Organic Electronics: Material Innovations, Synthesis Strategies, and Applications as Flexible Electronics

Chenchen Liu [*]

Department of Chemical Safety Engineering, China University of Petroleum, Qingdao, 266500, China

* Corresponding Author Email: 2103050214@s.upc.edu.cn

Abstract. Organic electronics has emerged as a transformative field in materials science, revolutionizing the development of flexible, lightweight, and cost-effective electronic components. Utilizing carbon-based organic small molecules and polymers, this technology diverges significantly from traditional inorganic electronic materials, offering unique advantages in terms of flexibility and processability. This paper provides a comprehensive review of the advancements within the field of organic electronics, focusing on essential materials such as conductive polymers, small molecule semiconductors, and organic photovoltaic materials. The paper highlights various production methods that enable large-scale and cost-effective manufacturing and explores innovations in chemical synthesis that enhance device performance and stability. Furthermore, it addresses the integration of these materials into practical applications, illustrating their potential to significantly impact the electronic device market. Despite the progress in material development, challenges remain in material durability, efficiency, and integration into existing systems. In conclusion, the field of organic electronics represents a dynamic and evolving area of materials science that holds significant promise for transforming the landscape of electronic devices.

Keywords: Organic electronics; synthesis method; conductive polymers, small-molecule semiconductors.

1. Introduction

Organic electronics utilizes carbon-based organic materials, differing fundamentally from traditional inorganic conductors and semiconductors. Organic electronics offer the potential to revolutionize technology through the development of lightweight, flexible, and cost-effective electronic components. These materials are instrumental in the production of advanced displays, photovoltaic cells, and sensors. The field of organic electronics has evolved significantly since the early 20th century. The discovery of conductive polymers in the 1970s marked a pivotal point, leading to significant advances in organic light-emitting diodes (OLEDs), organic photovoltaics (OPVs), and organic field-effect transistors (OFETs). Notable milestones include the invention of organic thin-film solar cells in 1986 by Tang at Eastman Kodak and the development of OLEDs by the same researcher a year later. The discovery of electroluminescence in poly (p-phenylene vinylene) (PPV) at the University of Cambridge in 1990 further catalyzed progress in the field. The 21st century has seen continued advancements, underscored by the Nobel Prize awarded to Heeger and colleagues in 2000 for their work on conductive polymers [1-3]. As a consequence, organic electronics stand at the forefront of materials science, offering transformative potentials for modern technology. With advancements in materials, production methods, and synthesis strategies, organic electronics continue to enhance the functionality and integration of electronic devices in a variety of applications. The evolution from early discoveries to recent innovations highlights a vibrant field poised for future growth and application expansion.

Thus, herein, this paper studies the significant advancements within the field of organic electronics, focusing on essential materials like organic semiconductors, conductive polymers, and small molecules such as polythiophene, polyacetylene, and fullerene derivatives, which are crucial for improving electronic functionalities. It explores various efficient production methods that enable large-scale and cost-effective manufacturing, particularly highlighting modern techniques like inkjet and screen printing. Innovations in chemical synthesis are discussed, emphasizing polymerization and molecular design tailored to enhance device performance and stability. Furthermore, the review addresses the integration of these materials into flexible electronics, showcasing applications in wearable technology, flexible solar cells, and bendable displays, which illustrate both current capabilities and future potential for organic electronics in enhancing everyday device functionality and user interaction.

2. Fundamental Materials in Organic Electronics

2.1 Conductive Polymers

Conductive polymers uniquely combine the attributes of plastics and metals, with the distinctive capability to conduct electricity [4]. Their molecular structure features conjugated chains with alternating single and double bonds, which enhance charge mobility. These polymers are often modified through doping, a process that alters their conductivity from insulating to metallic levels, thereby optimizing their physicochemical properties such as low density, high thermal stability, and environmental resistance [5]. Additionally, certain conductive polymers can be engineered to be biocompatible and biodegradable, enhancing their suitability for medical and environmental applications. These materials are highly valued for their ease of processing, lightweight nature, and tunable electrochemical characteristics, making them well-suited for a range of applications including flexible electronics, organic photovoltaics, and sensor technology. Notable examples such as polyaniline (PANI), polypyrrole (PPy), and polythiophene (PTh) each provide unique benefits tailored to specific technological needs.

