Properties and Sample Applications of Different Carbon Nanomaterial

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Carbon nanomaterials such as nanodiamond and nano-fullerene C60 are common examples of zero-dimensional carbon nanomaterials that are utilized in implantable brain interfaces. Carbon nanomaterials offer superior charge injection capabilities and high conductivity, enabling high-throughput electrode interfaces that can enhance signal recording quality and stimulation efficiency. In addition, the optical properties and chemical stability of carbon nanomaterials, along with their large surface area, make them ideal for surface charge modification and the incorporation of fluorescent tags, cell-specific targeting molecules, and disease-specific targeting molecules.

carbon nanomaterials   implantable brain–computer interface

1. Introduction

Carbon nanomaterials have emerged as promising candidates for biomedical applications in the past decade, owing to their unique physical and chemical properties. Unlike other nanoparticle materials, carbon is biocompatible and non-toxic, which makes it an ideal material for implantable neural interfaces [1]. The similar size of nanoparticles and certain essential proteins makes them suitable for in vivo applications [2]. The small size of nanocapsules and nanocarriers makes them useful for loading and delivering drugs and genes across the blood-brain barrier to specific sites in the brain [3]. Carbon nanomaterials offer superior charge injection capabilities and high conductivity, enabling high-throughput electrode interfaces that can enhance signal recording quality and stimulation efficiency. In addition, the optical properties and chemical stability of carbon nanomaterials, along with their large surface area, make them ideal for surface charge modification and the incorporation of fluorescent tags, cell-specific targeting molecules, and disease-specific targeting molecules [4][5].

2. Properties and Sample Applications of Different Carbon Nanomaterial

2.1. Zero-Dimensional Carbon Materials: Fullerene and Nanodiamond

Nanoparticles, quantum dots, and nanoclusters, which possess dimensions on the order of nanometers in all three directions, are considered zero-dimensional nanomaterials. Carbon nanomaterials such as nanodiamond and nano-fullerene C60 are common examples of zero-dimensional carbon nanomaterials that are utilized in implantable brain interfaces.

Nanodiamonds are a type of carbon-based crystal with a diamond-like structure and minimal cytotoxicity [6]. During production, Type Ib (dispersed state) nanodiamonds are annealed at high temperatures to create a nitrogen-vacancy (NV) color center. This defect center has strong absorption and emission at 560 nm and is located deep within the nanodiamond core, making it unaffected by surface chemistry [7]. The distinct fluorescence of negatively charged NV color centers can be selectively controlled by spin manipulation, making it useful in ultrasensitive biosensing applications [8]. The fluorescence change of NV color centers can be modulated by lasers and microwaves to achieve ultrasensitive sensing [9][10][11]. Moreover, nanodiamond surfaces can be modified to enable biomolecule binding. Thin films can be selectively biomodified and adsorbed to integrate DNA and other biomaterials with microelectronics to create bioelectronic sensing systems [12]. Nanodiamonds can also be used for cellular tracing in vivo for cancer cell and stem cell division and differentiation [13], as a coating material to promote the formation of functional neuronal networks [14][15], and as a fluorescent nanodiamond-assisted cellular in vivo imaging technology, among other applications [15].

Fullerenes are a zero-dimensional class of conjugated spherical molecules composed of sp2 hybridized carbon atoms that exhibit unique topological structure and photoelectrochemical properties compared to other carbon nanomaterials, including strong photoelectric and photothermal conversion effects, long-lived triplet states, and high visible-light absorption ability. Recent years have seen interesting applications of C60-based materials in analytical sensing. The properties of fullerenes are optimized by synthesizing C60 derivatives and non-covalent modifications and then employing them for the electrochemical and photoelectrochemical sensing of biomolecules. Chaniotakis et al. first described a fullerene-mediated electrochemical biosensor [16] for glucose. In this biosensor, C60 is adsorbed in a porous carbon electrode for electron transport. C60 serves as an efficient electron acceptor [17] and exhibits rich electrochemical behavior owing to its high number of conjugated double bonds and low-vacancy LUMO orbitals, endowing it with a strong electron acceptor ability. Furthermore, the unique cage structure of fullerenes enables the insertion of other small molecules into their cavities, leading to significant modifications in the physical and chemical properties of fullerene molecules in applications such as tumor imaging [18][19][20] and drug loading [21].

