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Review of Nanocomposites in Printed Electronics

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Abstract: In the age of swift advancements in science and technology, nanomaterials exhibit significant application potential across various domains owing to their distinctive physical and chemical features, including the realm of printed electronics. Based on the existing literature and data, the paper summarizes the application of nanocomposites in printed electronic applications such as high conductivity circuits and electrodes, sensors and display devices. At the same time, this paper also objectively points out the current nano composite applications in the field of some challenges, such as material dispersion and performance of balance, material green preparation process and large-scale production problems, etc., and the prospect of the future development trend, the study shows that the nanocomposite excellent performance because of unique properties, such as significantly improved conductivity, sensitivity and the optimization of display effect, they can not only promote printing electronic technology to the direction of high precision, high efficiency, more intelligent electronic devices, miniaturization and wearable provides the key material support.

1. Introduction

Today, the profound integration of information technology and materials science has rendered printing electronic technology, characterized by low cost, large-area manufacturing, and flexibility, a focal point of interest in fields such as flexible electrodes, solar cells, and sensors. This technology has emerged as a significant catalyst for the advancement of next-generation electronic devices [1]. Traditional silicon-based electronic devices are difficult to be lightweight, flexible and highly integrated due to their rigid substrate and complex process. This contradiction in the field of flexible supercapacitors (SCs) and conductive ink is prominent: although SCs are regarded as the ideal energy scheme of wearable electronic devices, but the existing electrode material rigidity characteristics seriously restricted the commercialization process and in terms of conductive ink, high silver nanoparticle composite material (AgNPs) content can significantly improve the conductivity, but the excessive stabilizer insulation effect and high cost of double barriers [2][3]. This review systematically combs the innovative applications of nanocomposites in flexible energy storage, intelligent sensing, new display and other fields, deeply analyzes their performance optimization mechanism, and puts forward breakthrough development strategies in view of the existing technical bottlenecks. Nanocomposites can not only promote the innovation of printed electronic technology, but also provide strong support for the intelligence, miniaturization and wearable of electronic products. Therefore, by establishing the theoretical framework for basic research and industrial application in related fields, this review reveals the internal correlation of material-structure-performance, which has important guiding value for accelerating the research and development process of next-generation electronic devices.

2. High Conductive Path And Electrode

2.1. High-Performance Electroconductive Ink

As the core material of printing electronic devices, high-performance conductive ink needs to have both key characteristics such as high electrical conductivity, printing suitability, substrate adhesion and environmental stability [4]. Consequently, printable conductive inks are essential for the production of conductive circuits that interconnect the functional components of electronic devices. Among the numerous conductive inks, currently, it has developed new inks based on silver nanoparticles (AgNPs) / silver ion composite structure, its innovative design has achieved multiple performance breakthroughs: first, silver ink organic ions selectively adsorbed on the surface of AgNPs, formation of the neck junction structure by in situ reduction. It effectively reduces the contact resistance between the adjacent nanoparticles; next, the introduction of diethanolamine (DEA) as a bifunctional additive, both as a reducing agent to promote the conversion of silver ions to the metallic state, and regulate the particle migration behavior during drying through intermolecular forces, Thus, a high-density conductive network is formed on the flexible phase paper substrate. It is worth noting that the silver content of the composite ink can be as low as 4.68 wt%, showing a significant cost advantage while maintaining excellent electrical conductivity (<5Ω/ sq). Its cycle life is more than 3.44×104times, providing a reliable solution for large-scale manufacturing of flexible printed electronics such as RF labels and stretchable electrodes [3].

2.2. Preparation of Flexible Electrodes

In recent years, the swift advancement of portable and wearable electronic gadgets has facilitated the innovative study and development of flexible energy storage systems. These devices require not only high energy density, power density, and extended cycle stability, but also enhancements in performance flexibility, safety, dependability, and mechanical properties. In this context, supercapacitors (SC) with flexible, flexible and stretchable characteristics have become ideal choices for energy storage systems for wearable electronic devices due to their unique mechanical adaptability. The development of supercapacitors is of great significance to alleviate the current energy crisis, and carbon fibers (CFs) are regarded as highly potential sustainable electrode materials due to their high elasticity, easy workability, excellent mechanical strength and environmentally friendly characteristics. It is worth noting that in the supercapacitor system, the carbon fiber assumes the dual function of both the electrode active material and the fluid collector. However, the core bottleneck of carbon fiber as an electrochemical reaction material lies in its lower intrinsic specific capacitance. In view of this problem, Susmi Anna et al. significantly improved the specific capacitive performance of combining carbon fiber with conductive polymer, nano-carbon materials, MXenes or transition metal oxides, etc., and significantly improved the specific capacitive performance of carbon fiber-based supercapacitors. Future research will focus on the development of new and more economical, environmentally friendly and efficient synthesis processes of carbon fiber-based electrode materials, and promote the in-depth application of flexible carbon fiber supercapacitors in miniaturization and wearable devices, so as to provide better energy solutions for daily life [2].

