

# Nanomaterials and Semiconductor Technologies for Neural Interfaces: Recent Advances and Future Perspectives

Zhenqin Zhu<sup>1\*</sup>

<sup>1</sup> School of Materials Science and Engineering Nanjing Tech University, Nanjing, China

\*Correspondence: Zhenqin Zhu

**Received:** 18 May 2026; **Accepted:** 23 June 2026; **Published:** 22 July 2026

---

## Abstract:

Neural interfaces, as a bridge for information exchange between the biological nervous system and electronic devices, are limited by the shortcomings of traditional rigid metal and silicon-based materials in terms of biocompatibility, channel density, and long-term stability. This review systematically explores the core roles of nanomaterials engineering and semiconductor technologies in overcoming these barriers, with a particular focus on how nanoscale interface modifications can enhance charge-transfer efficiency. Additionally, the review discusses how flexible integration technologies alleviate mechanical mismatch between soft and rigid materials and suppress immune responses. Furthermore, the potential of semiconductor integration processes to enhance signal acquisition throughput is evaluated. The paper also addresses key challenges that affect clinical translation, including power consumption management, structural durability, and large-scale manufacturing, and offers future perspectives. This review demonstrates that the synergy between nanomaterial engineering and semiconductor integration provides the fundamental technical foundation for high-performance, long-lasting neural interface systems.

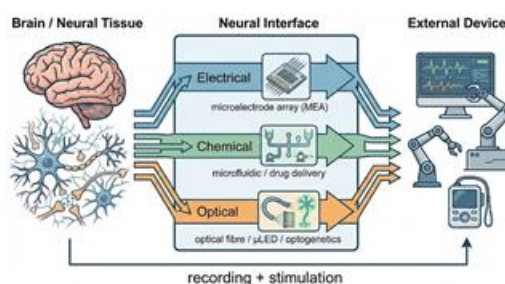
## Keywords:

Neural Interfaces, Nanomaterials, CMOS Integration, Biocompatibility

---

## 1. Introduction

Neural interfaces serve as critical conduits between biological tissues and external devices, enabling the recording and modulation of neural activity via electrical, chemical, and optical modalities (Figure 1). They have become indispensable for the treatment of neurological disorders, the modulation of neural circuits, and the regulation of neural function. An ideal neural interface is expected to provide cell- or tissue-selective recording and stimulation, support high-resolution signal acquisition, and maintain long-term operational stability. Building on early demonstrations of electrically evoked neural responses in the late nineteenth century, extensive research has pursued platforms that combine precision with scalability for large-scale recording and control. Progress in this area has materially advanced mechanistic understanding and intervention strategies for disorders such as epilepsy, major depressive disorder, Alzheimer's disease, and Parkinson's disease [1].



**Figure 1.** Conceptual Overview of Neural Interfaces.

Neural interfaces are constrained by power consumption, functional performance, and packaging reliability, all of which are ultimately bounded by safety considerations. The drive toward higher-resolution mapping of neural circuits necessitates a significant increase in the density of simultaneous recording channels. This push toward large-scale integration creates a critical conflict between the demand for high data throughput and the delicate physiological balance of brain tissue. Under stringent bio-thermal limits (e.g.,  $<0.5$  °C allowable temperature rise), achieving high-throughput wireless data transmission across thousands of channels together with efficient energy harvesting encounters severe physical bottlenecks [2]. High-channel-count neural interfaces place a steep power burden on the analogue front end, digitisation, on-chip processing, and especially wireless telemetry, where energy per bit scales unfavourably as data rate increases. In implantable applications, this dissipation is tightly constrained by tissue-safety constraints, because even small temperature rises can compromise biocompatibility and long-term function. As a result, power consumption becomes a primary bottleneck that limits simultaneous scaling of channel count, throughput, and device longevity [3].

To ease the coupled constraints among power consumption, throughput, and safety, materials and interface engineering has become an important complement to system and circuit optimisation. Nanomaterials, especially low-dimensional conductors and functional coatings, can reduce electrode-tissue impedance and enhance charge transfer [4], so similar recording fidelity and stimulation efficacy can be achieved with lower drive voltages and smaller currents [4]. Their high surface area and tunable surface chemistry also help form stable, low noise interfaces [5] and slow interfacial degradation [6]. Mechanically compliant nanostructures further accommodate tissue micromotion and support chronic reliability [7]. Together, these features make nanomaterials a strong materials basis for energy-efficient, high-density neural interfaces that meet stringent thermal safety limits [8].

Semiconductor technologies, particularly CMOS integration, enable high-density neural interfaces with dense arrays, on-chip amplification, multiplexed readout [9], and compact power management. They reduce interconnect complexity and support higher data throughput while keeping per-channel noise and power low [10]. When combined with on-chip amplification and multiplexed readout, nanomaterials help sustain high signal fidelity as channel count scales, while supporting safer operation under tight thermal and electrochemical constraints.

