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Review

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Implantable flexible neuroelectrodes: advances in material innovation, structural design, and performance optimization

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Abstract: In recent years, implantable neuroelectrodes have been widely applied in various fields, including deep brain electrical stimulation, neuroprosthesis and recording neuronal electrical activity in neuroscience research. However, with the rapid advancement of neuroscience and brain-computer interface technology, the limitations of traditional rigid neural microelectrodes have become increasingly evident. Flexible neuroelectrodes constructed from soft materials are emerging as a key research focus in the neural interface field. This review presents a systematic classification of the material selection, structural design, and key performance of implantable flexible neuroelectrodes and analyzes the optimization of achieving electrode flexibility in avoiding tissue damage and immune response. Furthermore, we summarized the contemporary challenges in performance optimization and material innovation, proposing potential solutions. By integrating and reviewing existing innovative approaches to flexible implantable neuroelectrodes, this review aims to provide an important theoretical foundation and technical guidance for the development of high-performance implantable neuroelectrodes.

Key words: Implantable; Neural microelectrodes; Electrode material; Electrode structure; Electrode key performance

1 Introduction

Neural interface technology is an essential bridge connecting the human nervous system with external devices and holds substantial potential for application in the fields of brain–computer interface, neuroprosthesis, and neuromodulation therapy, thereby enabling the treatment of epilepsy(Khodagholy et al., 2011; Fan et al., 2019; Ahmed Taha et al., 2024), Parkinson's disease(Mahlknecht et al., 2018; Jia et al., 2024; Shah et al., 2024; Cui et al., 2025), deafness(Boisvert et al., 2020; Tian et al., 2023), blindness(Palanker and Goetz, 2018; Mirochnik and Pezaris, 2019), and other neurological disorders. Electrode arrays such as cochlear implants for hearing restoration and prostheses for vision reconstruction are currently in use. Neuroelectrodes are core technological components that accurately record bioelectrical signals as information or transmit stimulatory electrical signals to neural tissues to modulate biological functions(Meyer, 2000; Zhang et al., 2019; Park et al., 2021b). Early neuromicroelectrodes predominantly used rigid materials such as metal- and silicon-based materials. Although they provide excellent conductivity, their physical properties and biocompatibility have limited their technological development. First, the Young's modulus of rigid materials is much higher than that of brain tissue. Postimplantation, mechanical stress can be easily generated owing to physiological pulsation, resulting in nerve cell damage and glial scar formation, making it difficult to realize long-term and stable signal acquisition(Luo et al., 2011; Sharafkhani et al., 2021; Hu et al., 2022; Ren et al., 2024; Khan et al., 2025). Second, adapting rigid structures to three-dimensional surfaces is difficult, limiting the

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accurate localization of deep or irregular areas. The emergence of flexible neural microelectrodes has solved the inherent limitations of rigid electrodes through the dual breakthrough of material innovation and structural design. Switching from rigid to softer electrode materials, such as hydrogels, or designing traditional planar structures into lattice-like structures can help mitigate mechanical damage and immunoreactivity, thereby achieving long-term recording stability. Breakthroughs in materials science and flexible electronics have transitioned neural microelectrodes from high modulus, low biocompatibility, short-term applicability, and single function to low modulus, high biocompatibility, long-term and stable applicability, and multifunctional integration. Such a novel flexible electrode expands the application of traditional rigid electrodes, plays an important role in the long-term management of neurodegenerative diseases, and helps sensory function reconstruction.

These flexible nerve microelectrodes can be implanted in the nerve tissue to achieve a high degree of fit, reducing the mechanical damage and immune response to the surrounding tissues. The flexibility of electrodes can generally be divided into two categories: material flexibility, mainly owing to the soft, bendable properties of the material used, and structural flexibility, achieved through an electrode with a unique structural design, for example, ultrathin electrodes and mesh structures. Although the material is relatively rigid, the fabricated electrode exhibits good flexibility and deformability owing to the design of these special structures, which can better fit tissues and cause minimum damage.

While recent reviews have extensively covered individual material classes or fabrication techniques, a comprehensive understanding of how to balance conflicting design requirements for long-term implantation remains limited. Unlike the literature, this review establishes a multidimensional framework to address the chronic reliability of neural interfaces. First, at the material level, this review provides a systematic classification of flexible conductive materials and evaluates their intrinsic physical and chemical characteristics for achieving mechanical compliance with neural tissue. Second, at the structural level, this paper reviews the engineering of neural microelectrodes across one-dimensional, two-dimensional, and three-dimensional configurations to optimize tissue integration. Finally, in terms of performance, this paper focuses on two core pillars. The first involves electrical properties required for high-fidelity recording and safe stimulation, while the second centers on long-term stability strategies, such as biocompatible coatings, to ensure reliability within harsh physiological environments. By integrating material selection, structural design, and performance optimization, this review provides a roadmap for overcoming the bottlenecks of current flexible neural electrodes and achieving stable, long-term neuroprosthetic function (Fig. 1).

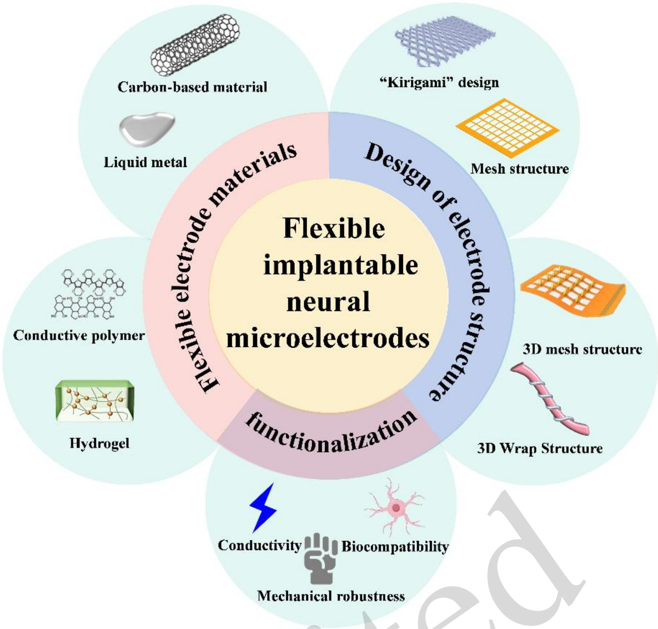

Fig. 1 Construction of flexible implantable neuro-microelectrodes from material and structural viewpoints.

2 Core conductive material selection

The core function of implantable flexible neural electrodes lies in enabling the long-term, stable recording of neural electrical signals and precise, safe stimulation. This places multiple stringent demands on their core conductive materials, including intrinsic mechanical properties compatible with neural soft tissue, outstanding intrinsic conductivity and electrochemical activity, good intrinsic biocompatibility and long-term in vivo stability, and formability and interfacial bonding capabilities suitable for micro- and nanofabrication processes. Currently, the conductive materials widely used in related research are primarily classified into three major categories: metallic materials, carbon-based materials(Deng et al., 2011; Zhang and Lieber, 2015; Ryu et al., 2017; Wang et al., 2019; Saunier et al., 2020), and conductive polymers(Cui and Martin, 2003; Castagnola et al., 2014; Pranti et al., 2018; Yang et al., 2022). The following sections will provide a systematic analysis of the intrinsic properties and research progress of representative materials within each category.

2.1 Metallic materials

Metal-based electrodes are the first large-scale commercial implantable electrode materials to have been clinically translated and are currently the most widely used. However, conventional systems primarily consist of bulk pure metals (e.g., Pt, Au), whose inherent high stiffness easily causes mechanical mismatch and tissue damage after implantation. To meet the growing demand for flexible implantable electrodes, it is essential to maintain high electrical conductivity while significantly reducing the effective modulus. Currently, research focuses on two main strategies to address this challenge. The first strategy transforms traditional bulk metals into nanostructures (such as nanoparticles and nanowires), while the second directly utilizes emerging liquid metals that combine excellent conductivity with extreme deformability.

First, traditional bulk metals can be transformed into nanoscale architectures to overcome the inherent mechanical limitations of conventional planar metals. One approach involves developing nanostructured metal coatings to replace rigid solid metal films. These nanostructures not only significantly enhance the material surface area and density of electrochemically active sites but also offer better structural compliance than continuous rigid films. For example, Boehler et al. designed a nanostructured Pt electrode coating (Fig. 2a),(Boehler et al., 2020) and Lu et al. constructed a PEDOT/3-MPA-Au layer (Fig. 2b)(Wu et al., 2024). However, these delicate nanostructures are prone to detachment during chronic micromotion, potentially causing inflammation. To fundamentally enhance the intrinsic mechanical durability of the conductive network, an alternative nanoscale approach is to transform bulk metals into high-aspect-ratio structures (such as gold nanowires, AuNWs). Rather than relying on surface coatings, this approach utilizes the bending flexibility of one-dimensional materials to balance the continuity of the conductive path with mechanical toughness. Brandt et al. developed a novel flexible electrode fabricated using high aspect ratio gold nanowires (Figs. 2c and 2d)(Seufert et al., 2024). This strategy enables the electrode to maintain conductive pathways even under bending or slight stretching, making it suitable for surface arrays attached to the cerebral cortex. Although metal nanowires balance conductivity with fatigue resistance, their fabrication complexity often limits electrode density.

Second, in contrast to solid metals, liquid metals (LMs) offer a fundamental solution to fracture risks due to their unique fluidity. However, the primary challenge for LMs is the risk of leakage. To mitigate leakage, advanced encapsulation and structural confinement strategies are essential. Park et al. designed a 3D stimulation electrode by integrating a flexible ultrathin phototransistor and eutectic gallium–indium (GaI) alloy. The alloy was 3D-printed as a high-resolution stimulation electrode and encapsulated with poly(parylene C). This pinhole-free polymer coating serves as a robust physical barrier to effectively prevent liquid metal leakage into surrounding tissues (Fig. 2e)(Chung et al., 2024). Wei et al. developed a liquid metal fiber mat as an implantable physiological electrode, combining high durability, breathability, and long-term biocompatibility; it was based on AgNPs, LMs, and porous poly(styrene block chain diene-methylene-methylene pen) fiber mats (pSBS). In this design, leakage is prevented through the structural confinement provided by the porous pSBS network and the stabilization effect of AgNPs, which anchor the liquid metal within the fiber matrix (Figs. 2f and 2g)(Zhou et al., 2025). Jiang et al. fabricated highly stretchable, neural electrode arrays mainly employing liquid metal and polydimethylsiloxane (PDMS). This approach addresses the leakage issue through a sandwich encapsulation strategy, where the liquid metal channels are fully sealed within the biocompatible PDMS elastomer, ensuring isolation from the biological environment (Figs. 2h and 2i)(Dong et al., 2021). Liquid metal electrodes eliminate fracture risks but trade fabrication resolution for extreme stretchability. The primary challenge lies in ensuring long-term encapsulation safety to prevent leakage, which restricts high-density micropatterning. Consequently, liquid metals are less suitable for high-channel-count cortical recording but are ideal for high-strain environments, such as spinal cord or muscular interfaces, where mechanical compliance is critical.

