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# *A Review on Flexible Electronic Sensors for Brain Monitoring*

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***Abstract.*** Flexible electronic sensors, due to their mechanical compliance with soft tissues and excellent biocompatibility, have demonstrated unique advantages in neuroscience research and clinical applications in recent years. Compared with traditional rigid electrodes, flexible sensors show greater potential in long-term stability, large-area coverage, and multimodal integration, thereby meeting the diverse needs of neural signal acquisition and functional monitoring. This review summarizes the latest advances in the application of flexible electronics for brain monitoring, covering electrophysiological signal acquisition, neurotransmitter detection, multimodal and region-synchronized recording, and clinical rehabilitation applications. It further discusses critical aspects influencing performance and applications, including material selection, device design, circuit integration, energy supply, and mechanical modeling. On this basis, the challenges and prospects regarding long-term stability, data processing, multimodal integration, and clinical translation are analyzed. Overall, flexible brain sensors are gradually progressing from laboratory validation to systematic applications, and their development is expected to exert profound impacts on neuroscience research, disease diagnosis and treatment, and intelligent rehabilitation in the future.

***Keywords:*** Flexible electronic sensors, Brain monitoring, Electrophysiological recording, Neurotransmitter detection, Multimodal integrated sensors

## 1. Introduction

The human brain, consisting of approximately 86 billion neurons and trillions of synaptic connections, is the most complex biological information processing system known to date [1]. Dysfunction of this system is closely related to numerous diseases, including epilepsy, Parkinson's disease, Alzheimer's disease, depression, and post-stroke cognitive and motor impairments. These conditions not only severely affect patients' quality of life but also impose tremendous socio-economic burdens. According to the World Health Organization (WHO), neurological disorders are among the leading causes of disability and mortality worldwide. Epilepsy alone affects over 50 million patients, and Alzheimer's disease exceeds 55 million cases, with annual incidence still on the rise. By 2030, the global burden of neurological disorders is projected to surpass cardiovascular diseases and cancer, becoming the greatest public health challenge.

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In neuroscience research and clinical practice, real-time, long-term, and stable monitoring of brain signals is a fundamental requirement. Traditional rigid electrodes (e.g., Michigan probes, Utah arrays), despite their high channel counts and resolution, have mechanical moduli (~165 GPa) far higher than brain tissue (0.5–15 kPa), which often induce immune responses and glial scarring after implantation, leading to signal degradation or failure [2-3]. In addition, rigid electrodes inherently lack compatibility in terms of coverage, tissue integration, and multimodal functionality.

Flexible electronic sensors, with their low modulus, favorable biocompatibility, and adaptability, have emerged as promising alternatives [1, 4]. Common substrates include polymers such as polyimide (PI), Parylene-C, and PDMS, or combinations with two-dimensional materials (graphene, MXene) and hydrogels, which better match the mechanical properties of neural tissue [2]. Recent developments in flexible sensors show three distinct trends: First, the research focus has shifted from single-modality electrophysiological monitoring to multimodal collaborative sensing, integrating electrical, chemical, and optical signals. Second, experimental applications have extended from small animal studies to non-human primate research and early clinical explorations, laying the groundwork for medical translation [5-6]. Third, the duration of experiments is moving from short-term to chronic implantation, with increasing attention on maintaining stable signal acquisition over months or longer [7-8].

This paper explores the current applications of flexible electronic sensors in brain monitoring, with emphasis on advances and challenges in electrophysiological signal acquisition and neurotransmitter detection. It aims to fill the gaps of existing reviews that mainly focus on single-dimension monitoring or localized applications, providing insights for interdisciplinary progress across neuroscience, materials science, and clinical medicine.

## 2. Application status of flexible sensors in brain monitoring

### 2.1. Electrophysiological signal detection

Electrophysiological signals directly reflect neural activity, including electroencephalography (EEG), electrocorticography (ECoG), micro-ECoG arrays (μECoG), action potentials, and local field potentials (LFPs). Flexible electronics significantly improve long-term implantation stability and expand the spatial scope of signal acquisition.

On the cortical surface, large-area flexible arrays can closely conform to brain tissue, avoiding the mechanical irritation often caused by rigid electrodes. For example, ultra-high-channel flexible ECoG systems have enabled functional connectivity mapping across brain regions [7]. Compared with rigid electrodes, μECoG arrays provide higher spatial resolution, and active systems integrated with front-end circuits further enhance signal fidelity and reduce noise [8].

