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Application of Nanomaterials in Brain-Computer Interfaces

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Abstract:

Brain–computer interfaces (BCIs) are reshaping how humans interact with machines by establishing direct neural pathways for communication. This review explores how nanomaterials—particularly graphene, carbon nanotubes, black phosphorus, and layered double hydroxides—are advancing BCI capabilities. These materials each bring something special to the table: graphene conducts electricity really well, carbon nanotubes pick up faint neural signals effectively, black phosphorus can adjust its electrical properties, and layered double hydroxides help ions move smoothly. But we‘re still facing some tough challenges. Black phosphorus tends to break down when exposed to air and moisture. Graphene electrodes sometimes struggle with signal quality at the connection points. Most importantly, we need to be sure these materials are safe to use in the human body over long periods. This analysis suggests that future breakthroughs will likely emerge from hybrid material systems rather than single-material solutions. In the future, the field needs to find a good balance between coming up with new materials and making sure they’re backed up by solid biological testing. That’s the only way to really release what neural interfaces can do.

Keywords: BCI; Nanomaterials; Graphene; CNTs.

1. Introduction

Brain–computer interfaces provide a direct interface between the human brain and external hardware by bypassing traditional neuromuscular control systems. By acquiring and processing brain signals (usually electroencephalography [EEG] or electrocorticography [ECoG]) and then translating these signals into useful information based on user intent, BCIs have been applied in both medical and non-medical scenarios. While medical applications using BCIs for restoring motor functions in paralyzed patients are the focus of BCI research, these devices have also been applied in gaming and virtual reality applications.

In earlier BCI systems, metallic materials such as silver foil, Ag/AgCl, and tungsten were primarily used because of their good electrical conductivity. However, these materials lack mechanical flexibility and have poor long-term stability in biological environments. In recent years, nanomaterials, polymers, and composite structures have been used, and have

shown improvements in the functional lifetime of devices, signal acquisition, and comfort during use. Nanomaterials have advantages in signal acquisition and transmission compared with conventional metal electrodes [1].

2. Brief Introduction to BCI System

2.1 Invasive BCI Systems

Invasive BCIs involve implanting electrodes into cortical or subcortical areas of the brain. This system can record neural activity with high spatial and temporal resolutions and is often used in prosthetic control and high-resolution neuroscience experiments. Medical supervision is strictly required for invasive BCI systems because of potential issues with biocompatibility, long-term stability, and infection.

2.2 Semi-invasive BCI Systems

Unlike invasive BCIs, semi-invasive BCIs do not embed electrodes into the brain. Semi-invasive BCIs typically locate electrodes on the surface of the brain or in the skull, but not in direct contact with brain tissue. The implantation method reduces surgery risks and has the potential to enhance the long-term stability. Semi-invasive BCIs typically offer higher signal quality and resolution compared to non-invasive BCIs, while presenting lower risks compared to invasive systems. There are multiple types of semi-invasive BCIs, ranging from ECoG (figure 1 shows ECoG) to subdural electrodes. Semi-invasive BCIs have already been used in several motor control, neuroprosthetics and speech synthesis applications [2].

2.3 Non-invasive BCI Systems

Non-invasive BCIs use external sensors to record brain activity, without any surgical procedures EEG — recording electrical activity through scalp electrodes is the most popular non-invasive method (figure 1 shows EEG) Other methods include functional near infrared spectroscopy (fNIRS) which measures blood oxygenation, and magnetoencephalography (MEG) which measures magnetic fields generated by electric currents in the brain (figure.1 shows fNIR and MEG). These systems are increasingly used in clinical and lifestyle applications, to improve the quality of life of people with neurological disorders [2].