In this review, we first summarise recent advances in nanomaterials that improve the electrode tissue interface by reducing impedance and polarisation and by stabilising chronic performance. We then review progress in semiconductor and CMOS technologies for high-density neural interfaces, with emphasis on integrated readout, multiplexing, and compact system integration. We next discuss strategies that

combine nanomaterials with semiconductor platforms and examine barriers to translation, including process compatibility, reproducibility, and long-term packaging under strict bio-thermal constraints. Finally, we outline future perspectives on co-designed materials, circuits, and packaging for scalable, energy-efficient, and clinically robust neural interfaces.

## 2. Nanomaterials for Neural Interfaces

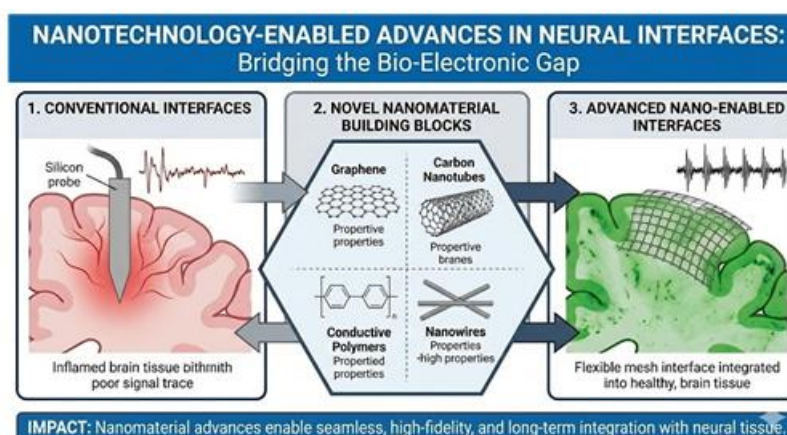
### 2.1. Overview and Core Advantages of Nanomaterials

Recent advances in nanomaterials have significantly advanced neural interface development, offering solutions to many of the field's critical challenges. As neural interfaces are increasingly expected to operate over extended periods in complex biological environments, the need for materials that can improve electrode performance, enhance biocompatibility, and ensure long-term stability has become evident. Nanomaterials, particularly two-dimensional materials and nanostructured composites, provide unique properties such as high surface area, low impedance, and enhanced charge transfer, making them ideal candidates for addressing these issues [1].

### 2.2. Material Innovations

Graphene and its derivatives are essential 2D materials for neural interfaces due to their flexibility and biocompatibility [11]. However, single-layer graphene microelectrodes have limited electrochemical performance, which hinders miniaturization [12]. Recent efforts have focused on multilayer porous structures. The main challenge is creating a material that is both densely packed and highly porous to ensure low ion transport resistance [13].

A major advance in this area is the development of Engineered Graphene for Neural Interfaces, or EGNITE. This technology uses hydrothermal reduction to turn stacked graphene oxide into a porous, conductive thin film. This structure contains nanoscale pores and capillaries that greatly increase the surface area. As a result, the interfacial capacitance reaches approximately  $13.9 \text{ mF} \cdot \text{cm}^{-2}$ , which is a 104 increase over single-layer graphene. This allows for  $25 \text{ } \mu\text{m}$  microelectrodes with low impedance and high charge injection capacity for high-resolution neural recording and stimulation [14]. (Figure 2)



**Figure 2.** Nanotechnology-Enabled Advances in Neural Interfaces.

While EGNITE offers exceptional interfacial capacitance, other nanomaterials present different trade-offs. Conductive polymers like PEDOT:PSS provide high charge injection capacity and excellent process compatibility, often utilizing biomimetic polydopamine structures to improve adhesion and tissue integration [4]. Conversely, noble metal coatings such as platinum nanoparticles exhibit superior electrochemical biostability during chronic stimulation. However, these alternatives generally lack the extreme mechanical conformity of ultra-thin porous graphene, and all passive nanomaterials share inherent limitations, including the trade-off between film thickness and flexibility, as well as vulnerability to metal track corrosion.

### ***2.3. Mechanical Compliance and Chronic Bio-integration***

The transition from rigid silicon probes to flexible, nano-enabled interfaces has effectively addressed the mechanical mismatch with soft neural tissue. Nanomaterial thin films, often as thin as 12  $\mu\text{m}$ , can conform to complex anatomical curvatures while maintaining electrical integrity [14]. For instance, nanoporous graphene arrays have demonstrated functional stability after repeated high-angle bending cycles, which is critical for interfaces in dynamic environments like peripheral nerves [14]. Recent advances also include hybrid encapsulation techniques, such as combining atomic layer deposition of metal oxides with polymers, to provide a more robust barrier against ionic infiltration in these thin-film systems [15].