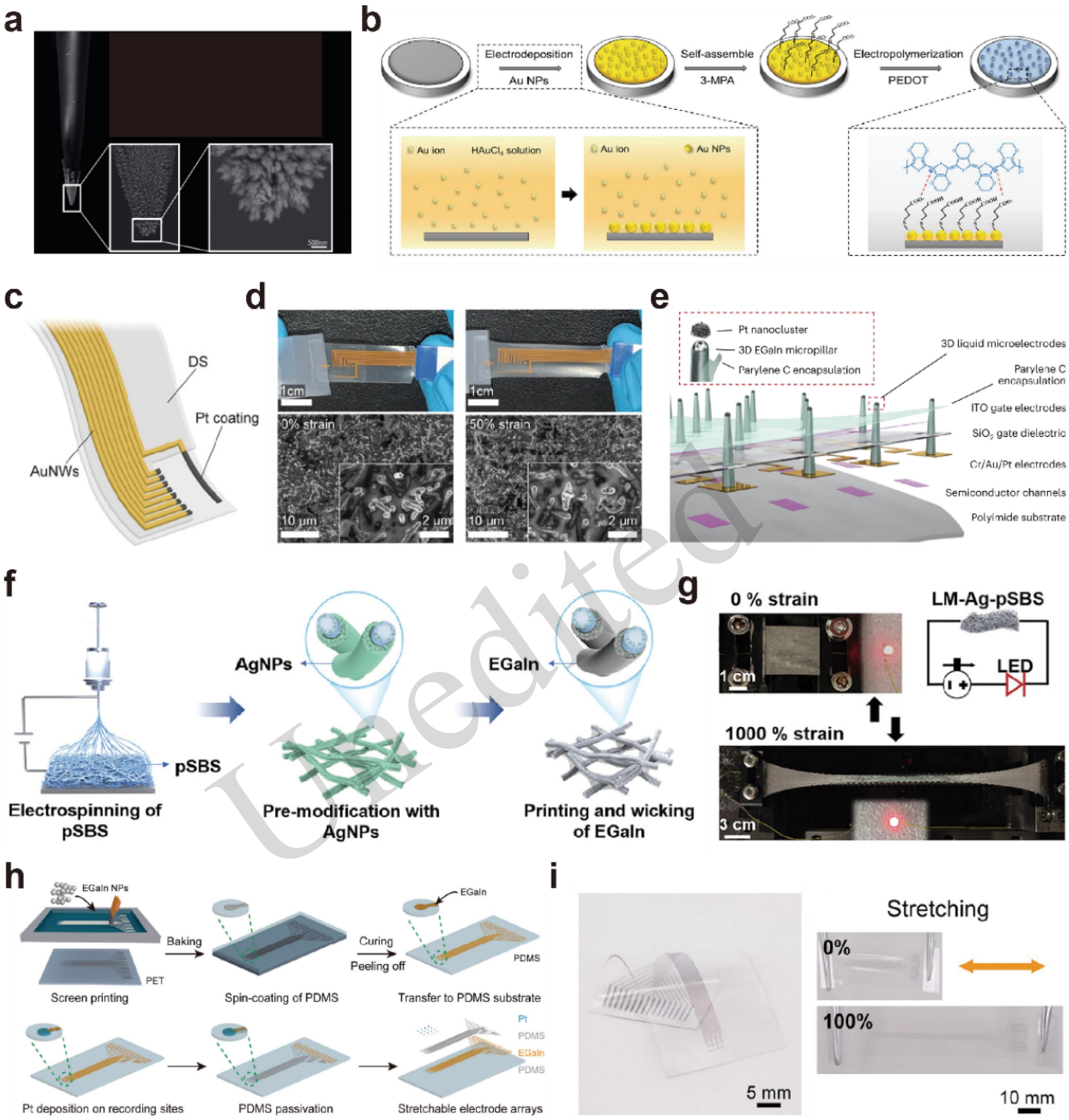

Fig. 2 Flexible neural microelectrodes based on metallic materials. (a) NanoPt coating on conical probes. Reproduced with permission from ref (Boehler et al., 2020). (b) A schematic indicating the preparation process of the PEDOT/3-MPA-Au neural electrodes. Reproduced with permission from ref (Wu et al., 2024). (c) A schematic of the multielectrode, cuff-based, soft AuNW-silicone composite. (d) Photographs and SEM characterization of the multielectrode cuff in relaxed and stretched states. Reproduced with permission from ref (Seufert et al., 2024). (e) A schematic representation of the adhesive-conducting PEDOT-MeOH:PSS/PDA interface prepared via a simple, two-step, electropolymerization approach. Reproduced with permission from ref (Chung et al., 2024). (f) A schematic of an artificial retina based on integrating a phototransistor with 3D LM microelectrodes (electrode structures are shown in the upper left corner). (g) Fabrication process of LM-AG-PSBS physiologic electrodes. Reproduced with permission from ref (Zhou et al., 2025). (h) A schematic indicating the fabrication of stretchable electrode arrays utilizing screen printing. (i) Optical microscopy images of liquid metal neural electrodes and their photographs after stretching under 0% and 100% strain. Reproduced with permission from ref (Dong et al., 2021).

2.2 Carbon-based materials

Carbon-based materials exhibit high electrical conductivity, exceptional chemical stability, and excellent biocompatibility, making them highly compelling candidates for fabricating flexible neural interfaces. The carbonaceous materials most commonly employed in this domain include graphene, carbon nanotubes (CNTs), and polymer-derived carbon. The following sections systematically review the structural designs and fabrication strategies associated with these distinct carbon-based microelectrodes.

Graphene-based materials are highly valued in neural engineering for their exceptional intrinsic properties and remarkable versatility in physical form factors. While graphene can be synthesized through various mainstream approaches—such as mechanical exfoliation, oxidation–reduction techniques, and chemical vapor deposition (CVD)—the chosen synthesis method fundamentally dictates the resulting design of the electrode. For instance, Viana et al. developed thin-film microelectrodes using nanoporous graphene (NPG) grown via CVD (Figs. 3a and 3b)(Viana et al., 2024). To further enhance these planar structures through interface engineering, Dong et al. proposed flexible graphene-based microelectrodes with tunable porous structures through optimized synthesis and posttreatment, significantly enhancing neural recording performance (Figs. 3c and 3d)(Dong et al., 2025). Furthermore, to achieve extreme mechanical compliance, Wang et al. utilized wet-spinning strategies to prepare one-dimensional graphene fiber-based microelectrodes, offering the extreme flexibility needed to accurately capture weak neuroelectric signals (Fig. 3e)(Wang, et al., 2019). However, the widespread implementation and clinical translation of graphene are often hindered by the complexities and scalability of these precise manufacturing processes. Despite these fabrication challenges, its outstanding electrochemical characteristics, tunable physical forms, and superior tissue conformability make graphene a highly promising candidate for developing high-resolution, conformal neural interfaces and ultraflexible microelectrodes.

Owing to their unique one-dimensional morphology and exceptional mechanical properties, CNTs have emerged as highly compelling candidates for flexible neural interfaces. Although individual CNTs are typically synthesized at the nanoscale via chemical vapor deposition (CVD), arc discharge, or laser ablation, translating these nanomaterials into functional implantable devices fundamentally relies on assembling them into macroscopic architectures. For instance, Lu et al. developed soft and MRI-compatible neural electrodes from CNT fibers fabricated through solution spinning and twisting processes (Fig. 3f)(Lu et al., 2019). Furthermore, beyond one-dimensional fibers, the high electrical conductivity, large electroactive surface area, and extraordinary mechanical flexibility of macroscopically assembled CNTs make them equally suitable for fabricating highly sensitive cortical surface microelectrode arrays. Despite these functional advantages, the biosafety of CNT-based neural microelectrodes remains a controversial issue. While surface-functionalized and properly dispersed CNTs generally exhibit favorable biocompatibility, unmodified or heavily agglomerated CNTs can induce oxidative stress, severe inflammatory responses, and potential cytotoxicity in neural tissues. Consequently, rigorous surface engineering and dispersion controls are essential prerequisites for their safe clinical translation.

Polymer-derived carbon materials, such as glassy carbon and polyimide (PI)-based carbon, offer a compelling combination of electrical conductivity, excellent biocompatibility, and compatibility with standard microfabrication processes. These properties enable the creation of structurally stable and customizable carbon-based neural microelectrodes. For example, Vomero et al. developed a flexible bioelectronic device featuring micropatterned monolithic carbon fiber (CF) pads on a PI substrate, achieved through the pyrolysis of photoresist precursors (Fig. 3g)(Vomero et al., 2020). However, the physical assembly of individual microscopic carbon fibers into dense arrays is highly labor intensive, which severely restricts their lateral spatial resolution. Consequently, such assembled CF arrays are less viable for high-density flexible surface electrocorticography (ECoG), although they remain exceptional tools for targeted deep-brain recordings where insertion trajectory precision and a minimal footprint are critical. To overcome the scalability limitations of individual fibers, researchers have increasingly turned to photolithographically patterned glassy carbon. In a separate study, Vomero et al. developed a novel glassy carbon electrode material that features an ultrasmall footprint and sufficient structural stiffness to optimally facilitate tissue penetration while minimizing acute insertion trauma (Vomero et al., 2017). Similarly, Castagnola et al. utilized photolithography to fabricate a glassy carbon microelectrode array capable of multimodal neural monitoring, enabling simultaneous electrophysiological recording and neurotransmitter detection(Castagnola et al., 2024). Despite these advanced microfabrication capabilities, photolithographically derived glassy carbon is inherently brittle and susceptible to cracking under significant dynamic deformation. Therefore, rather than being applied in highly dynamic environments (such as peripheral nerves), polymer-derived carbon is optimally suited for cortical surface arrays subjected to minimal mechanical strain or as structurally robust penetrating probes for long-term, stable chronic implantation.

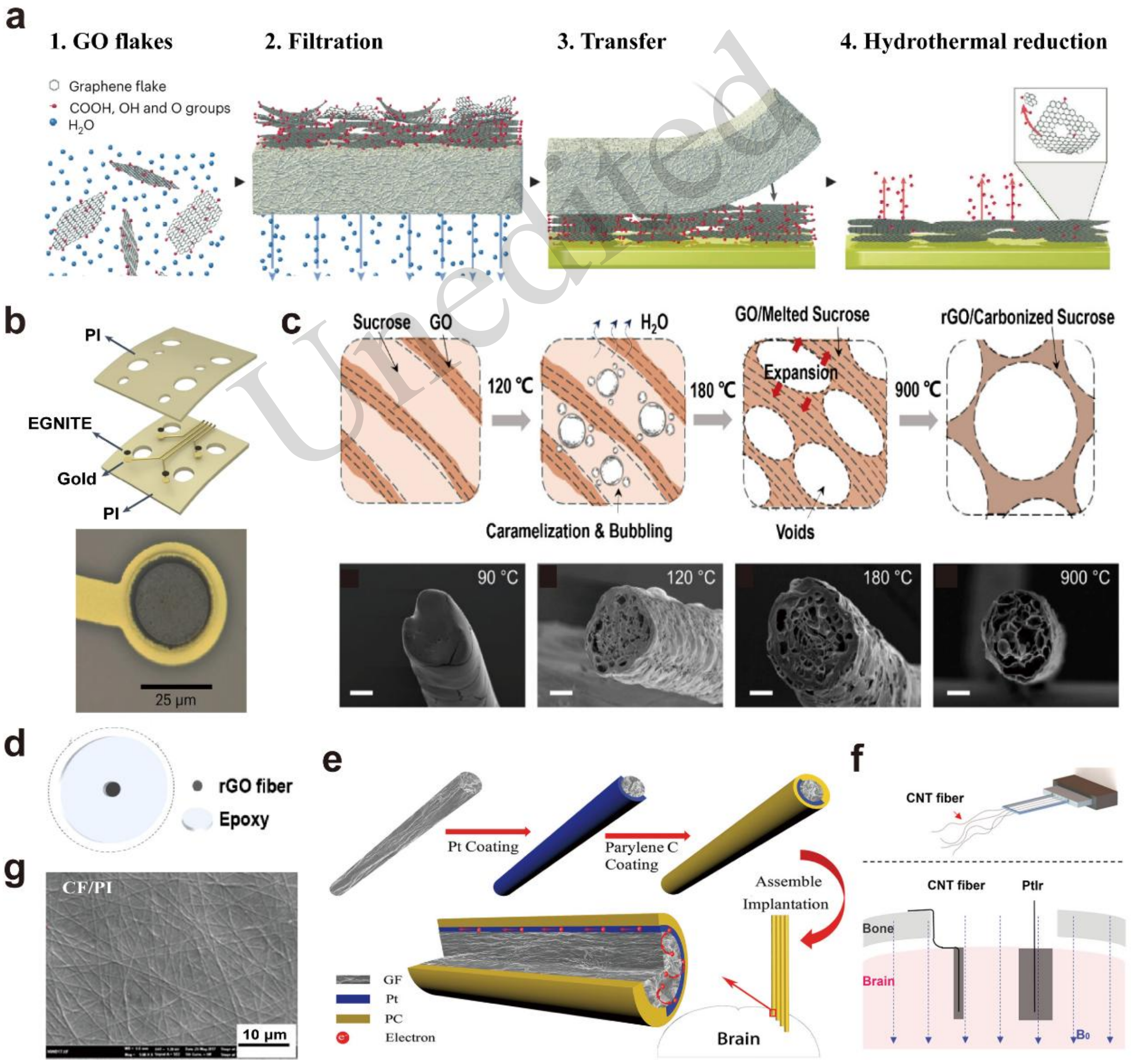

Fig. 3 Flexible neural microelectrodes were fabricated employing carbon-based materials. (a) Schematic indicating the preparation of the porous and reduced GO film, EGNITE. (b) A schematic describing the fabrication of the EGNITE flexible microelectrode array; micrographs of 25 μm diameter EGNITE microelectrodes. Reproduced with permission

from ref (Viana et al., 2024). (c)A schematic representation of the mechanism underlying the evolution of GO/sucrose hydrogel fibers during heat treatment and the microstructure of the GO fibers solidified in a 50% weight sucrose bath (GO-50) after vacuum drying at 90 °C, 120 °C, 180 °C, and 900 °C. (d) Fabrication of a single recording electrode by employing rGO-sucrose fibers. Reproduced with permission from ref (Dong et al., 2025). (e) A schematic indicating GF-Pt microelectrode fabrication. Reproduced with permission from ref (Wang, et al., 2019). (f) A schematic of the soft and MRI-compatible CNT fiber electrode. Reproduced with permission from ref (Lu et al., 2019). (g) Scanning electron microscopy image of a carbon fiber (CF) mat embedded in polyimide (PI). Reproduced with permission from ref (Vomero et al., 2020).