In deep brain recordings, flexible probes can access multiple layers with minimal tissue damage. When combined with novel front-end circuits, they maintain high resolution while reducing power consumption [9]. Moreover, three-dimensional fiber-shaped probes offer synchronized multi-region recording, showing potential for chronic implantation.

High channel density and integration represent another important direction. Proximal integration architectures improve both signal density and system stability while preserving flexibility [6]. Compared with Utah arrays, flexible electrodes provide broader coverage and better tissue compatibility. Overall, flexible electrodes are evolving from small-scale studies to large-scale, high-channel systems, paving the way toward clinical translation.

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### 2.2. Neurotransmitter and chemical signal detection

While electrical activity reveals firing patterns of neurons, it cannot uncover synaptic chemical mechanisms. Flexible chemical sensors thus provide a new dimension for brain studies.

Optical fluorescence probes enable real-time neurotransmitter detection in deep brain regions. For instance, flexible probes based on metal–organic frameworks can detect dopamine at submicromolar sensitivity and remain stable in freely moving animals [10]. Functional material modifications further extend this approach to glutamate, GABA, and other neurotransmitters, enabling multi-molecule monitoring.

Electrochemical flexible probes, known for high temporal resolution, achieve improved sensitivity and selectivity through conductive polymers or carbon-based surface modifications [4]. Such probes have successfully captured rapid dopamine dynamics during reward-related tasks, providing valuable insights for psychiatric research.

### 2.3. Multimodal and region-synchronized monitoring

Single-dimensional monitoring cannot meet the demands of studying complex neural circuits. Flexible devices are increasingly designed for multimodal integration, such as electrical–optical, electrical–chemical, and electrical–mechanical combinations [11].

For example, integrating flexible electrodes with optogenetics enables simultaneous recording and precise modulation of neural activity, with demonstrated stability in non-human primate experiments [5]. Electrical–chemical integration reveals correlations between electrical signals and neurotransmitter dynamics, while electrical–mechanical monitoring extends capabilities to intracranial pressure and other physiological parameters [12]. Such multimodal platforms provide new tools to study epilepsy propagation, cognitive coupling, and other complex phenomena.

### 2.4. Clinical and rehabilitation applications

The ultimate goal of flexible brain sensors is clinical and rehabilitative utility. They have shown advantages in epilepsy focus localization and intraoperative monitoring, providing more precise information with greater coverage and resolution [6, 8]. In rehabilitation, flexible EEG-based brain–machine interface exoskeletons have assisted post-stroke patients in regaining motor functions with improved comfort [13]. Flexible sensors are also being explored for intelligent communication and interaction, such as brain-controlled reconfigurable surface systems for smart homes and rehabilitation environments [14].

Nevertheless, clinical translation remains limited by challenges in long-term stability, standardization, and ethical concerns [3, 15]. These barriers highlight the need for not only technological breakthroughs but also interdisciplinary collaboration and regulatory frameworks.

## 3. Research exploration of flexible electronics in brain monitoring

### 3.1. Materials and interface optimization

The performance of flexible brain sensors largely depends on substrate materials and interface treatments. Common polymers such as polyimide, PDMS, and Parylene-C each have unique advantages: polyimide offers strength and process compatibility; PDMS matches tissue modulus to reduce stress; and Parylene-C provides transparency and biocompatibility [2]. With the rise of two-dimensional materials, graphene, carbon nanotubes, and MXene have been incorporated to improve

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conductivity and multimodal adaptability [11]. Another key challenge lies in balancing initial stiffness for implantation with long-term flexibility. Strategies such as degradable support layers and dynamic stiffness materials address this trade-off. Interface modification methods, including anti-inflammatory coatings and biomimetic surface treatments, further reduce immune responses and extend electrode lifespan [2]. The ultimate goal of materials and interface optimization is not only to enhance sensing performance but also to ensure safety and reliability during chronic use.