Polypyrrole, in particular, is a well-researched conductive polymer known for its robust stability and high conductivity. The interest in conductive polymers surged following the discovery that polyacetylene's conductivity could be enhanced by up to ten million times upon oxidation with iodine vapor [4]. Today, conductive polymers are typically synthesized using either chemical or electrochemical methods. Chemical synthesis involves mixing a monomer solution with an oxidizing agent like ferric chloride, whereas electrochemical polymerization takes place in a solution of polymer monomers, solvents, and dopants, initiated by the application of an electric current to an electrode.

2.2 Small Molecule Semiconductors

Small molecule semiconductors are low molecular weight organic compounds distinct from polymers due to their defined, crystalline structures, essential for efficient charge transport and strong optical properties in organic electronics. Their conjugated molecular structures allow π-electrons to move freely, enhancing charge carrier mobility. These semiconductors are characterized by high purity, thermal stability, and the ability to form uniform thin films via vacuum deposition, leading to excellent charge transport and electroluminescent efficiencies. Due to their reproducibility and uniform electronic properties, they are ideal for advanced optoelectronic applications like OLEDs and OPVs, offering significant advantages in device performance [6].

Small molecule semiconductors are categorized based on charge transport type into p-type, which uses holes as carriers, and n-type, which relies on electrons. P-type semiconductors often comprise benzene-like aromatic hydrocarbons and their derivatives, leveraging their extensive π-conjugated skeletons for effective hole transport. Scholars have conducted extensive research on these issues and reported important research results. It is worth noting that a recent study successfully designed and synthesized A’-D-A-D-A’ and A’-A-D-A-A’ type small molecule (SM) semiconductors [7]. These were developed by substituting TPD with BT, enhancing the electron-accepting characteristics at the core of the SM structure, as supported by prior computational studies [7].

Organic semiconductors have attracted great attention because of their advantages of structural tunability, flexibility, solution processability, and low cost. Therefore, they are widely used in the manufacture of OLEDs, OPVs, and OFETs [8].

2.3 Organic Photovoltaic Materials

OPV materials, comprised of conjugated polymers or small molecular substances, are specifically designed to convert solar energy into electrical energy. OPVs operate on the principle of absorbing sunlight and generating electricity, similar to other photovoltaic technologies. When incident light has energy equal to or exceeding the band gap, it excites electrons from the HOMO to the LUMO, creating an excited electron and a corresponding positively charged "hole." These oppositely charged particles attract each other to form electron-hole pairs or "excitons." The separation of these charged particles, known as "exciton dissociation," is crucial for extracting electricity from the solar cell. OPVs are characterized by their light absorption efficiency, carrier mobility, and mechanical flexibility, which are essential for enhancing solar cell performance. Although OPVs typically exhibit lower efficiencies compared to inorganic alternatives, their lighter weight, increased flexibility, and cost-effectiveness due to their solution-processability make them attractive. One of the primary benefits of OPVs is their adjustable optical and electronic properties, which enable customization to suit various lighting environments and facilitate integration into a wide range of applications, including building materials. Notable materials used in OPVs include poly (3-hexylthiophene) (P3HT) for electron-donating layers and fullerene derivatives like PCBM for electron-accepting layers, which contribute to the advancement of adaptable and sustainable solar energy solutions.

3. Synthesis Strategies and Production for Organic Electronic Materials

3.1 Synthesis Method

Polymerization techniques are classified into four main types: bulk, solution, suspension, and emulsion polymerization. Typically, polymerization is an exothermic process. The synthesis of organic materials at low temperatures, coupled with their inherent solubility, allows for their deposition on flexible substrates. This characteristic is crucial for enabling the creation of large-scale, continuously produced items. Such properties greatly expand the diversity of production methodologies, providing flexibility in the manufacturing processes for various devices. This adaptability enhances the potential for innovative applications in the field of device fabrication [9].

As a result, the temperature of the system is increasing rapidly as polymerization proceeds. Chemical Vapor Deposition (CVD) is a polymerization method used to create conductive films by depositing gaseous reactants onto a substrate, leading to chemical reactions that form a solid material. This method is prevalent in the electronics industry for manufacturing conductive films used in semiconductors, sensors, and integrated circuits. CVD offers advantages such as the production of uniform, high-purity films with precise control over thickness and composition, making it suitable for industrial scaling. However, the technique requires high operational temperatures, leading to potential substrate compatibility issues, and involves complex process controls and high energy consumption. Safety and environmental concerns also arise due to the use of toxic precursor chemicals.