Beyond physical flexibility, nanostructured surfaces play a vital role in modulating the chronic foreign body response. By utilizing high-surface-area and biomimetic coatings, these materials can foster better tissue-electrode integration compared to conventional metallic electrodes [16]. Longitudinal studies on nanoporous graphene have shown minimal microglial activation and no significant fibrous capsule formation after 12 weeks of cortical implantation [14]. Furthermore, the electrochemical stability of these interfaces is evidenced by their ability to sustain high charge injection and stable impedance over 15 million stimulation pulses without structural degradation [17]. Modern research into hierarchical micro-nanostructures and noble metal nanoparticle coatings continues to refine these properties, ensuring that high-resolution bidirectional communication remains reliable throughout the functional life of the implant.

### ***2.4. Challenges***

Nanomaterial thin films have successfully provided high-fidelity bidirectional links through low impedance and high charge injection, effectively solving the mechanical and electrical mismatches inherent in traditional electrodes. Despite these gains, long-term reliability is still hindered by the potential corrosion of metallic tracks, a vulnerability that even chemically stable nanomaterials cannot fully mitigate. There is also a persistent trade-off between increasing film thickness for performance and maintaining the extreme flexibility required for seamless integration. Furthermore, the chronic effects of secondary reactions, such as oxygen reduction, remain under-investigated. As arrays scale toward higher spatial resolutions, the resulting data volume creates a processing bottleneck that exceeds the capabilities of passive materials, driving the integration of active semiconductor technologies for advanced signal management.

### **3. Recent Advances in Semiconductor Technologies for Neural Interfaces**

#### ***3.1. High-Density CMOS Integration***

The scaling of neural interfaces toward higher channel counts is increasingly limited by the data-throughput and physical-wiring constraints of passive systems [18]. To overcome these bottlenecks, research has shifted toward active semiconductor architectures, particularly CMOS integration, which enables signal processing directly at the sensing site [19]. By enabling local amplification, multiplexing, and digitization, these technologies minimize noise and signal degradation while supporting thousands of recording sites. This transition redefines the neural interface as an integrated bio-electronic system capable of high-throughput signal management and efficient on-chip computation [20].

The advancement of semiconductor technologies, primarily driven by Complementary Metal-Oxide-Semiconductor (CMOS) integration, has enabled the development of high-density neural probes that significantly exceed the channel counts of passive arrays. Systems such as Neuropixels 2.0 and the recently developed Neuropixels Opto exemplify this progress by integrating thousands of recording sites with active circuitry for signal amplification and multiplexing on a single shank [21]. These systems-on-chip (SoC) architectures reduce interconnect complexity and minimize signal degradation by performing amplification and digitization directly at the sensing source [18]. Beyond data acquisition, the integration of wireless telemetry and power management has facilitated the development of fully implantable, tetherless interfaces that operate within stringent bio-thermal constraints. Emerging architectures, such as the BISC platform, further push these limits by utilizing ultra-thin substrates to achieve high-bandwidth communication while incorporating real-time on-chip processing to manage the massive data volumes inherent in high-resolution brain-machine interfaces [22]

Advanced architectures like Neuropixels 2.0 leverage deep-submicron CMOS processes (e.g., 130 nm) to achieve extreme miniaturization, seamlessly integrating dense sensing arrays and active circuitry onto highly compact shanks [21]. Building on this, systems such as Neuropixels Opto demonstrate the potential of heterogeneous integration—combining gallium nitride (GaN) optoelectronics with silicon logic to enable concurrent optical modulation and electrical recording on a single device [19]. Beyond penetrating probes, platforms like the Biological Interface System to Cortex (BISC) illustrate how single-chip designs can successfully support massive electrode arrays alongside high-bandwidth wireless telemetry [22]. Crucially, to manage this immense data throughput without violating stringent bio-thermal safety limits, these modern interfaces increasingly rely on on-chip neuromorphic processing. By performing real-time signal compression at microwatt power levels, neuromorphic architectures effectively resolve the fundamental conflict between high-channel-count data acquisition and the thermal constraints of biological tissues [20].

#### ***3.2. Active On-Chip Safety Management***

Beyond thermal management, recent safety research has shifted from passive biocompatibility to active on-chip circuit management. Modern CMOS architectures integrate real-time impedance monitoring and precision charge-balancing modules to maintain control over the electrode-tissue interface [18]. These active units detect

subtle deviations in electrochemical potential and automatically adjust stimulation waveforms accordingly. This ensures that charge injection remains strictly within the safe water window, effectively suppressing oxygen reduction reactions and localized pH fluctuations [20]. Such hardware-native closed-loop control fundamentally reduces the risk of tissue damage, significantly extending the operational lifespan of high-throughput interfaces in complex biological environments [23].

