Advancements in Materials for Flexible and Soft Brain-Computer Interface

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Abstract. This paper delves into the latest advancements in materials science within the field of Brain-Computer Interface (BCI) technology, comprehensively covering the application of classic polymer materials such as polydimethylsiloxane (PDMS) and polypyrrole (PPy), as well as the cutting-edge research on innovative modifications of these materials through surface functionalization, nanostructuring, and chemical modification to enhance their conductivity, biocompatibility, and mechanical strength. The article also looks forward to the exploration of emerging fields such as smart materials, self-healing materials, and biomaterials, aiming to further enhance the performance and durability of the BCI devices. Additionally, the paper details the diverse applications and unique advantages of metal materials, inorganic semiconductor materials, organic materials, and carbon materials in the BCI technology. Coupled with advanced manufacturing technologies such as 3D printing and laser processing, the article demonstrates how to precisely prepare complex structures and high-precision materials to promote the continuous progress and development of BCI technology.

Keywords: Brain-Computer Interface; Innovative modifications; Flexible materials.

1. Introduction

Brain-Computer Interface (BCI) is a cutting-edge technology that enables direct communication between the brain and external devices without relying on traditional neuromuscular pathways. Since its first proposal in the 1970s, BCI technology has made significant progress in various fields such as neuroscience, medical rehabilitation, and human-computer interaction. Its importance lies in providing a new means of communication and control of external devices for patients who are paralyzed due to disease or accidents, and it also opens up new application prospects for emerging fields such as augmented reality and virtual reality. This article aims to deeply explore the key role of materials in BCI, analyze the current state of material applications and the challenges they face, and look forward to future development directions. We will focus on the impact of material properties such as biocompatibility, conductivity, and flexibility on BCI performance, and how these properties affect the overall performance and reliability of BCI systems.BCI works by detecting neural signals generated by the brain and converting these signals into commands that can be recognized by external devices, thus achieving control and communication. Typically, BCI systems use electrode arrays to record brain electrical activity and employ complex signal processing algorithms to decode these signals. BCI technology has significant application value in the field of medical rehabilitation, such as helping paralyzed patients regain motor abilities; in the entertainment and gaming industry, BCI technology can be used to develop immersive interactive experiences; in neuroscience research, BCI technology is used to explore brain functions and the working mechanisms of neural networks [1].

To achieve efficient operation of BCI technology, the materials used must have high biocompatibility to avoid triggering immune responses or inflammation; at the same time, these materials should have high conductivity to ensure efficient signal transmission; furthermore, sufficient flexibility is essential to adapt to the dynamic changes and movements of brain tissue. The main challenges faced in material selection include long-term stability issues and signal attenuation caused by immune responses. In addition, the matching of material mechanical properties with brain tissue is a key issue that needs to be addressed through the combination of materials science and biomedical engineering [2].

2. Materials

The flexibility and elastic modulus of materials directly affect their compatibility with brain tissue. Materials with low elastic modulus can better adapt to the movement of brain tissue and reduce mechanical damage. High conductivity and low impedance are key to ensuring signal transmission efficiency. The electrical properties of materials determine the signal quality and stability of BCI. The stability and durability of materials in a biological environment determine their feasibility for long-term use. Materials with good chemical stability can reduce degradation and signal loss.

2.1. Metal Materials

Metal materials such as gold and silver are widely used in BCI systems due to their excellent conductivity. However, the rigidity of metal materials may cause tissue damage and signal instability. Although metal materials perform well in terms of conductivity, their mechanical rigidity limits their application in flexible BCI. For example, a new type of brain-computer interface (BCI) electrode material composed of Fe3O4@GO/P(NIPA-MAA) hydrogel with magnetorheological properties, which inherits the signal advantages of invasive electrodes, can also be actively controlled to unfold on the surface of the cerebral cortex through an external magnetic field, with a high signal-to-noise ratio and safety. At room temperature, this material exhibits significant superparamagnetism and can transition from a solution to a gel at body temperature, forming a three-dimensional porous crosslinked network structure to support signal transmission. This new material provides an ideal solution for the development of semi-invasive BCI electrodes. The potential application of liquid metals such as gallium-based alloys in flexible electrodes is enormous, as they combine high conductivity with low mechanical stiffness. These materials can maintain high conductivity while providing better flexibility [3].