3. Sensors

3.1. Chemical Sensor

Polylactic acid (PLA) nanocomposites provide superior attributes, including low weight, eco-friendliness, ease of fabrication, affordability, and exceptional biocompatibility. These attributes can be employed in numerous secure and effective applications, including biosensors, wearable electronics, and intelligent materials. Nanocomposites are often composed of a polylactic acid matrix infused with nanofillers, including carbon nanotubes, quantum dots, nanoclays, nanofibers, graphene, and various other polymers. PLA nanocomposites have superior electrical performance, enhanced thermal conductivity (thermoelectric power factor of 176 $\mu W \cdot m^{-1} \cdot K^{-2}$), reduced dielectric loss (minimum of 0.0008), improved thermal stability, and biodegradability compared to PLA, among other attributes. Enhanced performance can be achieved by precisely regulating the ratio of nanomaterials to the polylactic acid matrix, the temperature during the preparation process, and the shape of the final product. Consequently, PLA nanocomposites have been extensively utilized in water, piezoelectric/strain applications, and chemical/biological contexts.Sensor-based nanocomposites frequently integrate the benefits of individual components to enhance sensitivity, durability, and cost-effectiveness. The PLA and ZnO-based one-dimensional fiber nanocomposite, fabricated through electrospinning technology, functions as a relative humidity sensor. Additionally, piezostatic and strain sensors composed of polylactic acid nanocomposite are capable of measuring deformation and stress variations induced by mechanical loads, suitable for both static and dynamic measurements, and are designed for long-term use due to their durability. Consequently, PLA nanocomposites are anticipated to assume a progressively significant position in the advancement of diverse sensing technologies [5].

3.2. Pressure Sensor

The core characteristic of the pressure sensor is that the various pressure changes or mechanical deformation applied by the external environment can be accurately and efficiently converted into quantifiable and recordable electrical signals. This conversion mechanism is not only a bridge between the physical world and the electronic world, but also the key to monitoring, analyzing and understanding many complex physical processes. Conjugated polymers (CPs) show excellent electrical conductivity and mechanical flexibility with their unique π conjugated system, both biocompatibility and adjustable electronic characteristics (semiconductor to metal), and have important application value in capacitive, piezoresistive, piezoelectric and triboelectric sensors. Its delocalized π electronic system can improve the sensor stability, sensitivity and detection range through intermolecular interactions such as hydrogen bonding and charge transfer. For example, polypyrrole can significantly enhance the stretchability through composite flexible matrix materials. The Hajghassem team developed a carbon nanofiber/PAN/silicone rubber nanocomposite that establishes a conductive network via carboxylated carbon nanofiber loading and composite fabrication with silicone rubber. This resulted in a stretchable staggered capacitive strain sensor exhibiting high sensitivity and an extensive linear strain range, achieving a combination of elevated sensitivity and broad linear strain response [6]. The successful study and development of the sensor demonstrates the significant potential of conjugated polymers in pressure sensing, while also offering novel concepts and directions for the future advancement of sensor technology.

4. Display Device

4.1. The Liquid Crystal Display Liquid Crystal (LC)

The material's sensitivity to electric fields, magnetic fields, light fields, and surface interactions with external fields has significantly advanced liquid crystal display (LCD) technology, which now dominates global display demand [7]. A significant proportion of the atoms in the nanocrystals (NC) are located on the surface. Typically, surface atoms display surface-associated trap states that function as rapid non-radiative deexcitation pathways for light-induced charge carriers, impeding their luminous quantum yield (QY). To augment the luminescent quantum yield (QY), the epitaxial deposition of additional semiconductor materials (shell) onto the surface (core) of nanocrystals (NC) is employed to fabricate core-shell nanocrystals (CSNC). This core-shell architecture enhances luminescence efficiency, physical properties, and chemical stability of the nanocrystals, achieving a quantum efficiency of 61.2%, a high dispersion of 312 mg/mL, and a low quenching ratio, making it suitable for luminescence enhancement in liquid media. Consequently, CSNCs represent a prospective additive. Innovative CSNCs can function as efficient intermediaries for organizing the LC midphase due to their core-shell structure, which inhibits charge transfer and hence enhances the stability of the composite. The characteristics of CSNCs, including size, core material qualities, end sealer, and compatibility within the LC matrix, are essential for optimizing the performance of CSNCs/LC composites. The robust and adjustable luminescence of CSNCs can markedly enhance brightness (up to 1050 cd/m^2) and contrast, leading to a low-power, brighter display device utilizing CSNCs/LC composites [8].