2.3 Conductive Polymer Materials

Surface chemical modification of conductive polymer materials is highly adaptable; they also possess good biocompatibility and inherent softness, making them attractive candidates for bridging the mechanical gap between soft neural tissue and electronic devices(Cui and Martin, 2003; Marzocchi et al., 2015; Aqrawe et al., 2017; Wang et al., 2017; Feig et al., 2018; Liu et al., 2018; Yang, et al., 2022; Lee et al., 2024; Ma et al., 2024). Based on their structural composition and conductive mechanisms, conductive polymers applied in neural electrophysiology can be broadly classified into two main categories: intrinsically conductive polymers (ICPs) and conductive polymer composites (CPCs).

ICPs achieve electronic conduction through delocalized π bonds in their main chains. The most common intrinsically conductive polymers used for fabricating electrodes are PEDOT(Cui and Zhou, 2008; Venkatraman et al., 2011; Green et al., 2012; Khodagholy et al., 2013; Mandal et al., 2014), polypyrrole (PPy), poly(5-nitroindole), and polyaniline. Through electrochemical polymerization or film-forming processes, it is possible to create extremely thin, flexible interfaces that adhere closely to biological tissues. For instance, Abidian et al. developed an implantable neural microelectrode modified with PPy and PEDTO nanotube polymers (Fig. 4a)(Abidian and Martin, 2008). Middya et al. developed a PEDOT:PSS-based microelectrode cortical imaging (μECoG) array that enables simultaneous electrophysiology and MRI studies (Fig. 4b)(Middya et al., 2025). Furthermore, Yang et al. designed robust PEDOT neural interfaces using a poly(5-nitroindole) film as an interfacial layer (Fig. 4c)(Yang et al., 2021). However, ICPs tend to be quite brittle and are prone to cracking under large deformations, which limits their application in highly dynamic environments.

CPCs refer to composite systems formed by embedding conductive fillers into flexible polymer matrices (such as hydrogels or elastomers) to achieve a critical balance between high mechanical toughness and electrical conductivity. Depending on the desired electrochemical and mechanical profiles, various filler materials can be utilized. One primary approach involves metal-based composite fillers, where metal nanoparticles or nanowires are incorporated into a polymer matrix. This strategy leverages the high intrinsic conductivity of metals to construct a low-impedance interface. As a demonstration of this concept, Park et al. used Sn as the core conductive phase to prepare multielectrode fibers via a polymer thermal stretching process. Following surface functionalization, these fibers were seamlessly integrated into a hydrogel matrix to create a robust metal-polymer composite conductive interface (Fig. 4d)(Park et al., 2021). Alternatively, carbon-based composite fillers can be employed to enhance the structural integrity of the interface. By taking advantage of the superior electrical and mechanical properties of carbon materials, these composites simultaneously improve the electrical conductivity and mechanical toughness of the host polymer matrix. For example, Nam et al. developed a flexible neural interface composed of nonprotein hydrolyzed β-peptides and CNTs assembled in a hierarchical structure. Within this design, the beta peptide and conductive nanomaterials formed a 3D electrical network that effectively enhanced brain signal acquisition (Fig. 4e)(Nam et al., 2020). Beyond metallic and carbonaceous materials, another effective strategy is the development of intrinsically conductive polymer-filler composites. Illustrating this approach, Shur et al. reported a screen-printable PAAm-PEDOT:PSS conductive hydrogel (Fig. 4f)(Shur et al., 2020). By blending inherently conductive polymers with soft, insulating polymer networks, researchers can mimic the hydrated microenvironment of biological tissues while maintaining efficient charge transport and elastic mechanical properties. Building on similar principles, Zhang et al. prepared a PEDOT:Poly(SS-4VP) interpenetrating network hydrogel to modify a bioelectrode, achieving long-lasting and stable electrophysiological recordings and electrical stimulation (Figs. 4g and 4h)(Zhang et al., 2022). While the integration of substantial amounts of insulating polymers inevitably leads to a trade-off by reducing the overall electrical conductivity, these composite strategies remain essential for long-term chronic implants in dynamic environments. Their tissue-like modulus significantly mitigates mechanical mismatch, accommodates brain micromotions, and minimizes foreign body responses, thereby ensuring the enduring stability of the neural-electrode interface.

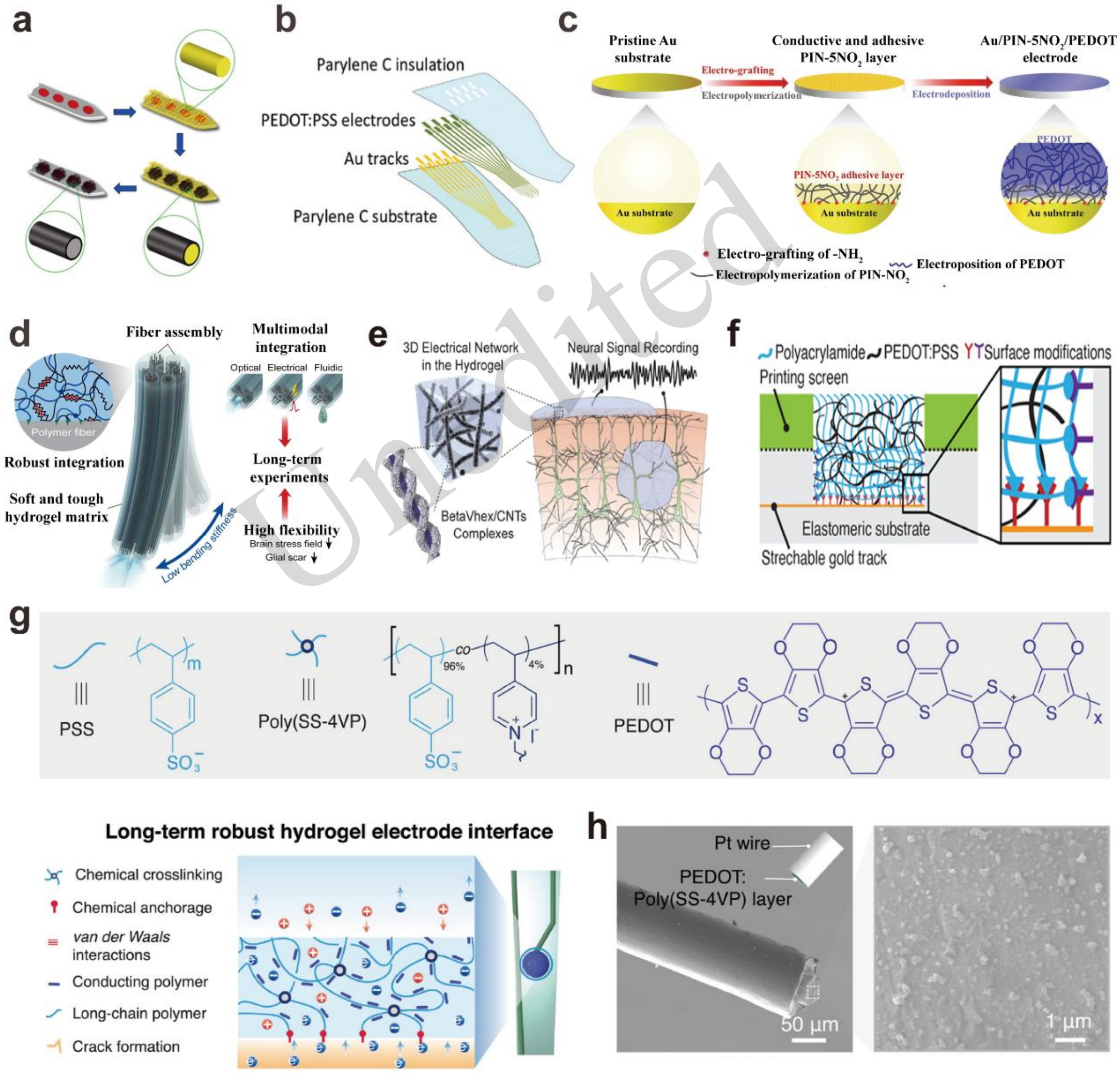

Fig. 4 Flexible neural microelectrodes fabricated using conductive polymers. (a) A schematic describing the preparation of conductive polymer (CP) nanotubes. Reproduced with permission from ref (Abidian and Martin, 2008). (b) A schematic of the PEDOT:PSS μECoG array. Reproduced with permission from ref (Middya et al., 2025). (c) A schematic representation of the Au/PIN-5 NO2/PEDOT electrode fabrication process. Reproduced with permission from ref (Yang et al., 2021). (d) Design of an adaptive, multifunctional hydrogel hybrid probe. Reproduced with permission from ref (Park et al., 2021). (e) A schematic of the supramolecular, β-peptide, hydrogel-based electrode. Reproduced with permission from ref (Nam et al., 2020). (f) A schematic of the PEDOT:PSS-based hydrogel electrode. Reproduced with permission from ref (Shur et al.,

2020). (g) A conceptual diagram of the CP hydrogel coating. (h) SEM image of the PEDOT:Poly(SS-4VP) layer present on the Pt line. Reproduced with permission from ref (Zhang et al., 2022).

3. Structural design

Selecting electrode materials with a low Young's modulus and flexible polymer substrates can significantly reduce the stiffness of nerve electrodes. However, the electrode structure design is also crucial to enhance the electrode flexibility and deformability through a proper structural design to better fit the complex curved surface of the nerve tissue.

3.1 One-dimensional structure

Silicon-based probes, represented by classic Michigan arrays, have long served as the standard for intracortical recording. These rigid shanks allow for precise depth insertion but often suffer from mechanical mismatch with soft brain tissue(Wise et al., 2004). Extensive research has shown that reducing the size and stiffness of nerve probes can dramatically suppress the trauma caused during insertion. Ultraflexible and micron-sized electrodes are well adapted to curved blood vessels, effectively reducing the risk of bleeding during penetration. They can work normally without causing significant interference to the surrounding tissue. Luan and his team designed and fabricated subcellular-sized, ultraflexible, nanoelectronic wires (NET-50 and NET-10) that can stably detect and track neural activity over long periods and enable seamless subcellular integration with local cell and vasculature system networks (Figs. 5a–5e)(Luan et al., 2017). While traditional 1D probes offer established fabrication processes, emerging one-dimensional, implantable, neural microelectrodes possess high temporal resolution and signal quality, with a significantly reduced chronic immune response. Moving from rigid shanks to ultraflexible threads represents a trade-off between insertion feasibility and chronic biocompatibility. While traditional probes (e.g., Michigan arrays) offer easy depth targeting but cause chronic tissue damage, subcellular-sized threads minimize inflammation at the cost of requiring complex insertion aids (e.g., stiff shuttles). Thus, ultraflexible 1D designs are superior for long-term, stable neural tracking where minimizing the foreign body response outweighs the initial surgical complexity.

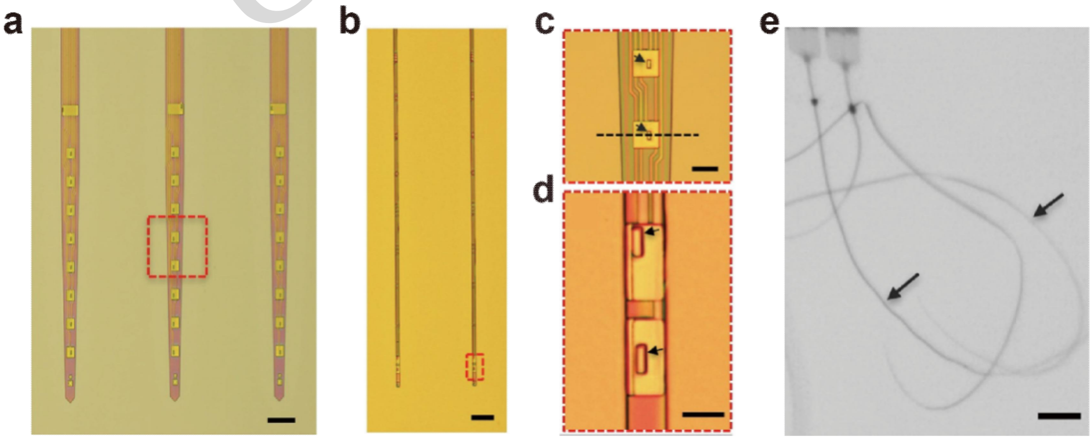

Fig. 5 One-dimensional electrodes comprising a nanoelectronic wire nerve probe. (a) NET-50 probe view. (b) NET-10 probe view. (c and d) Magnified views of the two electrodes marked by dashed boxes in (a) and (b), respectively. (e) Multiple NET-10 probes were suspended in water. Scale bars: 100 µm (a), 50 µm (b and e), and 10 µm (c and d). Reproduced with permission from ref (Luan et al., 2017).

