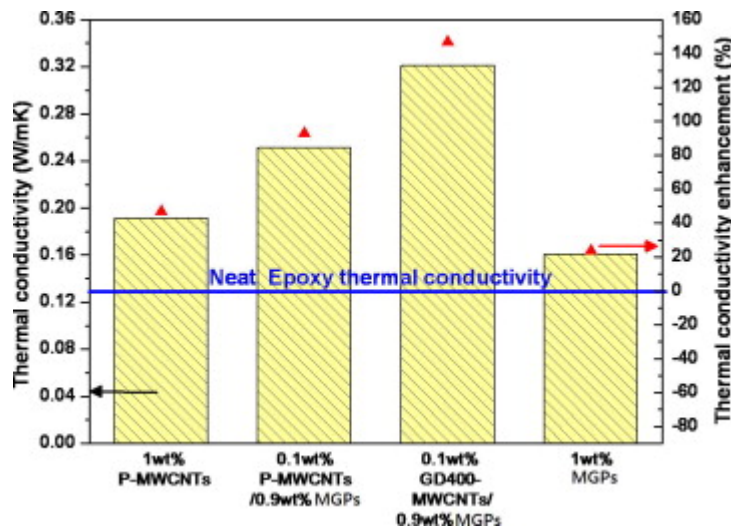


Figure 3. Thermal conductivity of epoxy composites with different carbon fillers [27]

3. Applications for functional polymer materials in flexible electronics

3.1. Materials integration and microstructure control

The electrical performance, stability, and structural dimensions of flexible electronic devices depend not only on the type of materials used but also on how these materials are assembled. Film formation, interfacial chemistry, and microstructure all influence charge transport, dielectric loss, breakdown strength, and fatigue performance. The performance of functional polymers in flexible electronics highly depends on material integration strategies and microstructure control methods, such as film formation and functional material embedding to structural micro-arrangement, all of which can significantly impact electrical performance and mechanical stability.

Among these, transfer printing technology can be used to precisely transfer micro-scale OTFTs, micro-LEDs, sensors, and interlayer materials onto polymer dielectric layers using compatible adhesives to maintain device characteristics and enhance integration density and interconnect reliability [28]. Additionally, methods such as nanoimprinting, soft lithography, inkjet printing, or screen printing can achieve micron-to-nanometer-scale patterning of polymer functional layers, supporting low-temperature, roll-to-roll manufacturing processes, significantly reducing costs and enhancing scalability [15]. This advanced manufacturing method significantly improves the integration density and operational reliability of hybrid functional systems while maintaining compatibility with flexible dielectric materials.

3.2. Device and system applications

By leveraging the integration and microstructural strategies, functional polymers find applications in flexible electronic devices and systems across multiple directions, including sensing, display, and energy systems.

3.2.1. Sensors and electric skin

By leveraging the synergistic effects of polymer and filler systems, flexible sensors highly sensitive to pressure, strain, temperature, humidity, and chemical analytes have been developed. Electronic skin systems typically integrate flexible OTFTs, conductive nanocomposite layers, and human-skin-inspired structures to achieve multi-point tactile, temperature, and humidity detection with high spatial resolution, finding widespread application in health monitoring, wearable devices, and soft robotics [29]. For example, electrospun PVDF-TrFE nanofiber arrays are used in ultra-sensitive pressure sensors with a response pressure as low as 0.1 Pa, suitable for wearable self-powered structures [30].

3.2.2. Flexible displays

As shown in Figure 4, the core components of flexible displays include organic semiconductor channel layers, transparent conductive electrodes, and flexible encapsulation layers, often based on OTFT, OLED, and flexible thin-film electrode systems. By using PEDOT: PSS or polyimide as transparent conductive layers and mechanical supports, rollable and highly bendable display devices can be achieved. Low-temperature processing, patterning precision, and microscopic structural control of encapsulation are also critical factors for ensuring long-term stability and high-resolution displays [31].

A research team led by Park from Ulsan National Institute of Science and Technology (UNIST) in South Korea has developed a stretchable transparent backplane based on oxide semiconductor TFTs. The stretchable transparent backplane utilizes oxide TFTs combined with graphene–gold nanotunnel (AuNT) composite electrodes: at a 91% transmittance, the sheet resistance is only $1 \pm 0.1 \, \Omega/\text{sq}$, and it remains functional even at 50% stretch (with a resistance increase of approximately 60%); When transferred to a $2 \, \mu\text{m}$ PI substrate, no cracks were observed, and the backplane was successfully integrated with OLED pixels to demonstrate a functional flexible display prototype [32].

