

Current and Future Applications of Carbon Nanotubes in Flexible Electronics

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Abstract. With the rapid development of wearable devices, smart medical and other industries, traditional rigid electronic materials are difficult to meet the requirements of modern electronic devices for flexibility and stability. Carbon nanotubes have become an ideal material for flexible electronic devices due to their unique performance characteristics. This paper focuses on the preparation and processing technologies of carbon nanotube flexible electronic materials, including the floating catalyst chemical vapour deposition method, solution method processing and selective deposition, dry transfer and orientation alignment, and other advanced technologies. It analyses the advantages and limitations of various technologies. Meanwhile, this study discusses in detail the specific applications of carbon nanotubes in three major fields, namely, flexible thin film transistors and logic circuits, flexible transparent electrodes, and multifunctional flexible sensors, demonstrating their potential for practical engineering applications. However, the technology still faces challenges such as difficult process control, complex processing, and insufficient long-term stability, which constrain its industrialisation. This study provides a systematic theoretical guidance and technical reference for the development of carbon nanotube flexible electronics, which is of great value in promoting the innovation and application of next-generation flexible electronic devices.

Keywords: Carbon nanotubes; Flexible electronics; Wearable sensors.

1. Introduction

With the rapid development of flexible electronics technology, traditional electronic materials have been difficult to meet the requirements of flexibility, stretching, and stability of materials in the fields of wearable devices, biomedical sensing, and soft robots. Carbon nanotubes (CNTs) are regarded as one of the ideal materials for flexible electronics due to their unique mechanical properties, excellent electrical characteristics, and good chemical stability. Studies have shown that carbon nanotubes can maintain the stability of electrical properties under large deformation, and at the same time possess high carrier mobility and mechanical strength, which provides an important material basis for the construction of high-performance flexible electronic systems [1].

In recent years, carbon nanotubes have made significant progress in the field of flexible electronics. Bao et al. developed high-performance flexible transistors based on orientationally aligned carbon nanotube films, achieving carrier mobility of more than $1000\text{cm}^2/\text{V}\cdot\text{s}$ and excellent mechanical stability [2]. Lianmiao Peng's team proposed an ultrashort carbon nanotube network preparation process, which shows great potential for low-power flexible display driver circuits [3]. In addition, researchers at MIT reported a multifunctional e-textile based on carbon nanotube fibres, enabling long-term stable monitoring of physiological signals. These results highlight the important role of carbon nanotubes in driving flexible electronics towards greater efficiency and stability [4].

The purpose of this paper is to systematically review the current research status and development trend of carbon nanotubes in the field of flexible electronics, focusing on their material preparation method, processing technology, and specific application scenarios, and analyze the current technical challenges and future development direction. By sorting out the key technical issues at multiple levels of flexible material devices, this study will provide a theoretical basis and technical reference for the

further development and application of carbon nanotube-based flexible electronic materials, which is of great significance in promoting the development of next-generation flexible electronic devices.

2. Preparation and Processing Techniques for Carbon Nanotube Flexible Electronic Materials

2.1. Floating Catalyst Chemical Vapour Deposition Direct Synthesis and In-situ Deposition

Floating Catalyst Chemical Vapour Deposition (FCCVD) Direct Synthesis and In-situ Deposition technique integrates the synthesis of CNTs with their deposition on flexible substrates in the same chemical vapour deposition (CVD) reactor. Typically, ferrocene is used as the catalyst precursor and sulphur or sulphur dioxide as the growth promoter, which are injected into the high-temperature reaction chamber along with a carbon source (e.g., ethanol, methane). The catalyst particles in aerosol state decompose at high temperatures, catalyse the growth of CNTs, and are carried by the gas flow and deposited directly onto a flexible substrate placed downstream of the reaction chamber, e.g., polyimide PI, quartz fibre cloth, etc., to form a homogeneous nanotube film or network. This method avoids complex transfer steps, reduces material contamination and damage, and makes it easy to achieve large-area, continuous production.

Jin Zhang et al. developed a ‘nanotube tentacle’ in situ growth strategy to grow vertical carbon nanotube arrays directly on the surface of ultra-tough carbon nanotube fibres. This method solves the key problems of surface inertness and poor interfacial bonding with the polymer matrix of traditional fibre materials. The prepared carbon nanotube/polymer composites show excellent mechanical properties and durability, laying the foundation for fabricating high-strength flexible conductors and sensors [5]. Ren Tianling et al. constructed a three-dimensional interconnected carbon network by growing CNTs in situ on the surface of porous graphene fibres using FCCVD. This structure effectively solves the problem of single material fracture under repeated deformation, and gives the fibre electrode high flexibility and stability, and the capacitance retention rate is more than 95% after 10,000 times of bending, which has been successfully applied to high-performance braidable supercapacitors [6].