3.2 Two-dimensional structures

3.2.1 Flexible film electrodes

Planar electrodes are widely employed for electrocortorticography (ECoG) to record macroscopic field potentials from the cortical surface. Ultrathin electrodes have a certain degree of flexibility, allowing conformal attachment to the curved surfaces of the neural tissues for the long-term recording of ECoG and LFP. Lee et al. designed an ultrathin, minimally invasive, neural probe (NeuroWeb) consisting of hexagonal boron nitride and graphene, with a total thickness of 100 nm (Figs. 6a and 6b)(Lee et al., 2023). Khodagholy et al. designed an organic electrochemical transistor embedded in an ultrathin organic film based on PEDOT:PSS, Au, and parylene (Figs. 6c and 6d)(Khodagholy, et al., 2013). Ultrathin planar films prioritize noninvasive conformability over depth resolution. While excellent for minimizing cortical compression and mapping macroscopic network dynamics (ECoG/LFP), they fundamentally trade off single-unit specificity for safety. Consequently, solid film designs are limited to applications requiring broad surface monitoring, as they cannot access deep neural spiking or facilitate fluid exchange across the blood–brain barrier, such as open-mesh structures.

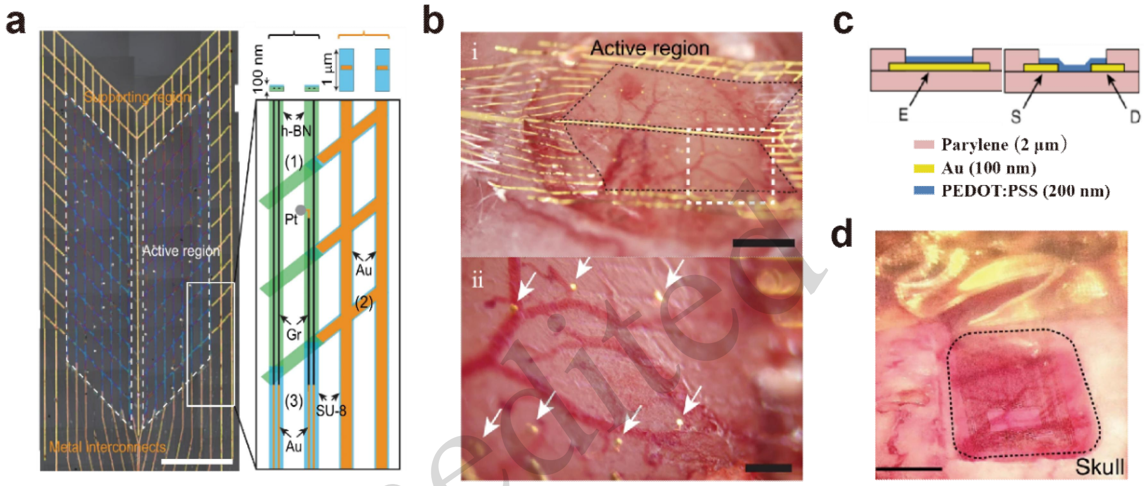

Fig. 6 Flexible thin-film electrode. (a) Optical microscopy images of the artificial neural nets. (b) (i) A magnified image of the active area of the neural net (black dashed line). Scale bar: 1 mm. (ii) A magnified image of the white dashed box in "i." Scale bar: 100 µm. Reproduced with permission from ref (Lee et al., 2023). (c) Structure of the ECoG probe. (d) An optical micrograph of the ECoG probe placed on the somatosensory cortex. Scale bar: 1 mm. Reproduced with permission from ref (Khodagholy, et al., 2013).

3.2.2 Mesh and Kirigami

The grid-like design provides more detection sites, enabling the electrodes to simultaneously record nerve signals from multiple sites and facilitate a better fitting of the electrodes to the nerves. Morikawa et al. designed an electrode consisting of a poly(p-xylene) polymer as a substrate and a nonstretchable metallic material, Pt/Ti, as an electrode material; it possessed the properties of high stretchability and deformability after patterning into a kirigami structure (Figs. 7a–7c)(Morikawa et al., 2017). Li et al. designed a stretchable mesh-based microelectronic system employing conductive hydrogel electrode arrays consisting of poly(3,4-ethylene dioxythiophene) polystyrene sulfonate (PEDOT:PSS) and the elastomer poly(styrene-ethylene-butadiene-styrene) (SEBS) as a substrate and encapsulant (Figs. 7d–7f)(Li et al., 2022). Zhang et al. designed a polymer-based, ultraflexible, microvascular endovascular (MEV) nerve probe loaded into a flexible microcatheter. The mesh structure relaxed and unfolded after injection; the microcatheter was then retracted, allowing the MEV probe to remain in place (Figs. 7g and 7h)(Zhang et al., 2023). Furthermore, Ryu et al. prepared multifunctional, nanogrid-structured electrodes based on a three-layer material of poly(p-xylene-c), gold (Au), and poly(3,4-ethylene dioxythiophene)-poly(styrenesulfonate) (PEDOT:PSS) (Figs. 7i and 7j)(Ryu et al., 2024). Mesh and kirigami architectures solve the fluid permeability and stretchability limitations of solid films, enabling true tissue integration. The critical trade-off lies in deployment complexity and structural fragility. Expanding these delicate networks often necessitates specialized delivery tools. Therefore, these open designs are superior for endovascular approaches.

Compared to one-dimensional neural microelectrodes, two-dimensional structured electrodes have a higher spatial resolution and cover a wider neural area. However, it is difficult to accurately distinguish and record signals from nerve cells distributed at different depths and varied locations using 2D electrodes.

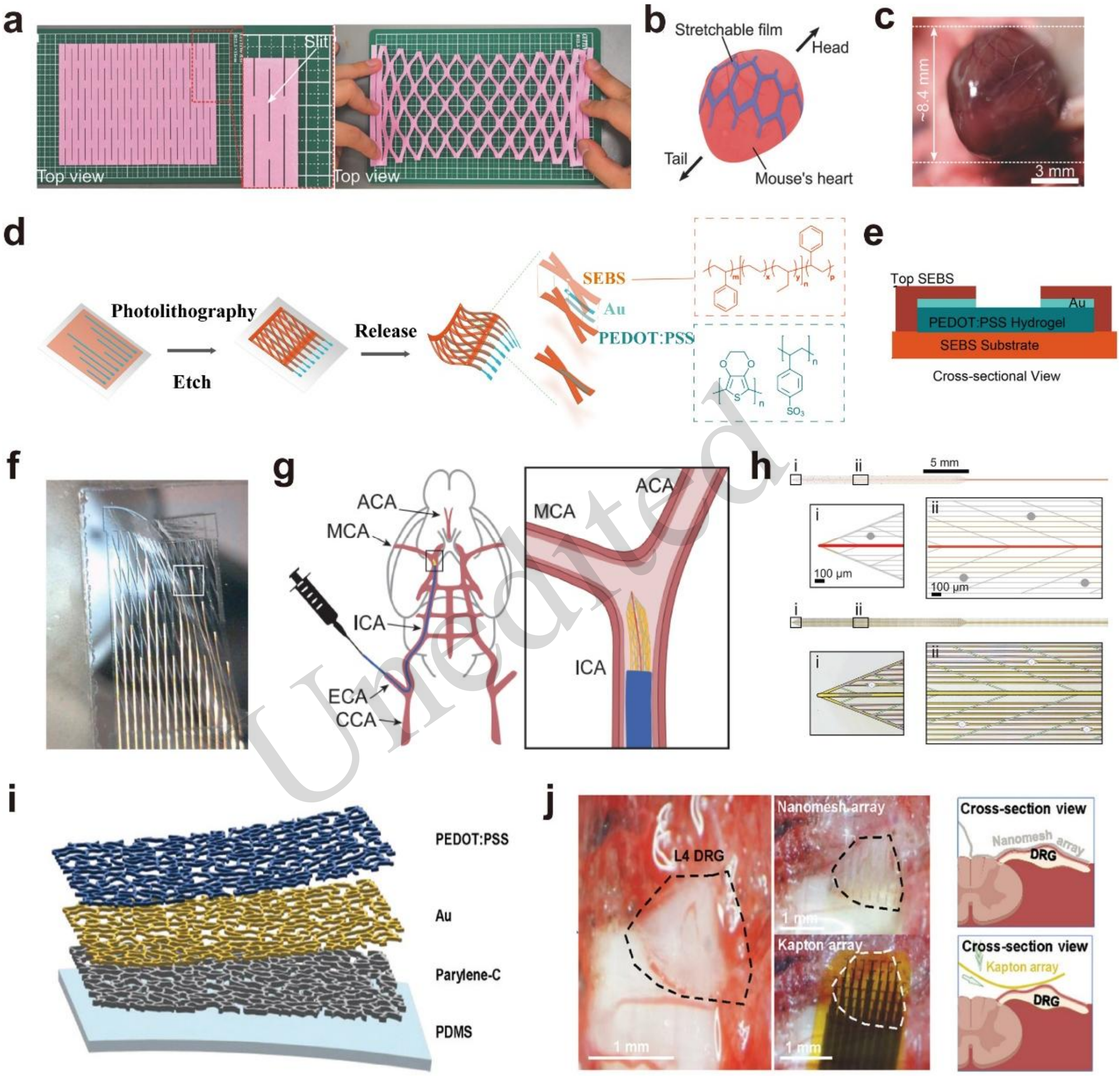

Fig. 7 A flexible mesh planar electrode. (a) Photographs and schematic diagrams of the stretched "Kirigami" paper (120 × 160 mm2). (b-c) Schematic diagrams and photographs of artificial, poly-para-xylene films placed on beating mouse hearts. Reproduced with permission from ref (Morikawa et al., 2017). (d) Stretchable SEBS and PEDOT:PSS materials patterned into a grid-like shape and their fabrication process. (e) A cross-sectional view of the electrode design. (f) A photograph of the mesh electrode. Reproduced with permission from ref (Li et al., 2022). (g) A schematic of the endovascular implantation procedure. (h) An enlarged view of the MEV probe tip and recording electrode. Reproduced with permission from ref (Zhang et al., 2023). (i) A detailed view of the multifunctional, nanonet-composed film. (j) In a similar design, a 64-ch nanoweb elastic electrode and 64-ch Kapton arrays were placed in the same DRG region; the nanoweb elastic electrode arrays were more conformal. Reproduced with permission from ref (Ryu et al., 2024).

3.3 Three-dimensional structures

Three-dimensional electrodes allow for the all-around, three-dimensional recording of neural activity. The Utah array is the most prominent example of a 3D electrode, consisting of rigid silicon microneedles that enable high-density population recording(Campbell et al., 1991). However, such rigidity limits conformity to soft tissues. To overcome this, novel 3D designs focus on accurate localization and selective stimulation while enhancing flexibility. Lee et al. developed a one-step, microelectrothermal molding (μETF) technology to fabricate flexible microelectrodes into neural interfaces with 3D microstructures for improved neural recording and stimulation (Fig. 8a)(Lee et al., 2025). Hiendlmeier et al. designed an electrode that can self-fold into a nerve cuff during insertion. It incorporates a sodium acrylate hydrogel, which swells maximally when immersed in an aqueous solution, allowing the electrode to gently fold around the nerve (Fig. 8b)(Hiendlmeier et al., 2023). Xia et al. developed helical electrodes for peripheral nerves using a bilayer rollable silk protein membrane and a MEMS process (Figs. 8c and 8d)(Zhu et al., 2024). Xiang et al. fabricated biocompatible, 3D, microneedle electrodes utilizing stretch lithography (Fig. 8e)(Xiang et al., 2016). Dong et al. developed a cuff that actively wraps around nerves when driven by a voltage of a few hundred millivolts. This smart nerve cuff uses dodecylbenzene sulfonate-doped polypyrrole as the actuating material, which can significantly change its volume under electrochemical stimulation. As the process is reversible, the cuff can withstand hundreds of folding and unfolding cycles within the physical environment and be adjusted multiple times to fit the nerve better (Figs. 8f–8h)(Dong et al., 2024). Although 3D electrodes enable comprehensive neural recording, they rely heavily on high-precision micromachining and entail greater invasiveness than surface arrays. The evolution from rigid Utah arrays to soft 3D architectures fundamentally trades implantation simplicity for chronic biocompatibility. Despite the elevated fabrication and surgical complexity, these conformal designs remain essential for high-fidelity volumetric mapping and dynamic peripheral interfaces, offering significant advantages in signal quality over planar alternatives.