2.2. One-Dimensional Carbon Materials: Carbon Nanotubes

Carbon nanotubes (CNTs) are a remarkable one-dimensional hollow tubular nanomaterial with an ultrahigh aspect ratio. They possess excellent electrical conductivity and flexibility, as well as a unique high aspect ratio and surface area, making them an ideal candidate for hosting drugs or biospecific molecules. In addition, CNTs exhibit exceptional drug loading capacity via covalent or non-covalent interactions. These characteristics have propelled CNTs as promising materials for various biomedical applications. In particular, their distinct electrical properties enhance biocompatibility investigations for brain applications. Furthermore, the needle-like shape of CNTs allows them to penetrate the cytoplasmic membrane, enabling the delivery of drugs across the membrane. These attributes make CNTs an exciting platform for drug delivery and medical applications.

Carbon nanotubes possess unique physicochemical properties that make them highly attractive for use in various neurological applications. One key advantage of these nanomaterials is their low impedance, high charge transfer capabilities, high sensitivity, and easy modifiability, which make them ideal candidates for use as electrode materials [22][23][24]. For instance, Gross et al. demonstrated that carbon nanotube coatings can reduce electrode impedance, increase charge transfer, and enhance the recording and stimulation properties of neural electrodes, enabling the sensitive and selective detection of in vivo diseases [25]. Lee et al. developed carbon nanotubes with a unique structure that can be utilized for a wide range of applications, including artificial synapses with proprioceptive feedback that ensure a steady transmission of nerve impulses to the muscles [26]. However, primitive carbon nanotubes are not completely soluble in all solvents, which can cause specific health issues. To address this, researchers are investigating their biological features in terms of toxicity [27]. The discovery of efficient techniques for chemically modifying carbon nanotubes has accelerated the development of soluble forms for a variety of biological applications, including drug administration [28][29][30][31]. To be effective in delivering therapeutic agents, a carrier must be able to efficiently penetrate cells. Functionalized carbon nanotubes (f-CNTs) have the ability to traverse cell membranes and localize to specific cellular compartments when treated with fluorescein isothiocyanate (FITC) or fluorescent peptides [32].

2.3. Two-Dimensional Materials: Graphene and MXene

Recently, there has been a growing interest in two-dimensional (2D) functional materials, specifically graphene. Graphene is a fundamental building block for various carbon materials, as it can be manipulated into zero-dimensional fullerenes and one-dimensional carbon nanotubes, and stacked into three-dimensional graphite [33]. Graphene consists of carbon atoms connected by sp2 hybrid orbitals, forming a carbon–carbon bond length of 0.142 nm [34]. The remaining electron in the carbon atom's p orbital produces the enormous π-bond, which contributes to the structural stability of graphene. The interaction between electrons in graphene and the periodic potential of its honeycomb lattice produces new quasiparticles known as massless Dirac fermions, which exhibit unique properties such as the anomalous quantum Hall effect [35][36]. Due to its exceptional electron mobility and electrocatalytic activity, graphene has emerged as a promising material for biosensing electrodes, making it increasingly relevant for a broad range of neurological applications [37][38][39].

MXenes refer to a group of two-dimensional (2D) metal carbides and nitrides that possess a honeycomb-like structure, consisting of numerous layers of transition metal (M) atoms [40][41][42]. These materials are produced by selectively etching A-layer atoms from the MAX phase, resulting in loosely stacked MX layers, which are commonly known as "MXene" and can be further separated into individual monolayer sheets [40]. It is predicted that metallic MXene monolayers possess a high electron density at the Fermi energy level [43][44]. MXenes exhibit robust electrical conductivity, feature abundant functional groups like hydroxyl, fluorine, and oxygen, and exhibit varying surface characteristics, which make them an excellent choice for bio-electronic interfaces.

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