2.2. Solution Method Processing and Selective Deposition

The solution method processing and selective deposition technology firstly disperses CNTs in a solvent by surfactant dispersion or covalent functionalization to form a stable CNT ink or solution. The CNT solution is then patterned and deposited onto a flexible substrate using a variety of printing techniques such as inkjet printing, aerosol spraying, screen printing, and various other printing techniques or coating techniques (e.g., spin-coating, drop-coating, and Meyer bar scraping). The core advantage of this method is its compatibility with existing patterning processes, which enables low-cost, large-area, customised patterning and is well-suited for the fabrication of flexible circuits.

Zhenan Bao et al. developed a high-purity, high-concentration semiconductor-based carbon nanotube ink and combined it with photolithography to achieve wafer-scale, high-uniformity patterning of carbon nanotube films. They solved the challenges of semiconductor-type CNT purity and deposition uniformity through fine polymer sorting and ink formulation optimisation, and prepared large-area flexible transistor arrays with highly consistent performance, which provides a key technology for future flexible displays and integrated circuits [7]. Scepter Zhang et al. used inkjet printing technology to print pre-prepared CNT ink directly onto the surface of porous elastomers, and the CNTs were able to penetrate and anchor in the elastomer's three-dimensional network. This method solved the problems of traditional surface-deposited CNTs with weak bonding to the substrate and easy to fall off or form cracks under stretching, and the prepared flexible sensors can still work stably under 50% tensile strain, which realizes the accurate monitoring of human body movement and large deformation [8].

2.3. Dry Transfer and Orientation Alignment Techniques

Dry transfer and orientation alignment techniques typically begin with the growth of high-quality, highly oriented carbon nanotube arrays or superparallel films by CVD on a rigid growth substrate (e.g., silicon wafer, quartz). These are then laminated intact, roll-to-roll or sheet-to-sheet, onto a target flexible substrate by a mechanically-assisted or solution-assisted transfer method. Commonly used methods include dry pick-up transfer using a PDMS stamp or transfer using roller embossing. The biggest advantage of this technique is that the excellent intrinsic properties of CNTs on the growth substrate (especially high carrier mobility and uniform orientation) can be retained almost without loss in the flexible device, which is an ideal way to realise high-performance transistors.

Peking University has developed a heat-releasing tape-based ‘lift-and-dry’ dry transfer technique, which is capable of nondestructively transferring wafer-scale high-density, high-semiconductor purity oriented carbon nanotube arrays onto flexible PI substrates. They successfully solved the industry problem that high-density CNT arrays are prone to wrinkles, rupture and performance degradation during the transfer process, and prepared flexible transistors with performance change of less than 10% after 1000 times of repeated bending under 5mm bending radius, with the performance index reaching the international leading level, which lays the foundation of constructing a flexible central processing unit (CPU) [9]. Ma Zhenqiang's team used a roller-assisted dry transfer technique to achieve continuous, large-area transfer of super-parallel-row carbon nanotube films from a growth substrate to a variety of heterogeneous flexible substrates. This method is highly efficient and scalable, and has successfully prepared large-area flexible transparent conductors with uniform properties, whose excellent conductivity and light transmission are expected to replace brittle indium tin oxide (ITO) films for flexible touchscreens and OLED lighting [10].

3. Major Applications of Carbon Nanotubes in Flexible Electronics

3.1. Flexible Thin-Film Transistors and Logic Circuits

Carbon nanotubes, especially semiconducting single-walled carbon nanotubes, have become one of the best candidates for constructing channel materials for flexible thin-film transistors (TFTs) due to their excellent performance advantages. Compared with traditional amorphous silicon or multi-metal oxide TFT, its carrier mobility is 1-2 orders of magnitude higher, enabling higher operating frequency and faster switching speed, laying the foundation for high-performance flexible display drivers and integrated circuits; at the same time, it has excellent switching ratios and carrier transport capabilities, which can significantly reduce device energy consumption; more importantly, the carbon nanotube network is intrinsically flexible and mechanically robust. More importantly, carbon nanotube networks are intrinsically flexible and mechanically robust, and can withstand great mechanical stresses, enabling transistor arrays to maintain stable performance under repeated bending and folding. Based on these advantages, carbon nanotube TFTs have shown potential for use in flexible display screen driver backplanes, and are expected to replace silicon-based transistors on rigid glass substrates, driving the development of foldable smartphones and TVs. In addition, its progress in building basic logic gates (e.g., inverters, NOR gates, and NAND gates) and complex circuits is accelerating the realisation of fully flexible microprocessors and wearable computing systems [11].