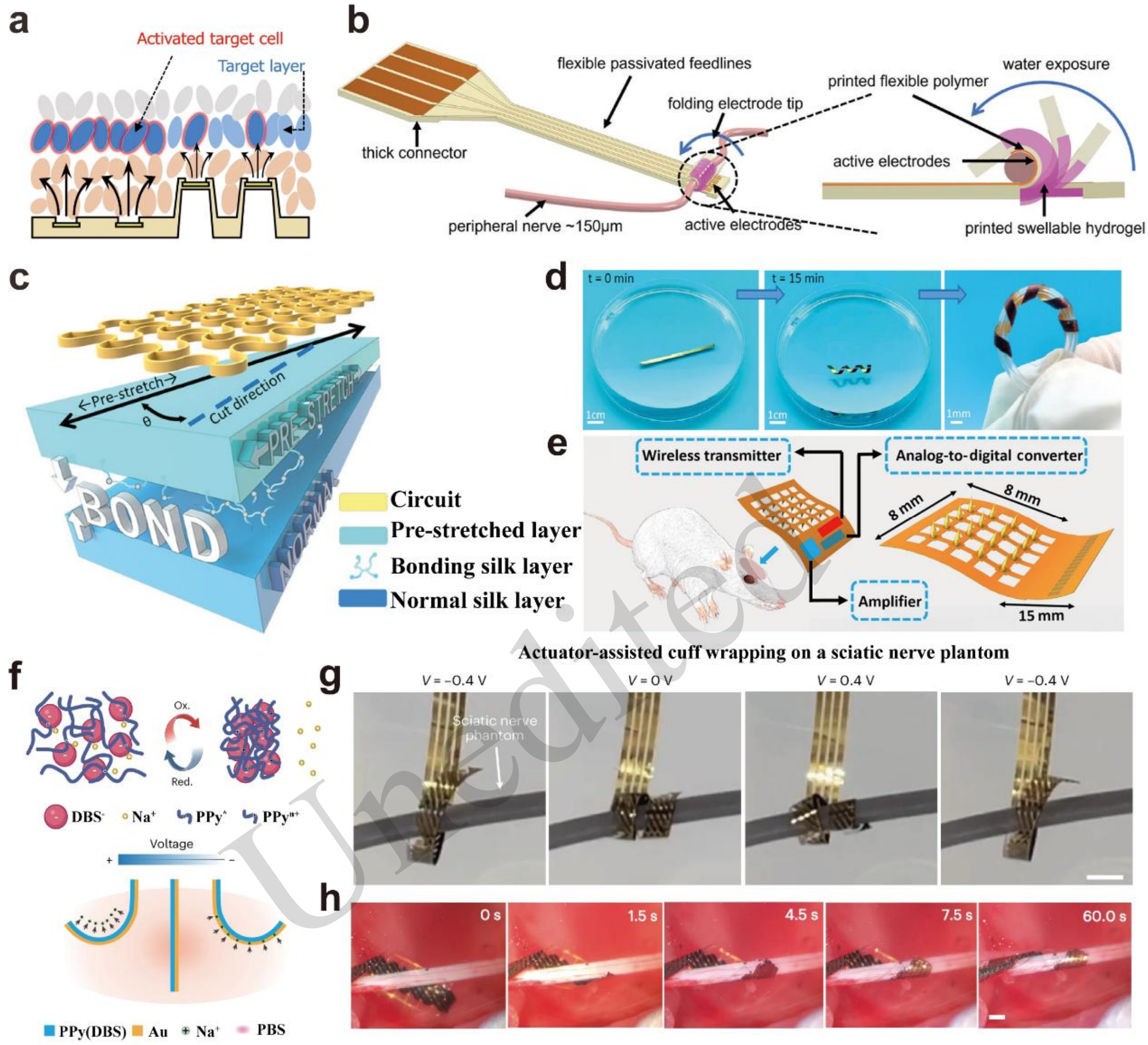

Fig. 8. A flexible 3D electrode. (a) The benefits of localized neural interfaces achieved through 3D structures. Reproduced with permission from ref (Lee et al., 2025). (b) A schematic of the cuff electrode with a collapsible tip and a close-up side view of the electrode tip. Reproduced with permission from ref (Hiendlmeier et al., 2023). (c) A schematic representing the standard, reconfigurable, silk bioelectronic device concept. (d) A photograph of a neural cuff during deformation and the bending of a silicone tube. Reproduced with permission from ref (Zhu et al., 2024). (e) The design and geometry of a flexible microneedle electrode. Reproduced with permission from ref (Xiang et al., 2016). (f) A schematic indicating the volume changes in PPy(DBS) and the reversible bending motion in PBS solution induced by binding to Au. (g) Nerve cuffs at different voltages. (h) The nerve envelope automatically wraps the sciatic nerve when the voltage is switched from −0.5 to 0 volts. Reproduced with permission from ref (Dong et al., 2024).

4 Vital properties of the implantable neural microelectrodes

Implantable neural microelectrodes act as the key interface connecting the nervous system and electronic instruments. Their performance directly determines the accuracy of neural signal acquisition, reliability of long-term implantation, and safety in clinical applications. The performance requirements for flexible microelectrodes have currently shifted to multidimensional synergistic optimization. In the following sections, this paper will focus on two key parameters, namely, electrical performance and long-term stability.

4.1 Electrical properties

Electrical performance is the core element that determines the functioning of an electrode. While low impedance and high signal-to-noise ratio (SNR) are essential for recording(Lim et al., 2021; Neto et al., 2021; Zeng et al., 2022; Horváth et al., 2024), parameters related to electrical stimulation, specifically charge storage capacity (CSC) and charge injection limit (CIL), are equally critical for therapeutic applications. A high CSC ensures sufficient charge delivery within safe voltage limits, while the CIL defines the maximum charge density that can be injected reversibly without inducing harmful faradaic reactions or tissue damage. Table 1 summarizes the electrochemical properties of various neural microelectrodes reported in recent studies.

To push the boundaries of recording and stimulation efficacy, contemporary electrode designs rely heavily on a dual approach: maximizing the effective electrochemical surface area and integrating advanced pseudocapacitive materials. First, surface nanostructuring significantly increases the electrochemical surface area, thereby boosting the charge storage capacity (CSC). For example, Zeng et al. developed platinum-iridium oxide neural microelectrodes based on a nanocone array structure, which provided a large surface area for charge transfer, and the CSCc and charge injection capacity (CIC) reached 52.44 ± 2.53 mC/cm^2 and 4.39 ± 0.36 mC/cm^2, respectively(Zeng, et al., 2022). In a related study, the same group demonstrated that electrodepositing iridium oxide onto platinum nanocones could achieve a low impedance of 2.45 kΩ cm^2 at 1 kHz and a high CSCc of 22.29 mC/cm^2 (Figs. 9a and 9b)(Zeng et al., 2017). Fiáth et al. developed a silicon-based neural probe integrated with densely packed low-impedance titanium nitride microelectrodes, enabling ultrahigh-resolution in vivo neural electrophysiological recording (Fig. 9c)(Fiáth et al., 2018). Second, incorporating conductive polymers and carbon nanomaterials creates hybrid composites with exceptional charge storage capabilities. For instance, Chen et al. designed a nanotunnel-like coating of PEDOT and carbon nanotubes (CNTs), which markedly reduced impedance and increased CSC by facilitating ion transport (Figs. 9d–9f)(Chen et al., 2020). Reddy et al. and Lee et al. demonstrated that PEDOT-based nanohybrids (with bionanotubes or graphene oxide) could significantly improve electrochemical stability and durability(Lee et al., 2019; Reddy et al., 2019). Additionally, Huang et al. developed polydopamine-doped PEDOT interfaces to enhance bioactivity and electrochemical performance. The CSC of the PEDOT/PDAM-modified electrodes is approximately 21.0 mC/cm^2, reaching 2.3 times that of unmodified electrodes (Figs. 9g–9i)(Huang et al., 2022). More recently, Yan et al. prepared PEDOT/PSS/PVA interpenetrating conducting polymer networks (ICPNs), which effectively combined the high conductivity of polymers with the soft mechanics of hydrogels, leading to robust electrical stability and enhanced charge storage performance (Figs. 9j and 9k)(Yan et al., 2023).

Table 1. Comparison of electrochemical properties of neural microelectrodes

Electrode Material	Impedance(1 kHz)	CSCc(mC/cm^2)	CIL(mC/cm^2)	Ref.
Pt-IrOx Nanocones	0.72 ± 0.04 kΩ cm^2	52.44±2.53	4.39±0.36	(Zeng et al., 2022)
PEDOT/Bionanotube	130 Ω	＞11	N/A	(Reddy et al., 2019)
PEDOT/CNT Nanotunnels	2.6 ± 0.4 kΩ	26.3±2.4	N/A	(Chen et al., 2020)
Electrodeposited lrOx on Pt Nanocones	2.45 kΩ cm^2	22.29	N/A	(Zeng et al., 2017)
PDA-Melanin/PEDOT	＜100 Ω	~21.0	N/A	(Huang et al., 2022)
PEDOT-Hydrogel IPN	1.14 kΩ	216.54 ± 9.61	N/A	(Yan et al., 2023)