2.2. Polymer Materials

Polymer materials such as polydimethylsiloxane (PDMS) and polypyrrole (PPy) have attracted attention due to their good flexibility and conductivity, making them suitable for the manufacture of flexible electrodes. These materials can provide better mechanical matching and reduce tissue damage. Researchers use PDMS as a substrate material to develop flexible EEG electrodes. These electrodes can conform to the scalp, providing high-quality brain signal recording while reducing discomfort for the wearer. In addition, by electrochemical polymerization technology, PPy is coated on a flexible substrate to form a conductive coating. Such electrodes are used for implantable neural stimulation and can effectively conduct electrical signals [4].

2.3. Carbon-based Materials

Carbon-based materials such as graphene and carbon nanotubes excel in enhancing conductivity and mechanical strength, making them suitable for high-performance BCI electrodes. Their high conductivity and flexibility make them an ideal choice for future BCI materials. For example, graphene's high conductivity and large surface area are used to develop high-sensitivity electrodes for neural signal detection. These electrodes can capture weak neural signals, suitable for fine neural research. In addition, by compounding CNTs with polymer materials, flexible electrodes with high conductivity and mechanical strength are manufactured. These electrodes are used for long-term implanted BCI devices, providing stable performance [5].

2.4. Smart Materials

Develop smart materials that can respond to external stimuli (such as temperature, pH, electric field) to achieve dynamic regulation and adaptive functions. Temperature-responsive polymer coatings can be used to adjust the interface characteristics between electrodes and brain tissue. For example, poly(N-isopropylacrylamide) (PNIPAM) can change its swelling state with changes in body temperature. This property can be used to adjust the contact area and interfacial impedance of the electrode, thereby optimizing signal transmission [6].

2.4.1 Self-healing Materials

Research materials with self-healing properties to enhance the durability and service life of brain-computer interfaces (BCI). For example, researchers apply polymer self-healing coatings to the surface of BCI electrodes to repair minor cracks and damage. These coatings use polymers with self-healing properties, such as polysulfides or polyurethanes, which can self-repair through the recombination of chemical bonds when mechanically damaged, thereby extending the service life of the electrodes.

2.4.2 Biomaterials

Explore the use of natural biomaterials (such as collagen, chitosan) or their composite materials to enhance biocompatibility and integration. For example, collagen-based electrodes are used to improve the biocompatibility of electrodes. Utilizing the natural biocompatibility and biodegradability of collagen, flexible electrodes are developed. These electrodes can bond well with brain tissue, reducing immune reactions and inflammation. Chitosan has good biocompatibility and antibacterial properties. By compounding with other conductive materials (such as graphene or carbon nanotubes), materials with both conductivity and biocompatibility are formed, used for coatings or scaffolds in neural interfaces [7].

3. Material Modifications

3.1. Surface Functionalization

By introducing bioactive molecules (such as peptides, proteins) onto the material surface, the biocompatibility of the material can be significantly enhanced, and the immune response can be reduced. The addition of coating materials has significantly improved the electrical performance and biocompatibility of neural electrodes, a breakthrough that has opened new avenues for the development of brain-computer interface technology. By introducing conductive polymer and metal nanoparticle coatings, not only has the electrode impedance been effectively reduced, but the efficiency of signal transmission has also been greatly improved. The addition of nanostructured coatings further increases the surface area of the electrode, enhancing electrochemical activity, making the capture and transmission of neural signals more precise and efficient. In terms of biocompatibility, bioactive coatings promote the adhesion and growth of neural cells, while reducing inflammation, and antibacterial coatings by adding antibacterial agents effectively reduce the risk of infection. In addition, the introduction of high-resolution patterning technology and intelligent coating design has provided endless possibilities for the performance improvement of neural electrodes. The perfect combination of these technologies and materials has enabled neural electrodes to achieve unprecedented heights in signal transmission efficiency and biocompatibility with tissue, laying a solid foundation for the future development of brain-computer interface technology.

3.2. Nanostructuring

Using nanotechnology to construct nanoscale structures on the material surface aims to enhance the conductivity and mechanical properties of the material while increasing the contact area with neural tissue. For example, flexible electrodes made of carbon nanofibers can be implanted, providing stable electrical signal recording without damaging brain tissue [8].