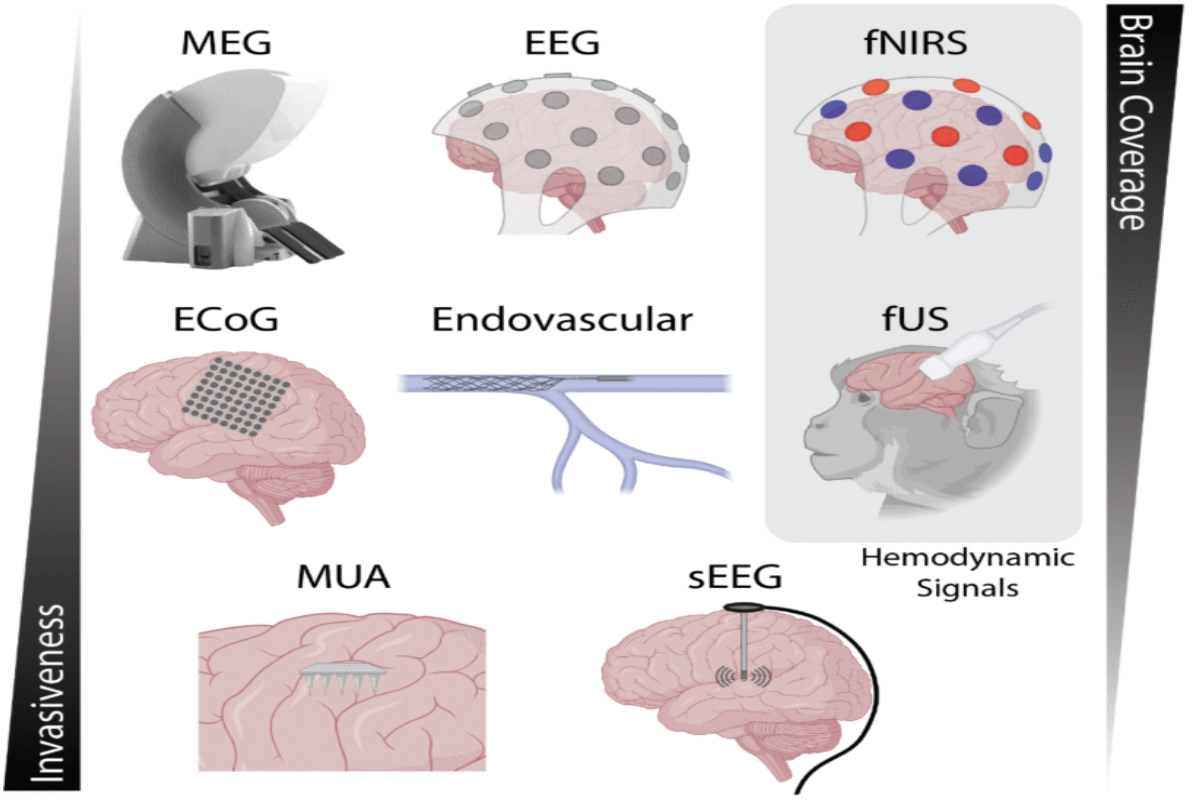

Fig. 1. Neural recording modalities used for brain-computer interface applications [2].
Non-invasive techniques include MEG, EEG and fNIRS. Semi-invasive approaches involve ECoG and relatively novel technologies such as endovascular electrodes and functional ultrasound (fUS). Invasive techniques include stereo-EEG (sEEG) penetrating electrodes.

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3. Nanomaterials in BCI

The performance of BCI systems is highly dependent on the materials used in electrodes and related applications. Conventional materials are often limited by high impedance, poor biocompatibility and lack of integration with the neural tissue. Nanomaterials provide possible solutions to these limitations. They can improve the electrical conductivity, reduce the impedance and promote the integration with the neural tissue to support both short- and long-term BCI functionality.

3.1 Graphene

Graphene, a two-dimensional material composed of a single layer of carbon atoms in a sp^2 hybridized honeycomb lattice, exhibits exceptional physicochemical properties due to its unique crystal structure. It demonstrates electron mobility values exceeding 2.5×10^5 $cm^2/V \cdot s$, far surpassing most conventional metals, which supports efficient neural signal transmission with minimal interfacial loss [3]. In terms of mechanics, graphene is extremely strong and highly flexible. The fracture strength of graphene is around 130 GPa and the Young's modulus is close to 1 TPa. It can adapt to the curved surface of the brain or the skull without damaging the tissue.

Several graphene-based electrode structures have been designed. For example, based on the report from Zheng et al., the gold-doped few-layer graphene (Au-FLG) electrodes obtained from vacuum filtration and thermal pressing exhibited a signal-to-noise ratio of 5.82 dB in physiological conditions which was superior to the conventional Ag/AgCl electrodes [4]. Additionally, these electrodes exhibited good stability for 30 days implantation and no obvious inflammatory response was observed in the surrounding tissue [4].