### 3.2. Device design and circuit integration

Device architecture and signal processing are equally critical. Unlike early thin-film electrodes with single functionality, recent trends emphasize integration with miniaturized circuits. High-channel arrays enable broader neural signal acquisition but impose greater data processing demands. Proximal integration strategies, embedding amplification and filtering functions near electrodes, significantly improve signal quality and reduce transmission noise [6]. Low-power front-end circuits are crucial for long-term and wireless use [9]. Hybrid soft–rigid architectures bridge flexible probes with silicon chips, preserving tissue compliance while leveraging computational capacity [8]. As channel counts continue to rise, efficient data compression and edge computing become essential to operate within power and bandwidth limits. In the future, flexible sensors will evolve into integrated and intelligent micro-systems, rather than mere signal collectors.

### 3.3. Wireless energy and signal management

Energy supply is a major bottleneck for implantable systems. While inductive coupling is well-established, its efficiency is limited in deep tissues. Alternative approaches such as RF, ultrasound, and capacitive coupling provide complementary strategies [11]. Across all methods, improving transfer efficiency while minimizing tissue absorption remains critical. On the data side, high-channel systems face dual challenges of bandwidth and power consumption. Event-driven sampling, on-chip compression, and edge computing reduce the burden of raw data transmission [7]. By incorporating intelligent on-sensor data filtering, systems can maintain signal fidelity while extending operational lifespan. These advances suggest that wireless powering and efficient data management are prerequisites for clinical translation of flexible electronics.

### 3.4. Mechanical modeling and optimization

The mechanical mismatch between flexible devices and brain tissue can create stress concentrations, necessitating careful design. Finite element modeling has been widely applied to predict stress distributions across varying thicknesses, moduli, and geometries. Results show that ultrathin substrates, serpentine interconnects, and island–bridge structures effectively mitigate tissue damage [2]. Modeling provides quantitative insights for optimization and enables early prediction of failure modes. With advances in computational tools, increasingly detailed multiscale models will guide probe design, enabling closer alignment between simulation and experimental outcomes [3].

## 4. Research prospects and challenges

Long-term stability and immune responses remain core challenges for clinical translation of flexible brain sensors. Chronic inflammation often leads to gradual signal attenuation and eventual device failure. Strategies such as drug-eluting coatings, dynamic stiffness materials, and degradable supports have shown promise in animal models but lack validation in long-term human use.

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Balancing device performance and minimizing tissue reactions remains a key focus for future research.

At the same time, the rapid increase in channel counts exacerbates bandwidth and power constraints. Conventional continuous sampling is no longer feasible for large-scale systems. Event-driven sampling and on-sensor preprocessing are becoming mainstream. Integration with artificial intelligence is another emerging trend. By embedding preliminary classification and pattern recognition at the sensor level, flexible systems can reduce external processing loads and enable closed-loop brain–machine interfaces.

Furthermore, single-modality monitoring cannot fully address the complexity of brain function. Future systems will likely combine electrical, optical, chemical, and mechanical modalities within unified platforms. Such multimodal integration can provide more comprehensive physiological mapping and cross-scale functional insights. Achieving this requires breakthroughs in materials, signal synchronization, and data fusion. System-level integration will transform flexible electronics into comprehensive brain research tools.

## 5. Conclusion

The development of flexible electronic sensors for brain monitoring has established a complete pathway from materials improvement to system integration. They not only provide unprecedented signal acquisition capabilities in basic research but also demonstrate application potential in epilepsy localization, rehabilitation training, and intelligent interaction. However, limitations in long-term stability, energy supply, data processing, and ethical regulation continue to hinder large-scale clinical adoption. Successful translation requires interdisciplinary collaboration, integrating materials science, electronic engineering, neuroscience, and medical ethics.

This review also has certain limitations. Although it consolidates many key research achievements, some of the latest clinical trial data and engineering details were not fully covered. The reference selection emphasized representative works, but did not encompass all contributions across materials innovation, integration strategies, and translational studies. Future reviews should aim for greater comprehensiveness and deeper comparisons of methods, to serve as more robust references.

Looking forward, research on flexible brain sensors can prioritize the following directions: enhancing multimodal integration to achieve high spatiotemporal resolution across electrical, chemical, and mechanical dimensions within unified systems; developing more efficient and safe wireless energy and data transmission solutions for chronic implantation; advancing AI and edge computing at the sensor level to transition from data acquisition tools to intelligent interactive platforms; and strengthening clinical validation and ethical frameworks to ensure sustainable application in healthcare.

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