3.2. Flexible Transparent Electrodes

Carbon nanotube networks are regarded as an ideal material to replace conventional indium tin oxide (ITO) transparent electrodes due to their high electrical conductivity, excellent optical transmittance, and outstanding mechanical robustness. They exhibit multiple advantages in flexible transparent conductive applications. First, the carbon nanotube network has intrinsic flexibility, which fundamentally overcomes the shortcomings of ITO prone to brittle cracking, and is suitable for flexible devices that can be repeatedly bent and folded; second, it has excellent chemical stability, and is more tolerant to water and oxygen environments, which is conducive to enhancing the reliability of the device under complex conditions; in addition, carbon nanotube materials are highly

compatible with the solution method of processing process, which can be realised through the coating, printing and other means. In addition, carbon nanotube materials are highly compatible with solution-based processing and can be patterned by coating, printing, etc., which provides an important way for industrial applications. Based on these characteristics, carbon nanotube transparent electrodes have demonstrated their potential for a wide range of applications in a number of cutting-edge fields, such as being used as the sensing layer and electrodes in flexible touchscreens to realise the touch function of bendable smartphones and tablets; being integrated as the anode or cathode in OLED lighting and displays to promote the development of curling light-emitting panels; and acting as transparent electrodes in flexible solar cells to effectively enhance the performance of lightweight and deformable photovoltaic devices. charge collection efficiency of lightweight and deformable photovoltaic devices [12].

3.3. Multifunctional Flexible Sensors

Carbon nanotubes are ideal for building highly sensitive, wearable sensors due to their large specific surface area and electrical properties that are highly sensitive to external environmental stimuli. Their significant advantages include high sensitivity and the ability to induce significant resistance changes through small strains or trace molecular adsorption. Carbon nanotubes have a wide sensing range, capable of detecting weak physiological signals such as pulse and respiration, as well as sensing large limb movements, and good multifunctional integration potential, enabling parallel detection of multiple physical or chemical signals on a single platform through surface functionalization. Based on these characteristics, carbon nanotube sensors can be implanted into textiles or directly attached to the skin as strain/pressure sensors for real-time monitoring of physiological parameters such as pulse and joint activity; modified with specific polymers to form gas/chemical sensors for selective detection of hazardous gases, such as NO₂ and NH₃, in the environment; and, further, integrated into bionic electronic skins as the core sensing elements. As a core sensing element to achieve multi-modal sensing of pressure, temperature, humidity, etc, on a flexible substrate, providing skin-like sensing capability for robotics.

4. Challenges and Development

Despite the great potential of carbon nanotubes in the field of flexible electronics, they still face a series of serious challenges in moving from the laboratory to industrialisation. Firstly, in terms of material preparation, there is still a lack of efficient, low-cost batch synthesis of high-purity semiconductor-type carbon nanotubes; the residual metal-type tubes will seriously reduce the performance of the device, and the difficulty of the chiral control makes it difficult to ensure the consistency of the electrical properties. Secondly, at the level of processing technology, the existing technology is difficult to achieve high-precision, high-resolution patterning of carbon nanotubes on flexible substrates, traditional photolithography and other processes, and flexible substrates with poor compatibility, while the emerging printing technology is faced with the problem of nanotube dispersion stability and uniformity of the imprint. Finally, the interfacial bonding strength between carbon nanotubes and polymer substrates is insufficient, and is prone to performance degradation under complex mechanical stresses such as repeated bending and stretching, as well as poor barrier properties to external environmental factors such as oxygen and water vapour, which affects its long-term work stability. These factors together constrain its commercial application process.

Future development will focus on a number of key directions. At the material level, there is an urgent need to develop a new generation of gas-phase or solution-phase synthesis and separation technologies to achieve precise regulation of the chirality, diameter, and conductive properties of carbon nanotubes, so as to break through the bottleneck of low-cost, batch preparation of high-purity semiconductor-type carbon nanotubes, and provide a stable and reliable material base for industrial applications. Secondly, the manufacturing process focuses on the development of large-area, high-throughput processing solutions that can be deeply integrated with roll-to-roll printing technology, such as high-uniformity nanotube ink preparation, high-speed patterning on flexible substrates, and a

low-temperature integration process, to significantly reduce the cost of production and meet the needs of large-scale manufacturing. In addition, at the system and application levels, it is necessary to actively promote the innovation of new multifunctional integrated systems for specific scenarios, such as IoT sensing nodes and smart medical implantable/attachable devices, and to construct intelligent flexible microsystems by heterogeneously integrating sensing, storage, computation, and communication units, so as to ultimately realise the fundamental leap of carbon nanotube flexible electronics technology from a single high-performance device to an integrated, adaptive, and complex system.

5. Conclusion

This study shows that carbon nanotubes have become a key material to promote the development of flexible electronics technology by virtue of their excellent electrical properties, excellent mechanical flexibility, and huge specific surface area. Advanced preparation techniques, such as floating catalyst chemical vapour deposition, solution processing, and dry transfer, enable the preparation of high-performance and highly uniform carbon nanotube films and arrays. Based on these materials, core devices including flexible transistors, transparent electrodes, and multifunctional sensors have been successfully constructed, and have shown great application potential in the fields of flexible displays, wearable health monitoring, and bionic electronic skin, proving the unique advantages of carbon nanotubes in realising high-performance and highly integrated flexible electronic systems. In this study, the whole chain of carbon nanotube flexible electronics technology from material preparation, device processing, to system integration, is systematically sorted out. In the future, carbon nanotube flexible electronics technology is expected to fundamentally change the form and function of electronic products.

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