The surface modification of graphene has also been extensively studied. By introducing oxygen-containing functional groups or biomolecules, the neural compatibility of graphene can be further improved. For example, Lee et al. fabricated graphene–silk fibroin composites which could tune surface roughness and chemical composition to promote neuronal synapse growth and differentiation [5]. From a practical point of view, graphene can be used as an independent electrode or mixed with metals or polymers to improve the quality of signals and mechanical robustness [5].

3.2 Carbon nanotubes (CNTs)

As for carbon nanomaterials, graphene possesses more advantages, but other carbon nanomaterials such as carbon nanotubes (CNTs) are also widely used in the manufacturing of BCI devices. CNTs can be classified into single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs) according to their structural characteristics. The SWCNTs have diameters ranging from 0.8 to 2 nm and high specific surface area, which makes it possible to use them to collect weak neural signals. MWCNTs have layered structure, and they have better mechanical strength and stability, so they can be used in long-term implants [6].

Owing to their high surface area and electrical conductivity, CNTs enhance charge transfer at the electrode–tissue interface. They facilitate neuronal adhesion and help reduce impedance. Work by Keefer et al. demonstrated that CNT-coated electrodes can reduce impedance by nearly 60% while increasing charge storage capacity more than threefold [7]. This improvement supports both high-fidelity neural recording and effective electrical stimulation.

Beyond traditional coatings, CNTs are now integrated into a variety of BCI components, including flexible electrode arrays, stretchable interconnects, and neural guidance conduits. For example, when combined with elastomers such as polydimethylsiloxane (PDMS), CNTs enable conductive composites that retain electrical functionality even when stretched beyond 100% [8].

A lingering concern is the long-term biological safety of CNTs. Their degradation products and potential cytotoxicity in neural tissues are not yet fully understood. Moreover, achieving uniform CNT alignment and reproducible batch-to-batch properties remain challenging for large-scale manufacturing.

3.3 Black phosphorus

BP has shown significant potential in BCI applications due to its unique combination of properties. BP has high carrier mobility, tunable bandgap, and excellent biocompatibility. Its most notable characteristic is a layer-dependent tunable bandgap, continuously adjustable from 0.3 eV in bulk material to 2.0 eV in monolayers. And the tunable bandgap enables BP to be used in adaptation to different electrophysiological signal detection requirements. Electrically, black phosphorus exhibits a room-temperature hole mobility of up to 1000 $cm^2/V \cdot s$ with significant anisotropy, providing new degrees of freedom for designing neural interface devices with specific functions.

BP exhibits exceptional carrier mobility, a tunable bandgap (0.3-2.0 eV), and inherent biocompatibility. Its anisotropic electrical properties enable directional signal processing in neural interfaces. These advantages position it as a promising material for specialized BCI applications, though practical implementation requires further investigation.

From a stability standpoint, black phosphorus faces chal-

lenges under ambient conditions. To solve the problem, researchers have turned to protective strategies such as atomic layer deposition of alumina or magnesium fluoride coatings [9]. An alternative route involves blending exfoliated BP nanosheets with polymers. This composite approach improves environmental resilience, but further research is needed on the trade-off between its processability and electronic performance.

BP shows potential for use in specific brain–machine interfaces. For example, composite patches containing BP nanosheets (CPB) have been reported to effectively regulate tissue interface humidity, thereby maintaining the stability of electrode–skin contact and avoiding the common drying problems associated with traditional wet electrodes [10]. Experimentally, BP-based electrodes also exhibit a relatively flat frequency response in the 0.1–100 Hz range, which is valuable for acquiring clean, broadband EEG signals. However, these advantages must be weighed against the structural characteristics of the material. BP has an uneven surface morphology and weak interlayer interactions, which increase the complexity of its manufacturing process and long-term performance.

When BP gets exposed to moisture and oxygen, it will tend to break down. The application of black phosphorus requires the development of scalable and reproducible synthesis methods, and it must not pose any biosafety hazards. Setting clear and consistent ways to describe black phosphorus and understanding how its structure affects its properties are really important steps. These will be key if black phosphorus is ever going to move from being just an interesting material to a reliable part of brain-computer interfaces in real use.