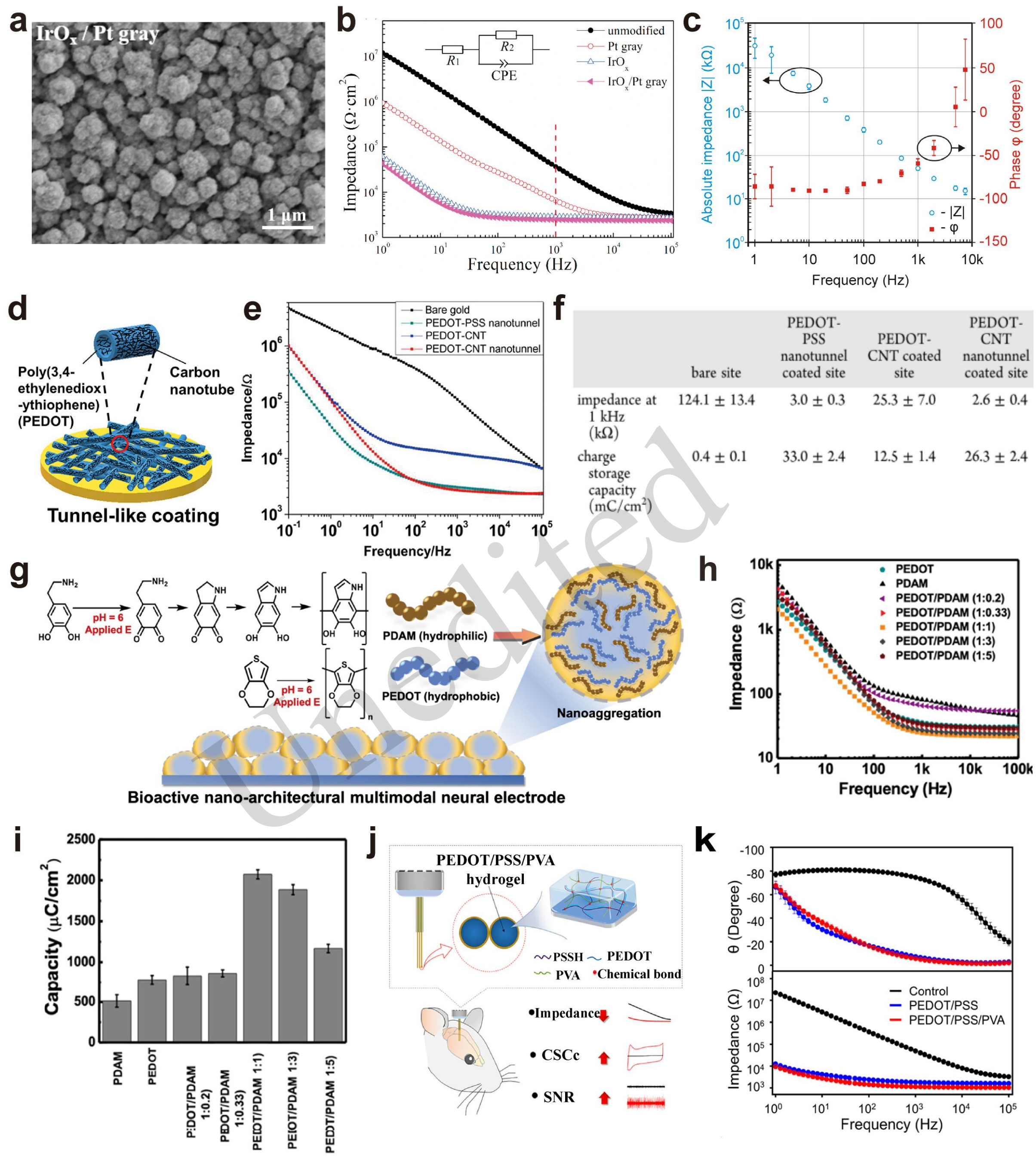

Fig. 9 Strategies to enhance the electrical performance of flexible neural microelectrodes. (a) SEM images of the IrOx/Pt gray-coated microelectrodes. (b) Porter's plot indicating the electrochemical impedance of the IrOx/Pt-coated microelectrode. Reproduced with permission from ref (Zeng et al., 2017). (c) Average impedance magnitude and phase values for TiN electrodes measured at 13 frequencies. Reproduced with permission from ref (Fiáth et al., 2018). (d) A schematic of the PEDOT-CNT nanotunnel-like coating. (e) AC impedance spectra of bare and coated electrodes. (f) Electrochemical properties of bare and coated electrodes. Reproduced with permission from ref (Chen et al., 2020). (g) A schematic diagram indicating the synthesis of the self-assembled nanostructured PEDOT/PDAM membrane. (h, i) Measured impedance values and calculated charge storage capacity at 1 kHz for membranes with different EDOT/DA ratios. Reproduced with permission from ref (Huang et al., 2022). (j) A schematic of the poly(3,4-ethylenedioxythiophene)/poly(styrenesulfonic acid)/poly(vinyl alcohol) (PEDOT/PSS/PVA) interpenetrating conducting polymer network (ICPN). (k) Potter's plots of the electrochemical impedance of bare platinum (Pt),

poly(3,4-ethylene dioxythiophene)/polystyrene sulfonate (PEDOT/PSS)-modified Pt, and ICPN-modified Pt electrodes. Reproduced with permission from ref (Yan et al., 2023).

4.2 Long-term stability

Neural microelectrodes must be stable for longer periods after surgical implantation, and their performance must meet certain standards. For long-term applications, a low Young's modulus may provide a certain degree of protection against loss of performance due to encapsulation by microglia. In the previous discussion, we introduced ways to achieve flexibility at the material and structural level. Next, we focus on other strategies that can enhance the long-term stability of electrodes. Specifically, surface engineering, such as implementing immuno-modulatory coatings to mitigate foreign body responses and reinforcing interfacial adhesion to prevent material delamination, is essential. The following studies highlight recent advancements in these two critical areas. To reduce immune rejection, Wang et al. developed a bioadhesive and immuno-evasive, hydrogel-integrated, brain–computer interface by introducing catechol functional groups into a hydrogel, which offers the possibility of long-term and stable operability (Figs. 10a and 10b)(Wang et al., 2022). Similarly, targeting the tissue inflammatory response, Golabchi et al. developed an amphoteric ionic polymer/polydopamine coating, which could effectively reduce the acute inflammatory tissue reaction induced by neural implants (Fig. 10c)(Golabchi et al., 2019). Furthermore, Lee et al. developed a polypyrrole/heparin (ppy/hep) bionic electrode with an immunocompatible morphology that modulated macrophage responses, thereby inhibiting inflammation (Fig. 10d)(Lee et al., 2022). In addition to biological compatibility, maintaining the physical integrity of the electrode coatings is equally important. Ouyang et al. proposed a method to effectively improve the adhesion of PEDOT to solid substrates, and an electrically grafted methylamine-functionalized EDOT derivative (EDOT-NH2), which could withstand 1 h of sonication without significant cracking or delamination, was proposed (Fig. 10e)(Ouyang et al., 2017). Inoue et al. proposed the use of a hydrophilic and polymeric adhesive layer a few nanometers thick to achieve interfacial bonding between wet conducting polymers and various substrates (Figs. 10f and 10g)(Inoue et al., 2020). In summary, by combining biofriendly surface modifications with robust interfacial bonding techniques, these strategies effectively overcome both biological encapsulation and mechanical degradation, thereby providing a comprehensive framework for designing durable and reliable long-term neural implants.

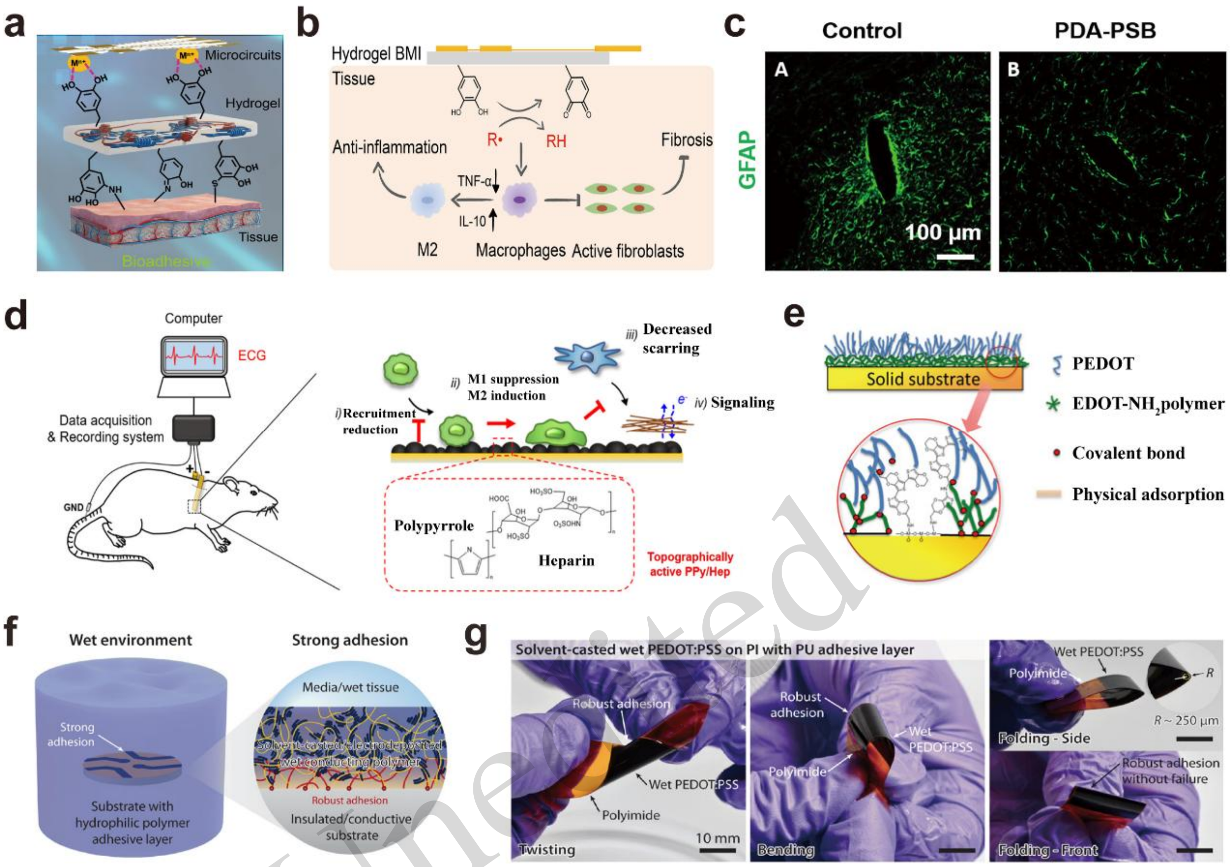

Fig. 10 Strategies for achieving the long-term stability of flexible neural microelectrodes. (a) The mechanism of adhesion between hydrogel neural interfaces with soft tissues and metal substrates. (b) A schematic representation of the potential mechanism underlying the immune evasive behavior of the dPEDOT-CA-PDA-PAM hydrogel. Reproduced with permission from ref (Wang et al., 2022). (c) Representative images of GFAP staining of reactive astrocytes one week after implantation of an uncoated probe (A) versus a probe coated with PDA-PSB (B) on a 100 µm scale. Reproduced with permission from ref (Golabchi et al., 2019). (d) A schematic of PPy/Hep with optimal surface roughness exhibiting high performance and biocompatibility. Reproduced with permission from ref (Lee et al., 2022). (e) A schematic representation of PEDOT deposited on the electrically grafted P(EDOT-NH2) layer. Reproduced with permission from ref (Ouyang et al., 2017). (f) Strong binding of the conductive polymer to the substrate via an adhesive layer in humid environments. (g) PEDOT:PSS can withstand mechanical deformation, including twisting, bending, and folding around a substrate with a PU adhesive layer. Reproduced with permission from ref (Inoue et al., 2020).

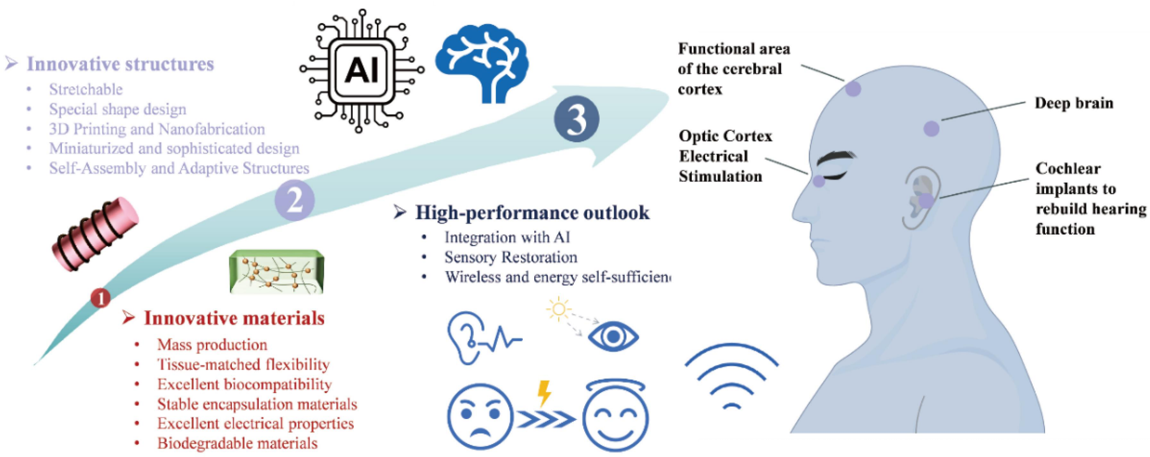

Fig. 11 Future perspectives concerning implantable neural interfaces

5 Summary and outlook

In summary, we have highlighted that the future of neural electrodes lies not only in softer materials but also in the synergistic optimization of the mechanical-electrical-biological interface. From a future perspective, research on implantable neural microelectrodes can be organized in several important directions. The first is the innovation of bionic materials and structures. The use of biodegradable materials holds enormous promise due to the ability of these materials to avoid secondary damage to the brain tissue when the electrodes are removed at the end of treatment. However, this approach requires precise control of the material degradation rate to achieve maximal synchronization with the treatment cycle. Scientists can try to precisely control the degradation rate by exploring the use of degradable polymers, such as polylactic acid, as electrode materials and adjusting their molecular structure or adding specific degradation regulators. Concurrently, constructing a material system with mechanical properties highly similar to brain tissue and designing the electrode as a 3D bionic structure via 3D printing technology can maximize the contact area between the electrode and brain tissue. It effectively reduces mechanical damage, lowers the immune response, prevents the electrode from being wrapped by gelatinous scarring, and prevents the loss of performance. Moreover, multimodal function integration is a crucial future research topic. Considering sensory simulation as an example, scientists can further improve the fineness of the simulation. As the number of retinal neurons is in millions, in terms of visual simulation, future studies must achieve a matching electrode density to provide a more detailed, realistic, and long-term stable simulation of the visual scene. This achievement requires breakthroughs in electrode materials, manufacturing processes, and signal processing algorithms to develop high-resolution and low-noise microelectrode arrays, which can be combined with advanced image processing and neural coding technologies to accurately convert visual information into electrical signals and stimulate retinal nerve cells. In addition, functional breakthroughs are expected in the field of energy self-supply. Using biocompatible piezoelectric materials or glucose biomicrofuel cells, a continuous energy supply can be achieved using tiny mechanical vibrations generated by cerebrospinal fluid or glucose flow around brain tissue. For example, they can convert the mechanical energy generated by the flow of cerebrospinal fluid into electrical energy to provide electrodes with the energy required to work, thus eliminating the requirement of a traditional wired power supply and improving the portability and long-term stability of implantable neuromicroelectrode systems. In contrast, glucose biomicrofuel cells can employ abundant glucose resources around brain tissues to generate electrical energy through biochemical reactions, providing stable energy for electrodes. Finally, for neuroscience applications, the remarkable heterogeneity of neural circuits can enable individualized treatment protocols for psychiatric disorders such as depression. The AI-driven closed-loop feedback system can parse brain signals in real time and dynamically optimize the stimulation parameters. For example, machine learning algorithms are employed to analyze the collected EEG signals and identify the patterns of neural activity associated with depression. Then, the stimulation parameters of the electrodes can be precisely adjusted according to the brain status of individual patients in real time. These include stimulation intensity, frequency, and waveform to achieve personalized and precise neuromodulation therapy, providing new and effective means for treating depression and other neuropsychiatric diseases. These research directions can break through the current technical bottlenecks faced by implantable neuromicroelectrodes and provide solid and powerful technical support for improving the quality of life of patients with neurological disorders and expanding the boundaries of human–computer interaction applications.