4.2. Organic Light-emitting Diode (OLED)

Traditional OLED electron injection efficiency, hole leakage and large area device uniformity, and the new design of organic-inorganic nanocomposites, such as carbon point, and carbon nanotube material, both flexible / film of organic materials and high carrier mobility of inorganic materials, can greatly optimize the charge management [9]. Carbon points (CD) are hybrid carbon atoms including sp2 and sp3 configurations, featuring hydrophilic functional groups on their surface. This substance exhibits low toxicity, high solubility in water and specific organic solvents, as well as adjustable electrical and optical characteristics. Heteroatom doping, surface modification, and passivation of organic compounds are techniques to augment charge density properties. The nitrogen doping process is both straightforward and successful, making it one of the most extensively researched techniques. Nitrogen-doped carbon dots (N-CD) often exhibit a high photoluminescence quantum yield (PLQY); the conjugated structure of N-CDs and the active sites created by nitrogen doping facilitate electron migration and enhance the conductivity of the composite. Many of the studied nitrogen-doped carbon point / zinc-oxide nanocomposites (N-CDs / ZnO) serve as intermediate layer in OLED prepared by solution method, whose main function is to improve the device performance by optimizing charge transmission and interface characteristics; N-CDs have good processing stability and compatibility, stable and stable in solution processing and device working conditions, not easy to decompose or reunite. After composite with ZnO, the material can still be prepared by spin coating, ink jet printing and other solution processes to meet the manufacturing requirements of low-cost flexible OLED. At the same time, it has a photoelectric synergistic effect, and the fluorescence characteristics of N-CDs combine with the semiconductor characteristics of ZnO, which may optimize the device efficiency through resonance energy transfer or interface charge separation [10].

5. Discusssion

5.1. Related Challenges

Although nanocomposites have been widely used in the field of printing electronics, there are still some challenges at this stage:

5.1.1. Challenges of the Dispersion and Property Balance of Nanomaterials

In the field of printed electronics, the high surface energy of nanoparticles (such as carbon nanotubes and metal nanowires) can easily lead to the agglomeration phenomenon, which directly leads to the fracture of the conductive network and the deterioration of the printing pattern uniformity. To improve dispersity, existing solutions usually use surface modification or dispersant optimization, but such methods may sacrifice the material's intrinsic conductivity for the introduction of insulating layers or impurities [3]. This "dispersion-conductivity" has become the core contradiction restricting the performance improvement of nanocomposites.

5.1.2. Technical Bottlenecks of the Integration of a Flexible Sensor Systems

The ultimate goal of flexible wearable sensor system is to realize the efficient integration of pressure sensors, multimodal sensors and miniature power supply on a single chip. However, this field still faces two challenges: limited chip area needs to be compatible with heterogeneous sensors, involving a complex micro-nano processing process and interface compatibility; technical problems of data acquisition (pressure / temperature / strain) and real-time analysis of low power consumption.

5.1.3. Emergency Needs of High-performance Material Development and Green Manufacturing

Material level: It is urgent to develop new conjugated polymers with high tensile (> 200% strain) and stable electrical response, and to expand the sensitivity linear range of the pressure sensor (target> 100 kPa -1), shorten the response time (<10 ms), reduce the detection limit (<1 Pa), and improve the cycle stability (> 104times).

Process level: at present, the synthesis of high purity inorganic nanomaterials (such as ZnO with uniform size) depends on complex processes, resulting in high cost; and the use of toxic solvents such as chlorobenzene in solution processing forces the industry to accelerate the development of water-based / bio-friendly solvent system to meet the industrial emission standards [4].

5.2. Development Trend

The future development trend of nanocomposites in the field of printed electronics will revolve around the three core directions of high performance, intelligence and green and sustainable.

5.2.1. Development of New Functional Materials

The design of two-dimensional materials (such as MXene and black phosphorus) and nanocomposite systems with heterogeneous structures will break through the limits of traditional electrical/dielectric properties. For example, self-healing nanocomposites can extend the life of devices through dynamic bonding, meeting the needs of wearable devices [11].

5.2.2. Green Manufacturing and Circular Economy

Bio-based nanomaterials (e.g. cellulose nanocrystalline / conductive polymer complexes) will replace petroleum-based feedstocks, combined with the water-based ink and solvent-free printing process, greatly reduce the carbon footprint. At the same time, biodegradable nanocomposites and the modular design will promote e-waste recycling, such as reversible crosslinked nanosilver-bioplastic systems.

5.2.3. Scale and Integrated Production

Capacitors are lightweight, integrated, and intelligent devices that are continuously advancing flexible dielectric materials with high power density and superior energy storage capabilities. Polyvinylidene difluoride (PVDF)-based nanocomposites exhibit significant potential for extensive practical applications owing to their high polarization and ease of production. At the same time, multi-material coprinting technology will promote the integration of system-level printing electronics into [12].

6. Conclusion

With their structural design ability and performance tunability, nanocomposites have become an indispensable core material to promote the innovation of printed electronic technology, especially in high conductive circuit, sensors and display devices. In the field of conductive circuit and electrodes, the silver-based composite ink realizes the unification of low temperature curing and high electrical conductivity through the nanoparticle-ion synergistic effect; in sensor application, the polylactic acid-based nano-composite realizes high sensitivity detection to the pressure and humidity signals, and the response speed and durability are close to the biological sensing system; in terms of display device, the composite system of CSNCs and liquid crystal optimizes the luminescence efficiency through energy belt engineering, which significantly improves the charge carrier balance and device life of flexible OLED. However, problems such as dispersion and performance balance of nanomaterials and integration of flexible sensor system still need to be solved. In the future, breaking through the bottlenecks such as material cost, environmental compatibility and multi-functional integration, high-performance material development and green manufacturing will accelerate the printing electronic technology to high-performance, intelligent and sustainable development.

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