3.4 Layered double hydroxides (LDHs)

Layered double hydroxides (LDHs) are a class of anionic clay materials with unique layered structures, chemically represented as [M1−x2+Mx3+(OH)2]x+(An−)x/n·mH2O. This distinctive structure provides multiple advantages in BCI applications. Their tunable layered structure offers several advantages: adjustable electrochemical properties, exchangeable interlayer anions for functionalization, and an inherent buffering capacity that helps maintain interfacial stability under physiological conditions.

In neural interfaces, LDHs aid ion transport, enhance charge transfer, and enable controlled release of bioactive agents. For Mg–Al LDHs intercalated with inorganic anions, ionic conductivities on the order of $1.1\times10^{-2} S \bullet cm^{-1}$ have been reported [11]. This adjustable conductive characteristic enables adaptation to specific signal acquisition requirements in different brain regions.

Regarding material design strategies, researchers have developed various LDH-based composite materials. For example, three-dimensional conductive networks constructed by combining LDHs with graphene maintain high ionic conductivity while introducing electron conduction pathways, achieving mixed ion/electron conduction mechanisms. Another innovative design combines LDHs with temperature-sensitive polymers to develop smart electrode materials with adaptive characteristics that can adjust interface properties according to local temperature changes.

Although LDH materials show promising application prospects, their long-term stability under electrical polarization and physiological conditions remains a concern. Future studies could focus on developing novel LDH composites and employing advanced microscopy and spectroscopy techniques to better understand the relationship between material structure and interfacial performance.

3.5 Conductive polymers

Research on conductive polymers in BCI applications has established a relatively comprehensive technical system. Based on conduction mechanisms, these materials can be classified into electronic conductive polymers (such as polypyrrole and polyaniline) and ionic conductive polymers (such as polyvinyl alcohol-ionic liquid composites). In practical applications, researchers continuously optimize the performance indicators of conductive polymers through molecular design, doping modification, and composite processing.

Polypyrrole (PPy) has become one of the most extensively studied conductive polymers due to its good biocompatibility and moderate electrical conductivity. The PP-rGO composite material developed by Wang et al., prepared through electrochemical polymerization, exhibits excellent electrochemical performance in 0.9% NaCl solution: charge storage capacity reaches 350 mC/cm², interface impedance remains below 1 kΩ at 1 kHz, and performance degradation is less than 15% after 200 bending cycles [12]. This material demonstrated good tissue compatibility in animal experiments, maintaining stable electrical performance after 8 weeks of implantation [12].

In terms of material innovation, various novel conductive polymer systems have emerged in recent years. For instance, conductive hydrogels based on poly(3,4-ethylenedioxythiophene) (PEDOT) achieve both high conductivity and excellent mechanical properties through dual-network structures. Another trend involves developing stimulus-responsive conductive polymers, such as pH-sensitive or glucose-sensitive smart materials that can automatically adjust their interface characteristics according to physiological environment changes.

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Despite significant progress, the performance stability of conductive polymers during long-term implantation remains a critical concern. Particularly, degradation mechanisms under in vivo enzymatic action and oxidative stress conditions, and the effects of degradation products on neural tissue, require systematic evaluation. Future research should focus on developing novel stabilization strategies and validating long-term reliability through multi-level in vitro and in vivo experiments.

4. Conclusion

Nanomaterials have significantly advanced BCI technology by improving electrode performance, signal transmission, and biocompatibility. Graphene, CNTs, conductive polymers, and LDHs contribute high conductivity, flexibility, and large surface areas, enabling more accurate and reliable neural interfaces. Nevertheless, challenges related to long-term stability under physiological conditions—such as hydration, pH changes, and oxidative damage—require further investigation.Combining different materials, such as conductive polymers with carbon-based composites, may enhance both stability and electrochemical performance. As BCI applications expand into healthcare, entertainment, and virtual reality, demand for high-performance nanomaterials will grow. Future research should not only focus on improving material properties but also on optimizing manufacturing processes and cost-effectiveness.

In summary, nanomaterials hold great promises for the continued development of BCI systems. Through interdisciplinary innovation, these materials are expected to enable more efficient, reliable, and durable BCIs, thereby advancing medical rehabilitation, intelligent control, and human–technology interaction.

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