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Author contributions

J.S.: Investigation, Writing, Editing. H.W.: Conceptualization, Writing, Review, Editing, Supervision, Funding Acquisition. L.H.: Guidance. R.C.: Guidance. R.H.: Guidance. S.S.: Investigation. All authors have reviewed and approved the final version of this paper for publication.

Conflict of interest

The authors declare no competing interests.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Abidian MR, Martin DC, 2008. Experimental and theoretical characterization of implantable neural microelectrodes modified with conducting polymer nanotubes. *Biomaterials*, 29(9):1273-1283. https://doi.org/10.1016/j.biomaterials.2007.11.022

Ahmed Taha B, Addie AJ, Saeed AQ, et al., 2024. Nanostructured photonics probes: A transformative approach in neurotherapeutics and brain circuitry. *Neuroscience*, 562:106-124. https://doi.org/10.1016/j.neuroscience.2024.10.046

Aqrawe Z, Montgomery J, Travas-Sejdic J, et al., 2017. Conducting polymers for neuronal microelectrode array recording and stimulation. *Sensors and Actuators B: Chemical*, 257:753-765. https://doi.org/10.1016/j.snb.2017.11.023

Boehler C, Vieira DM, Egert U, et al., 2020. Nanopt—a nanostructured electrode coating for neural recording and microstimulation. *ACS Applied Materials & Interfaces*, 12(13):14855-14865. https://doi.org/10.1021/acsami.9b22798

Boisvert I, Reis M, Au A, et al., 2020. Cochlear implantation outcomes in adults: A scoping review. *PLOS ONE*, 15(5):e0232421. https://doi.org/10.1371/journal.pone.0232421

Campbell PK, Jones KE, Huber RJ, et al., 1991. A silicon-based, three-dimensional neural interface: Manufacturing processes for an intracortical electrode array. *IEEE Transactions on Biomedical Engineering*, 38(8):758-768. https://doi.org/10.1109/10.83588

Castagnola E, Cao Q, Robbins E, et al., 2024. Glassy carbon fiber-like multielectrode arrays for neurochemical sensing and electrophysiology recording. *Advanced Materials Technologies*, https://doi.org/10.1002/admt.202400863

Castagnola V, Descamps E, Lecestre A, et al., 2014. Parylene-based flexible neural probes with pedot coated surface for brain stimulation and recording. *Biosensors and Bioelectronics*, 67:450-457. https://doi.org/10.1016/j.bios.2014.09.004

Chen N, Luo B, Patil AC, et al., 2020. Nanotunnels within poly(3,4-ethylenedioxythiophene)-carbon nanotube composite for highly sensitive neural interfacing. *ACS Nano*, 14(7):8059-8073. https://doi.org/10.1021/acsnano.0c00672

Chung WG, Jang J, Cui G, et al., 2024. Liquid-metal-based three-dimensional microelectrode arrays integrated with implantable ultrathin retinal prosthesis for vision restoration. *Nature Nanotechnology*, 19(5):688-697. https://doi.org/10.1038/s41565-023-01587-w

Cui X, Martin DC, 2003. Electrochemical deposition and characterization of poly(3,4-ethylenedioxythiophene) on neural microelectrode arrays. *Sensors and Actuators B: Chemical*, 89(1-2):92-102. https://doi.org/10.1016/s0925-4005(02)00448-3

Cui X, Wu L, Zhang C, et al., 2025. Implantable self-powered systems for electrical stimulation medical devices. *Adv Sci (Weinh)*, 12(24):e2412044. https://doi.org/10.1002/advs.202412044

Cui XT, Zhou DD, 2008. Poly (3,4-ethylenedioxythiophene) for chronic neural stimulation. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 15(4):502-508. https://doi.org/10.1109/tnsre.2007.909811

Deng M, Yang X, Silke M, et al., 2011. Electrochemical deposition of polypyrrole/graphene oxide composite on microelectrodes towards tuning the electrochemical properties of neural probes. *Sensors and Actuators B: Chemical*, 158(1):176-184. https://doi.org/10.1016/j.snb.2011.05.062

Dong C, Carnicer-Lombarte A, Bonafè F, et al., 2024. Electrochemically actuated microelectrodes for minimally invasive peripheral nerve interfaces. *Nature Materials*, 23(7):969-976. https://doi.org/10.1038/s41563-024-01886-0

Dong M, Yang J, Zhen F, et al., 2025. Graphene-based microelectrodes with reinforced interfaces and tunable porous structures for improved neural recordings. *ACS Applied Materials & Interfaces*, https://doi.org/10.1021/acsami.4c19445

Dong R, Wang L, Hang C, et al., 2021. Printed stretchable liquid metal electrode arrays for in vivo neural recording. *Small*, 17(14):e2006612-e2006612. https://doi.org/10.1002/smll.202006612

Fan JJ, Shan W, Wu JP, et al., 2019. Research progress of vagus nerve stimulation in the treatment of epilepsy. *CNS Neurosci Ther*, 25(11):1222-1228. https://doi.org/10.1111/cns.13209

Feig VR, Tran H, Lee M, et al., 2018. Mechanically tunable conductive interpenetrating network hydrogels that mimic the elastic moduli of biological tissue. *Nature Communications*, 9(1):1-9. https://doi.org/10.1038/s41467-018-05222-4

Fiáth R, Raducanu BC, Musa S, et al., 2018. A silicon-based neural probe with densely-packed low-impedance titanium nitride microelectrodes for ultrahigh-resolution in vivo recordings. *Biosensors and Bioelectronics*, 106:86-92. https://doi.org/10.1016/j.bios.2018.01.060

Golabchi A, Wu B, Cao B, et al., 2019. Zwitterionic polymer/polydopamine coating reduce acute inflammatory tissue responses to neural implants. *Biomaterials*, :225119519.

https://doi.org/10.1016/j.biomaterials.2019.119519

Green RA, Hassarati RT, Bouchinet L, et al., 2012. Substrate dependent stability of conducting polymer coatings on medical electrodes. *Biomaterials*, 33(25):5875-5886. https://doi.org/10.1016/j.biomaterials.2012.05.017

Hiendlmeier L, Zurita F, Vogel J, et al., 2023. 4d-printed soft and stretchable self-folding cuff electrodes for small-nerve interfacing. *Advanced Materials*, 35(12):e2210206-e2210206. https://doi.org/10.1002/adma.202210206

Horváth C, Csikós K, Árkossy B, et al., 2024. Polymer-based laminar probes with an ultra-long flexible spiral-shaped cable for in vivo neural recordings. *Sensors and Actuators B: Chemical*, 417:136220-136220. https://doi.org/10.1016/j.snb.2024.136220

Hu Z, Niu Q, Hsiao BS, et al., 2022. Bioactive polymer-enabled conformal neural interface and its application strategies. *Materials Horizons*, 10(3):808-828. https://doi.org/10.1039/d2mh01125e

Huang W-C, Hung C-H, Lin Y-W, et al., 2022. Electrically copolymerized polydopamine melanin/poly(3,4-ethylenedioxythiophene) applied for bioactive multimodal neural interfaces with induced pluripotent stem cell-derived neurons. *ACS Biomaterials Science & Engineering*, 8(11):4807-4818. https://doi.org/10.1021/acsbiomaterials.2c00822

Inoue A, Yuk H, Lu B, et al., 2020. Strong adhesion of wet conducting polymers on diverse substrates. *Science Advances*, 6(12):eaay5394. https://doi.org/10.1126/sciadv.aay5394

Jia Q, Liu Y, Lv S, et al., 2024. Wireless closed-loop deep brain stimulation using microelectrode array probes. *J Zhejiang Univ Sci B*, 25(10):803-823. https://doi.org/10.1631/jzus.B2300400

Khan WU, Shen Z, Mugo SM, et al., 2025. Implantable hydrogels as pioneering materials for next-generation brain–computer interfaces. *Chemical Society Reviews*, 54(6):2832-2880. https://doi.org/10.1039/d4cs01074d

Khodagholy D, Doublet T, Gurfinkel M, et al., 2011. Highly conformable conducting polymer electrodes for in vivo recordings. *Advanced Materials*, 23(36):H268-H272. https://doi.org/https://doi.org/10.1002/adma.201102378

Khodagholy D, Doublet T, Quilichini P, et al., 2013. In vivo recordings of brain activity using organic transistors. *Nature Communications*, 4(Mar.):1575. https://doi.org/10.1038/ncomms2573

Lee DH, Park Y, Seo Y, et al., 2025. Microelectrothermoforming (μetf): One-step versatile 3d shaping of flexible microelectronics for enhanced neural interfaces. *npj Flexible Electronics*, 9(1):5-5. https://doi.org/10.1038/s41528-024-00378-0

Lee JM, Pyo Y-W, Kim YJ, et al., 2023. The ultra-thin, minimally invasive surface electrode array neuroweb for probing neural activity. *Nature Communications*, 14(1):7088. https://doi.org/10.1038/s41467-023-42860-9

Lee S, Eom T, Kim M-K, et al., 2019. Durable soft neural micro-electrode coating by an electrochemical synthesis of pedot:Pss / graphene oxide composites. *Electrochimica Acta*, 313:79-90. https://doi.org/10.1016/j.electacta.2019.04.099

Lee S, Park J, Kim S, et al., 2022. High-performance implantable bioelectrodes with immunocompatible topography for modulation of macrophage responses. *ACS Nano*, 16(5) https://doi.org/10.1021/acsnano.1c10506

Lee S, Min K, Jung J, et al., 2024. Implantable conductive polymer bioelectrode with enzymatic antioxidant activity for enhanced tissue responses and in vivo performance. *Chemical Engineering Journal*, 494:152861-152861. https://doi.org/10.1016/j.cej.2024.152861

Li TL, Liu Y, Forro C, et al., 2022. Stretchable mesh microelectronics for the biointegration and stimulation of human neural organoids. *Biomaterials*, 290:121825. https://doi.org/10.1016/j.biomaterials.2022.121825

Lim C, Hong YJ, Jung J, et al., 2021. Tissue-like skin-device interface for wearable bioelectronics by using ultrasoft, mass-permeable, and low-impedance hydrogels. *Science Advances*, 7(19) https://doi.org/10.1126/sciadv.abd3716

Liu Y, Mcguire AF, Lou H-Y, et al., 2018. Soft conductive micropillar electrode arrays for biologically relevant electrophysiological recording [engineering]. *Proceedings of the National Academy of Sciences of the United States of America*, 115(46):11718-11723. https://doi.org/10.1073/pnas.1810827115

Lu L, Fu X, Liew Y, et al., 2019. Soft and mri compatible neural electrodes from carbon nanotube fibers. *Nano Letters*, 19(3):1577-1586. https://doi.org/10.1021/acs.nanolett.8b04456

Luan L, Wei X, Zhao Z, et al., 2017. Ultraflexible nanoelectronic probes form reliable, glial scar-free neural integration. *Science Advances*, 3(2):e1601966. https://doi.org/10.1126/sciadv.1601966

Luo X, Weaver CL, Zhou DD, et al., 2011. Highly stable carbon nanotube doped poly(3,4-ethylenedioxythiophene) for chronic neural stimulation. *Biomaterials*, 32(24):5551-5557. https://doi.org/10.1016/j.biomaterials.2011.04.051