CVD includes a variety of processes, including atmospheric CVD, metal-organic CVD, low-pressure CVD, laser CVD, photochemical vapor deposition, plasma-assisted CVD, and plasma-enhanced CVD, among others. These methods generally generate thin films through gas-phase and gas-solid chemical reactions [9]. Compared to physical vapor deposition (PVD) methods, the CVD process is often more complex due to thermodynamic and kinetic limitations and depends on the flow dynamics of gaseous reactants and products. However, principles from physical chemistry, heat and mass transfer, and fluid dynamics provide a solid framework for analyzing and optimizing these processes. In CVD, under optimal temperature and pressure conditions, using the concept of a chemically reactive gas solution, an insoluble solid film can be controlled and precipitated onto the substrate. This chapter discusses strategies to ensure efficient vapor precipitation aimed at producing amorphous, polycrystalline, and epitaxial films with the desired composition, morphology, and structure [10].

Oxidative Polymerization is another approach where monomers like aniline or pyrrole are polymerized in the presence of an oxidizing agent within a solvent, commonly producing conductive polymers such as polyaniline and polypyrrole. This method is extensively utilized to create polymers for electrochromic devices, supercapacitors, and anti-corrosion coatings. Advantages include room temperature operations that reduce energy requirements and ease of scaling. It also allows for in-situ doping of polymers to enhance their conductivity. Nevertheless, the method faces challenges such as inconsistent polymer molecular weights and structures, requiring additional processing or doping post-synthesis. The use of hazardous oxidizing agents also introduces safety and environmental disposal issues.

3.2 Production Method

The rapid evolution of flexible organic electronic devices (FEDs) is poised to transform various aspects of everyday life, introducing significant innovations through their diverse applications. While there has been considerable advancement in flexible inorganic devices, particularly with solution-processed silicon, the development of organic, inorganic, and hybrid materials has also seen notable progress. These materials are being specifically engineered for desired properties and enhanced stability, benefiting from interdisciplinary research efforts in their synthesis and preparation. Moreover, the advent of cost-effective, large-scale roll-to-roll production methods for integrating organic electronic devices onto flexible polymeric substrates is set to accelerate their commercialization, expanding their applications across fields such as displays, lighting, photovoltaics, RFID circuitry, chemical sensors, and other cutting-edge technologies [11]. Currently, the production of organic light-emitting diodes (OLEDs) predominantly employs evaporation techniques, where organic materials are deposited onto glass sheets using thin metal stencils known as 'shadow masks.' However, inkjet OLED printing is emerging as a promising alternative. This technique involves the precise ejection of small droplets of liquid organic material onto substrates, offering several advantages including reduced costs, high-quality output, vibrant color production, and ease of use. This method represents a significant step forward in the manufacturing flexibility and scalability of OLED technologies.

4. Applications as Flexible Electronic Materials

Flexible organic electronic devices (FEDs) are expected to change a series of areas, including information visualization, communications, information technology, renewable energy power generation, building lighting, and high-resolution imaging systems [11]. Among their potential applications, prominent are flexible displays, especially flexible organic light-emitting diodes (FOLEDs) and lighting modules, as well as flexible organic photovoltaic cells (OPVs), as well as various data systems and media. Compared with traditional equipment, the fed has significant advantages such as lightweight, thin, strong, and strong adaptability [11]. Currently, flexible OLED technology is predominantly utilized in small-sized flat panel displays, with its commercial application in larger-sized displays progressing rapidly. This technology caters to the growing demand for thinner and lighter smartphones and wearable devices, thereby accelerating advancements in flexible OLED research.

The recent surge in smart materials and wearable electronic technologies has carved a new niche for wearable electronic devices. Unlike traditional electronic devices that are rigid and brittle, wearable electronics conform seamlessly to the human body's uneven surface, enabling precise monitoring of physiological signals. These devices are inherently flexible, comfortably adhering to the skin to detect various bodily signals and environmental data. Consequently, the wearable technology sector is witnessing significant growth, fueled by applications in health monitoring, portable medical equipment, and human-computer interaction.

5. Challenges and Future Directions

Organic/inorganic film packaging technology plays a crucial role in protecting electronic devices such as OLEDs, quantum dot displays, and organic photovoltaic cells from environmental degradation. Researchers globally have experimented with various methods to encapsulate these devices, aiming to shield the active functional materials from air, water, and oxygen. This protective measure is essential to prevent corrosion, oxidation, and the resultant performance decline [12]. The effectiveness of this packaging is dependent on its ability to withstand external stresses and strains without compromising its protective qualities.