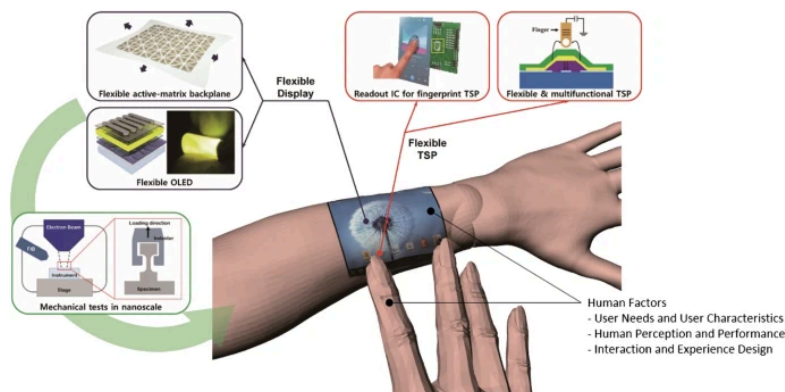


Figure 4. Components and human-factor considerations of flexible displays (backplane, OLED, TSP, fingerprint IC, nanoscale mechanics) [32]

3.2.3. Energy harvesting, storage, and multifunctional integration

Flexible functional polymers are not only used for energy harvesting (such as piezoelectric and triboelectric nanogenerators) but also in flexible batteries and supercapacitors. Conductive polymers serve as electrodes or electrolyte components, enhancing transport stability and mechanical toughness. By integrating functional modules with structural components, such as 3D hierarchical chip systems based on SIS or transfer printing technology, independent, wearable electronic systems can be developed [33].

3.2.4. Biomedical and transient systems

Bio-based and biodegradable polymers can be used to prepare skin patches, implantable transient sensors, and dissolvable stimulators. The devices can safely degrade after use, reducing electronic waste; cellulose-based substrates and sensors are typical representatives of this direction.

A research team led by Professor Kyowon Kang has developed a fully implantable wireless power-supply tactile sensing system (WTSA) that combines an artificial skin layer with a neural interface, enabling both the restoration of tactile perception and the promotion of wound healing in severely damaged skin [34]. Additionally, the system integrates biocompatible collagen-based artificial skin with hydrogel-coated neural electrodes to minimize foreign body reactions, demonstrating stable performance under varying pressure conditions and providing quantitative readings. This approach offers a feasible pathway toward developing closed-loop, clinically applicable electronic skin.

4. Conclusion

This study aims to elucidate the fundamental importance and current state of development of functional polymer materials in the field of flexible electronics. Functional polymer materials are increasingly significant in flexible electronics due to their unique combination of tunable chemistry, flexible mechanical properties, and scalable, low-temperature processing characteristics. Based on this consideration, we focus on five key areas—conductive/semiconductor, dielectric-piezoelectric, self-healing/ionic, natural-biodegradable, and polymer-two-dimensional hybrid materials—and demonstrate how device performance can be enhanced through material integration and microstructural control, including conductivity, dielectric constant/breakdown strength, piezoelectric response, and fatigue life.

In functional polymer materials, conductive/semiconductor polymers achieve low-voltage actuation and printable interconnects through doping and framework planarization, making them the primary materials for printed circuits and OTFTs. Conductivity or high dielectric constant versus loss is a common trade-off consideration. Dielectric-piezoelectric polymers in high breakdown, low-loss linear media and β -phase PVDF systems offer the best cost-performance ratio for energy storage and self-powered sensing. Meanwhile, high-voltage electrical response, hysteresis, and depolarization will continue to challenge researchers for years to come. Biodegradable polymers offer skin-friendly substrates and programmable pathways, supporting disposable devices. However, sustainability in design remains a challenge, including the use of bio-based raw materials and recyclable inks. Additionally, many polymer materials exhibit reliability and accurate lifespan prediction deviations under coupled stress conditions.

At the microstructural level, the same polymer can exhibit significant differences in electrical and mechanical performance through solvent selection, orientation and crystallization control, and

interface design. Future research directions could include using lamination for heterogeneous integration to ensure alignment and yield. Nanoimprinting and soft lithography could be employed to achieve low-temperature, roll-to-roll (R2R) compatible patterning. Alternatively, gradient interfaces, surface grafting, and π - π /hydrogen bond/ionic bond mechanisms could be utilized to stabilize interfaces, reduce losses, and enhance breakdown and fatigue life.

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