Ma L, Wisniewski DJ, Cea C, et al., 2024. High-density, conformable conducting polymer-based implantable neural probes for the developing brain. *Advanced Healthcare Materials*, 13(24):e2304164-e2304164. https://doi.org/10.1002/adhm.202304164

Mahlknecht P, Georgiev D, Akram H, et al., 2018. Parkinsonian signs in patients with cervical dystonia treated with pallidal deep brain stimulation. *Brain*, 141(10):3023-3034. https://doi.org/10.1093/brain/awy217

Mandal HS, Knaack GL, Charkhkar H, et al., 2014. Improving the performance of poly(3,4-ethylenedioxythiophene) for brain-machine interface applications. *Acta Biomaterialia*, 10(6):2446-2454. https://doi.org/10.1016/j.actbio.2014.02.029

Marzocchi M, Gualandi I, Calienni M, et al., 2015. Physical and electrochemical properties of pedot:Pss as a tool for controlling cell growth. *ACS Applied Materials & Interfaces*, 7(32):17993-18003. https://doi.org/10.1021/acsami.5b04768

Meyer JU, 2000. Micromachined, polyimide-based devices for flexible neural interfaces. *Biomedical Microdevices*, 2(4):283-294. https://doi.org/10.1023/A:1009955222114

Middya S, Carnicer‐Lombarte A, Sawiak S, et al., 2025. Conducting polymer microelectrode arrays for simultaneous electrophysiology and advanced brain imaging. *Advanced Functional Materials*, 35(24):2417312-2417312. https://doi.org/10.1002/adfm.202417312

Mirochnik RM, Pezaris JS, 2019. Contemporary approaches to visual prostheses. *Military Medical Research*, 6(1):19. https://doi.org/10.1186/s40779-019-0206-9

Morikawa Y, Yamagiwa S, Sawahata H, et al., 2017. Ultrastretchable kirigami bioprobes. *Advanced Healthcare Materials*, 7(3):n/a-n/a. https://doi.org/10.1002/adhm.201701100

Nam J, Lim H-K, Kim NH, et al., 2020. Supramolecular peptide hydrogel-based soft neural interface augments brain signals through a three-dimensional electrical network. *ACS Nano*, 14(1):664-675. https://doi.org/10.1021/acsnano.9b07396

Neto JP, Costa A, Vaz Pinto J, et al., 2021. Transparent and flexible electrocorticography electrode arrays based on silver nanowire networks for neural recordings. *ACS Applied Nano Materials*, 4(6):5737-5747. https://doi.org/10.1021/acsanm.1c00533

Ouyang L, Wei B, Kuo C-C, et al., 2017. Enhanced pedot adhesion on solid substrates with electrografted p(edot-nh2). *Science Advances*, 3(3):e1600448-e1600448. https://doi.org/10.1126/sciadv.1600448

Palanker D, Goetz G, 2018. Restoring sight with retinal prostheses. *Physics Today*, 71(7):26-32. https://doi.org/10.1063/pt.3.3970

Park S, Yuk H, Zhao R, et al., 2021a. Adaptive and multifunctional hydrogel hybrid probes for long-term sensing and modulation of neural activity. *Nature Communications*, 12(1):3435-3435. https://doi.org/10.1038/s41467-021-23802-9

Park Y, Chung TS, Lee G, et al., 2021b. Materials chemistry of neural interface technologies and recent advances in three-dimensional systems. *Chemical Reviews*, 122(5):5277-5316. https://doi.org/10.1021/acs.chemrev.1c00639

Pranti AS, Schander A, Bödecker A, et al., 2018. Pedot: Pss coating on gold microelectrodes with excellent stability and high charge injection capacity for chronic neural interfaces. *Sensors and Actuators B: Chemical*, 275:382-393. https://doi.org/10.1016/j.snb.2018.08.007

Reddy S, Xiao Q, Liu H, et al., 2019. Bionanotube/poly(3,4-ethylenedioxythiophene) nanohybrid as an electrode for the neural interface and dopamine sensor. *ACS Applied Materials & Interfaces*, 11(20):18254-18267. https://doi.org/10.1021/acsami.9b04862

Ren X, Bai W, Chen S, et al., 2024. Uniaxial extending neural probes for bleeding-absent implantation. *npj Flexible Electronics*, 8(1) https://doi.org/10.1038/s41528-024-00323-1

Ryu J, Qiang Y, Chen L, et al., 2024. Multifunctional nanomesh enables cellular-resolution, elastic neuroelectronics. *Advanced Materials*, 36(36):e2403141. https://doi.org/10.1002/adma.202403141

Ryu M, Yang JH, Ahn Y, et al., 2017. Enhancement of interface characteristics of neural probe based on graphene, zno nanowires, and conducting polymer pedot. *ACS Applied Materials & Interfaces*, 9(12):10577-10586. https://doi.org/10.1021/acsami.7b02975

Saunier V, Flahaut E, Blatché M-C, et al., 2020. Carbon nanofiber-pedot composite films as novel microelectrode for neural interfaces and biosensing. *Biosensors and Bioelectronics*, 165:112413. https://doi.org/10.1016/j.bios.2020.112413

Seufert L, Elmahmoudy M, Theunis C, et al., 2024. Stretchable tissue-like gold nanowire composites with long-term stability for neural interfaces. *Small*, 20(43):e2402214. https://doi.org/10.1002/smll.202402214

Shah DD, Carter P, Shivdasani MN, et al., 2024. Deciphering platinum dissolution in neural stimulation electrodes: Electrochemistry or biology? *Biomaterials*, 309:122575. https://doi.org/10.1016/j.biomaterials.2024.122575

Sharafkhani N, Kouzani AZ, Adams SD, et al., 2021. Neural tissue-microelectrode interaction: Brain micromotion, electrical impedance, and flexible microelectrode insertion. *Journal of Neuroscience Methods*, 365:109388. https://doi.org/10.1016/j.jneumeth.2021.109388

Shur M, Fallegger F, Pirondini E, et al., 2020. Soft printable electrode coating for neural interfaces. *ACS Applied Bio Materials*, 3(7):4388-4397. https://doi.org/10.1021/acsabm.0c00401

Tian G, Yang D, Chen C, et al., 2023. Simultaneous presentation of dexamethasone and nerve growth factor via layered carbon nanotubes and polypyrrole to interface neural cells. *ACS Biomaterials Science & Engineering*, 9(8) https://doi.org/10.1021/acsbiomaterials.3c00593

Venkatraman S, Hendricks J, King ZA, et al., 2011. In vitro and in vivo evaluation of pedot microelectrodes for neural stimulation and recording. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 19(3):307-316. https://doi.org/10.1109/tnsre.2011.2109399

Viana D, Walston ST, Masvidal-Codina E, et al., 2024. Nanoporous graphene-based thin-film microelectrodes for in vivo high-resolution neural recording and stimulation. *Nature Nanotechnology*, 19(4):514-523. https://doi.org/10.1038/s41565-023-01570-5

Vomero M, Castagnola E, Ciarpella F, et al., 2017. Highly stable glassy carbon interfaces for long-term neural stimulation and low-noise recording of brain activity.

Scientific Reports, https://doi.org/10.1038/srep40332

Vomero M, Gueli C, Zucchini E, et al., 2020. Flexible bioelectronic devices based on micropatterned monolithic carbon fiber mats. *Advanced Materials Technologies*, 5(2):n/a-n/a. https://doi.org/10.1002/admt.201900713

Wang K, Frewin CL, Esrafilzadeh D, et al., 2019. High - performance graphene - fiber - based neural recording microelectrodes. *Advanced Materials*, 31(15):e1805867. https://doi.org/10.1002/adma.201805867

Wang X, Sun X, Gan D, et al., 2022. Bioadhesive and conductive hydrogel-integrated brain-machine interfaces for conformal and immune-evasive contact with brain tissue. *Matter*, 5(4) https://doi.org/10.1016/j.matt.2022.01.012

Wang Y, Zhu C, Pfattner R, et al., 2017. A highly stretchable, transparent, and conductive polymer. *Science Advances*, 3(3):e1602076- e1602076. https://doi.org/10.1126/sciadv.1602076

Wise KD, Anderson DJ, Hetke JF, et al., 2004. Wireless implantable microsystems: High-density electronic interfaces to the nervous system. *Proceedings of the IEEE*, 92(1):76-97. https://doi.org/10.1109/jproc.2003.820544

Wu Y, Wang L, Yan M, et al., 2024. Poly(3,4-ethylenedioxythiophene)/functional gold nanoparticle films for improving the electrode-neural interface. *Advanced Healthcare Materials*, 13(23):e2400836-e2400836. https://doi.org/10.1002/adhm.202400836

Xiang Z, Liu J, Lee C, 2016. A flexible three-dimensional electrode mesh: An enabling technology for wireless brain–computer interface prostheses. *Microsystems & Nanoengineering*, 2:16012. https://doi.org/10.1038/micronano.2016.12

Yan M, Wang L, Wu Y, et al., 2023. Conducting polymer-hydrogel interpenetrating networks for improving the electrode–neural interface. *ACS Applied Materials & Interfaces*, 15(35):41310-41323. https://doi.org/10.1021/acsami.3c07189

Yang M, Yang T, Deng H, et al., 2021. Poly(5-nitroindole) thin film as conductive and adhesive interfacial layer for robust neural interface. *Advanced Functional Materials*, 31:2105857. https://doi.org/10.1002/adfm.202105857

Yang X, Pei W, Wei C, et al., 2022. Chemical polymerization of conducting polymer poly(3,4-ethylenedioxythiophene) onto neural microelectrodes. *Sensors and Actuators A: Physical*, 349 https://doi.org/10.1016/j.sna.2022.114022

Zeng Q, Xia K, Sun B, et al., 2017. Electrodeposited iridium oxide on platinum nanocones for improving neural stimulation microelectrodes. *Electrochimica Acta*, 237:152-159. https://doi.org/10.1016/j.electacta.2017.03.213

Zeng Q, Yu S, Fan Z, et al., 2022. Nanocone-array-based platinum-iridium oxide neural microelectrodes: Structure, electrochemistry, durability and biocompatibility study. *Nanomaterials*, 12(19):3445-3445. https://doi.org/10.3390/nano12193445

Zhang A, Lieber CM, 2015. Nano-bioelectronics. *Chemical Reviews*, 116(1):215-257. https://doi.org/10.1021/acs.chemrev.5b00608

Zhang A, Mandeville ET, Xu L, et al., 2023. Ultraflexible endovascular probes for brain recording through micrometer-scale vasculature. *Science*, 381(6655):306-312. https://doi.org/10.1126/science.adh3916

Zhang J, Wang L, Xue Y, et al., 2022. Engineering electrodes with robust conducting hydrogel coating for neural recording and modulation. *Advanced Materials*, 35(3):e2209324-e2209324. https://doi.org/10.1002/adma.202209324

Zhang Y, Zheng N, Cao Y, et al., 2019. Climbing-inspired twining electrodes using shape memory for peripheral nerve stimulation and recording. *Science Advances*, 5(4):eaaw1066-eaaw1066. https://doi.org/10.1126/sciadv.aaw1066

Zhou N, Ji J, Qu R, et al., 2025. Permeable and durable liquid - metal fiber mat as implantable physiological electrodes with long - term biocompatibility. *Advanced Materials*, 37:2413728. https://doi.org/10.1002/adma.202413728

Zhu Z, Yan Z, Ni S, et al., 2024. Tissue/organ adaptable bioelectronic silk-based implants. *Advanced Materials*, 36(38):e2405892. https://doi.org/10.1002/adma.202405892

中文概要

题　目：植入式柔性神经电极：材料创新、结构设计与性能优化的进展

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目　的： 近年来，基于软材料构建的柔性神经电极正成为神经接口领域的重要研究方向。通过整合并评述现有柔性植入式神经电极的创新方法，本文旨在为高性能植入式神经电极的发展提供重要的理论基础与技术指导。

创新点： 本文构建了一个“材料选择-结构设计-性能优化”的多维度研究框架，以解决神经接口的长期可靠性难题。

方　法： 首先，在材料层面，本文对柔性导电材料进行了系统分类，并评估了其内在物理与化学特性，以实现与神经组织的力学匹配。其次，在结构层面，本文回顾了一维、二维和三维

构型下的神经微电极工程，以优化组织整合。最后，在性能方面，本文聚焦于两大核心支柱：其一涉及高保真记录与安全刺激所需的电学特性，其二则围绕长期稳定性策略（例如生物相容性涂层），以确保在严苛生理环境中的可靠性。

结　论：通过整合材料选择、结构设计和性能优化，本综述为克服当前柔性神经电极的瓶颈、实现稳定长期的神经假体功能提供了方向。

关键词：植入式神经微电极、电极材料、电极结构、电极关键性能