3.3. Chemical Modification

Chemical methods are used to adjust the molecular structure of materials to enhance their conductivity, flexibility, and durability. Introducing functional groups (such as carboxyl, hydroxyl, or amino groups) onto the surface of graphene can improve its dispersibility in water and its interaction with biomolecules. This modification not only increases the conductivity of graphene but also enhances its compatibility with biological tissues. Through copolymerization reactions, flexible monomers (such as vinyl ethers) are combined with conductive polymers (like polypyrrole) to form copolymers. Such chemical modifications can improve the flexibility of the material while maintaining its conductivity. Surface modification of neural electrodes with anti-fouling molecules, such as lubricin (biological anti-adhesive glycoprotein) and zwitterionic coatings (such as carboxybetaine, sulfobetaine), effectively reduces the adsorption of biomolecules, mitigates inflammatory responses, and extends the service life of neural electrodes. Additionally, polymerizing PEDOT directly on the electrode surface through chemical polymerization achieves impedance and stability similar to those of electropolymerization, a method that improves the modification efficiency of multi-channel electrodes [9].

4. Processing Technology

Micro-nano processing technology and 3D printing technology play a significant role in the preparation of high-precision neural probes. These technologies enable the manufacturing of complex structures and enhance the performance of electrodes. Coating technology is used to enhance the biocompatibility and functionality of materials. Surface modification can reduce immune responses and improve signal transmission efficiency.

Designing better brain-computer interface (BCI) materials requires combining the latest advances in materials science, engineering technology, and biomedical engineering. The following are some possible strategies and methods to enhance the performance of BCI materials through modification or other means [10].

4.1. Multifunctional Integration

Integrating sensing and stimulation functions: Fusing sensing, stimulation, and data processing functions within a single material to enhance the overall performance of BCI. For example, conductive polymers such as polypyrrole (PPy) are combined with carbon nanotubes to form materials with high conductivity and flexibility. These materials can detect neural electrical signals and regulate neural activity through electrical stimulation. Moreover, the flexibility of the material allows it to conform to brain tissue, reducing mechanical damage [11].

4.2. Personalized Design

Customized design: Designing BCI materials based on individual physiological characteristics and needs to improve applicability and comfort. Computational simulation: Utilizing computer simulation and machine learning technologies to optimize material design and performance prediction. For instance, by using 3D scanning technology to obtain individual brain morphology data and employing 3D printing technology to manufacture electrodes that fit individual anatomical structures. Such customized design can increase the contact area and signal transmission efficiency of the electrodes while reducing discomfort after implantation. By analyzing individual skin sensitivity and biocompatibility, appropriate flexible materials (such as silicone, polymers) are selected for electrode manufacturing. This personalized choice can improve the comfort and long-term safety of the device. Customized design of signal processing algorithms based on individual neural signal characteristics can improve signal recognition rates and response speeds. This method can enhance the applicability of BCI among different individuals.

4.3. Manufacturing Process Innovation

Advanced manufacturing technology: Employing advanced manufacturing technologies such as 3D printing and laser processing to achieve complex structures and high-precision material preparation. Using 3D printing technology, the shape and internal structure of electrodes can be precisely controlled. This technology can be used to manufacture electrodes with flexibility and porous structures to improve signal transmission efficiency and compatibility with brain tissue. Laser direct writing or laser etching techniques can precisely generate micro-patterns or porous structures on the surface of electrodes. This not only increases the surface area of the electrodes and enhances signal transmission capabilities but also improves the contact efficiency between the electrodes and brain tissue.

Biodegradable materials: Researching biodegradable materials to ensure safe removal from the body after completing tasks. Magnesium is a metal material with excellent biodegradability and can gradually degrade in the body environment. Neural electrodes made of magnesium can self-degrade after completing specific tasks, allowing safe removal from the body without the need for surgery. PLA is a commonly used biodegradable polymer that can gradually hydrolyze into lactic acid in the body and be metabolized. PLA-based electrodes are suitable for short-term tasks, avoiding postoperative device removal. Silk protein is used to manufacture biosensors and flexible electronic devices due to its biocompatibility and biodegradability. Such devices can naturally degrade after use, reducing the biological burden.

Through these strategies, future BCI materials will better meet the requirements of biocompatibility, conductivity, and mechanical properties, thereby promoting further development and application of BCI technology [12].