This type of packaging, particularly organic/inorganic film packaging, represents the cutting edge in flexible device protection. It effectively prevents gases such as water and oxygen from interacting with the electron and hole transport layers within the devices, thereby averting device failure [13]. This method aligns with the broader trend of enhancing device performance through iterative improvements in materials and manufacturing processes.

In the realm of organic electronics, the development trajectory typically involves the application of newly synthesized organic semiconductor materials to organic transistors, continuous optimization of thin film deposition and liquid phase processes, and determination of the optimal device structure and fabrication method. The performance of these materials is then evaluated through device operation, guiding further enhancements in material performance.

The production of organic materials involves relatively simple processes that lower both the cost and the investment risk, making this technology accessible and appealing for various applications. Despite the nascent stage of organic solar cells (OSCs), they have shown considerable promise due to their low cost, lightweight, wide material availability, and the ability to tailor and modify their molecular structure. The simple manufacturing process of OSCs also facilitates the creation of large-area flexible devices. Looking forward, OSCs hold the potential to power a diverse array of applications, from watches and portable calculators to toys and flexible, integrated systems.

6. Conclusion

In conclusion, the field of organic electronics represents a dynamic and continually evolving frontier in materials science, offering substantial transformative potential across a wide spectrum of applications. This paper has explored the critical aspects of organic electronics, including conductive polymers, small molecule semiconductors, and organic photovoltaic materials, highlighting their unique properties, synthesis techniques, and applicability in various domains. Conductive polymers blend the flexibility of plastics with the electrical capabilities of metals, while small molecule semiconductors provide precise and reproducible electronic properties essential for high-performance optoelectronics. Advancements in production techniques have significantly reduced costs and barriers to entry, paving the way for more widespread adoption and implementation of organic electronics. These technologies not only enhance the performance and utility of electronic devices but also contribute to the sustainability of manufacturing practices.

While challenges remain in enhancing the stability and performance of organic electronic materials, the continued interdisciplinary research and development efforts are likely to overcome these hurdles, heralding a new era of electronic devices that are as flexible and versatile as the materials from which they are made.

References

[1] Pope M, Swenberg C E. Electronic processes in organic crystals and polymers. Oxford University Press, 1999.

[2] Gordon G, Spinks G M, Kane-Maguire L A P. Conductive Electroactive Polymers: intelligent materials systems. CRC Press, 2003.

[3] Balint R, Cassidy N J, Cartmell S H. Conductive polymers: Towards a smart biomaterial for tissue engineering. Acta biomaterialia, 2014, 10(6): 2341-2353.

[4] Gelmi A, Higgins M J, Wallace G G. Physical surface and electromechanical properties of doped polypyrrole biomaterials. Biomaterials, 2010, 31(8): 1974-1983.

[5] Zhou D D, Cui X T, Hines A, et al. conducting polymers in neural stimulation applications. Implantable Neural Prostheses 2: Techniques and Engineering Approaches, 2010: 217-252.

[6] Kyeong M, Park Y, Gu A, et al. Small molecule semiconductors for organic photovoltaics: a truncation approach. Synthetic Metals, 2018, 245: 10-17.

[7] Yang B. Design, synthesis, assembly of N-type small molecule semiconductor materials and their application in organic field-effect transistors. Nanjing University of Posts and Telecommunications, 2023.

[8] Abu-Thabit N Y. Chemical oxidative polymerization of polyaniline: A practical approach for preparation of smart conductive textiles. Journal of Chemical Education, 2016, 93(9): 1606-1611.

[9] Singh T B, Sariciftci N S. Progress in plastic electronics devices. Annu. Rev. Mater. Res., 2006, 36: 199-230.

[10] Nanocoatings and ultra-thin films: technologies and applications. Elsevier, 2011.

[11] Logothetidis S. Flexible organic electronic devices: Materials, process and applications. Materials Science and Engineering: B, 2008, 152(1-3): 96-104.

[12] Feng E, Dong M, Han X, et al. Research progress on organic/inorganic thin film packaging technology for flexible electronic devices. Surface Technology, 2024, 53(03): 101-112.

[13] Seo S W, Chae H, Joon Seo S, et al. Extremely bendable thin-film encapsulation of organic light-emitting diodes. Applied Physics Letters, 2013, 102(16).