5. Conclusion

This article comprehensively reviews the current research trends and technological bottlenecks in the field of brain-computer interface (BCI) materials, highlighting the core role of materials in optimizing BCI performance. The article points out that the leap in BCI technology relies on the biocompatibility, excellent conductivity, and outstanding flexibility of materials. The appropriate selection of materials is directly related to the enhancement of device performance and the upgrade of user experience. However, existing materials face severe challenges such as insufficient long-term stability, signal attenuation induced by immune responses, and mismatched mechanical properties between materials and brain tissue. Noteworthy is that carbon-based materials such as graphene and carbon nanotubes, with their exceptional electrical and mechanical properties, are considered preferred materials for constructing high-performance BCI electrodes. At the same time, liquid metals like gallium-based alloys, with their perfect combination of high conductivity and low mechanical stiffness, show great potential in the field of flexible electrodes. In addition, the introduction of chemical modification techniques not only enhances the conductivity, flexibility, and durability of materials but also promotes harmonious coexistence between materials and biological tissues. The exploration of self-healing materials and natural biological materials (such as collagen, chitosan) has opened new avenues for improving material durability and biocompatibility. Looking to the future, BCI technology will develop towards multifunctional integration and personalized design, aiming to integrate sensing, stimulation, and data processing functions into one and customize materials and devices according to individual needs. In this process, advanced manufacturing technologies such as 3D printing and laser processing will help achieve the preparation of complex structures and high-precision materials. At the same time, research into biodegradable materials will also become an important topic, aiming to ensure safe removal from the body after completing their mission, thereby reducing the burden on the organism. The article concludes by emphasizing that future research should focus on the development of new materials and the advancement of multifunctional integration to drive BCI technology towards a more brilliant future.

References

[1] Xin Tang, Hao Shen, Siyuan Zhao, Na Li, Jia Liu, Flexible brain–computer interfaces. Nature Electronics, 2023, 6 (2): 109–118.

[2] Antoine Remy, Xinyi Lin, Jia Liu, Materials for flexible and soft brain-computer interfaces, a review. MRS Communications, 2024,.

[3] Guangwei He, Xufeng Dong, Min Qi, From the perspective of material science: a review of flexible electrodes for brain-computer interface. Materials Research Express, 2020, 7 (10): 102001.

[4] Guangwei He, Yu Tong, Chi Zhang, Beibei Xue, Xufeng Dong, Shouhu Xuan, Peixin Sun, Min Qi, A novel brain–computer interface flexible electrode material with magnetorheological properties. Materials Advances, 2021, 2 (22): 7389–7399.

[5] Yang Li, Yuzhe Gu, Junchen Teng, Shuwen Zheng, Yuncong Pang, Xiaomin Lu, Baoguang Liu, Shujuan Liu, Qiang Zhao, Advancing EEG-based brain-computer interface technology via PEDOT:PSS electrodes. Matter, 2024, 7 (9): 2859–2895.

[6] Jinning Li, Yuhang Cheng, Minling Gu, Zhen Yang, Lisi Zhan, Zhanhong Du, Sensing and Stimulation Applications of Carbon Nanomaterials in Implantable Brain-Computer Interface. International Journal of Molecular Sciences, 2023, 24 (6): 5182.

[7] Sen Lin, Jingjing Jiang, Kai Huang, Lei Li, Xian He, Peng Du, Yufeng Wu, Junchen Liu, Xilin Li, Zhibao Huang, Zenan Zhou, Yuanhang Yu, Jiaxin Gao, Ming Lei, Hui Wu, Advanced Electrode Technologies for Noninvasive Brain–Computer Interfaces. ACS Nano, 2023, 17 (24): 24487–24513.

[8] Minh Anh Huynh, Thanh-Ha Nguyen, Tuan-Khoa Nguyen, Nam-Trung Nguyen, Convergence of Implantable Bioelectronics and Brain–Computer Interfaces. ACS Applied Electronic Materials, 2023, 5 (11): 5777–5793.

[9] Antoine Remy, Xinyi Lin, Jia Liu, Materials for flexible and soft brain-computer interfaces, a review. MRS Communications, 2024,.

[10] Nathan Semertzidis, Fabio Zambetta, Florian “Floyd” Mueller, Brain-Computer Integration: A Framework for the Design of Brain-Computer Interfaces from an Integrations Perspective. ACM Transactions on Computer-Human Interaction, 2023, 30 (6): 1–48.

[11] Haowen Yuan, Yao Li, Junjun Yang, Hongjie Li, Qinya Yang, Cuiping Guo, Shenmin Zhu, Xiaokang Shu, State of the Art of Non-Invasive Electrode Materials for Brain–Computer Interface. Micromachines, 2021, 12 (12): 1521.

[12] Simanto Saha, Khondaker A. Mamun, Khawza Ahmed, Raqibul Mostafa, Ganesh R. Naik, Sam Darvishi, Ahsan H. Khandoker, Mathias Baumert, Progress in Brain Computer Interface: Challenges and Opportunities. Frontiers in Systems Neuroscience, 2021, 15 578875.