### ***3.3. Hermeticity and Hybrid Packaging***

As previously highlighted regarding passive thin films, hybrid encapsulation is crucial for bio-integration. However, for the heterogeneous integration of ultra-thin CMOS dies, these physical barriers must achieve an even higher standard to protect sensitive active circuitry. A pivotal development centers on using Atomic Layer Deposition (ALD) to construct high-density, nanometer-scale inorganic ceramic layers (e.g., Al<sub>2</sub>O<sub>3</sub> or HfO<sub>2</sub>), achieving nearly pinhole-free ionic isolation [24]. By interleaving these highly hermetic inorganic layers with flexible polymers like Parylene-C, researchers create advanced multilayer architectures that successfully harmonize the mechanical compliance required for soft tissue with the rigorous hermeticity needed for active silicon electronics [25]. This transition to atomic-level precision protection ensures that CMOS-based high-throughput interfaces can maintain electrical stability for years within corrosive physiological environments [26].

### ***3.4. Translational Bottlenecks and Integration Challenges***

Despite breakthroughs in safety and integration, semiconductor-based neural interfaces still face critical translational bottlenecks. A primary limitation remains the mechanical mismatch between silicon dies and ultra-soft neural tissue, which continues to drive chronic inflammatory responses even with thinned substrates. Regarding performance scaling, the stringent bio-thermal limit of 0.5 °C imposes a physical ceiling on the computational density of on-chip processing, constraining the deployment of complex real-time algorithms [26]. Furthermore, while hybrid encapsulation shows promise in simulated models, its long-term stability within dynamic human physiological environments lacks sufficient long-term in vivo validation [27]. Future improvements must prioritize the optimization of heterogeneous integration to bridge the gap between CMOS logic and flexible nanomaterials, ensuring functional high-density systems with minimal biological disruption [28].

## **4. Discussion and Future Perspectives**

Future progress depends on bridging the gap between materials and semiconductor engineering. Integrating flexible nanomaterials directly onto chip surfaces can reduce mechanical damage to neural tissue. This approach maintains high performance while ensuring a stable interface. To solve heat issues, neuromorphic computing architectures offer a new path. They allow decoding algorithms to run efficiently on the device, reducing data transfer and meeting safety standards [26]. Future interfaces will actively adjust to stay in balance with the biological environment. As manufacturing becomes standardized and testing matures, these systems will move from the lab to become general human-machine interaction platforms.

And scaling neuromorphic computing is essential for clinical neural interfaces. These architectures minimize power consumption by mimicking the brain's sparse

activity patterns [29]. This efficiency enables local decoding, which avoids the thermal limits typically imposed by high-speed wireless transmission. Beyond energy savings, neuromorphic systems offer a way to address neuroplasticity. Localized learning allows the interface to track shifts in neural circuits and update parameters in real time. This transition toward adaptive logic ensures long-term synergy between electronic and biological systems, facilitating the development of symbiotic interaction paradigms.

## 5. Conclusions

It is argued that the fusion of nanomaterials engineering and semiconductor integration constitutes a paradigm shift for neural interface design. This synergy moves the field beyond rigid probes toward active, bio-fused systems that prioritize long-term biocompatibility, extreme channel density, and operational stability. The integration of nanostructured interfaces with CMOS-based logic is pivotal, enabling not only high-fidelity signal management but also the mitigation of mechanical mismatch and chronic immune responses through flexible architectures. Crucially, this approach incorporates active circuit management to ensure that system operation remains strictly within the 0.5 °C bio-thermal safety limit. This hybrid framework establishes a new foundation for future research, poised to significantly advance our capabilities in engineering clinically robust, safe, and symbiotic systems for seamless human-machine interaction.

## Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

## Funding

This research received no specific grant from any funding agency in the public, commercial or not-for-profit sectors.

## References

- [1] S. Gou.; S. Yang.; Y. Cheng.; S. Yang.; H. Liu.; P. Li.; Z. Du. Applications of 2D Nanomaterials in Neural Interface. *IJMS*, 2024, 25(16), 8615, DOI: 10.3390/ijms25168615.
- [2] A. Nurmikko. Challenges for Large-Scale Cortical Interfaces. *Neuron*, 2020, 108(2), 259-269, DOI: 10.1016/j.neuron.2020.10.015.
- [3] Z.T. Irwin.; D.E. Thompson.; K.E. Schroeder.; D.M. Tat.; A. Hassani. Enabling Low-Power, Multi-Modal Neural Interfaces Through a Common, Low-Bandwidth Feature Space. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 2016, 24(5), 521-531, DOI: 10.1109/TNSRE.2015.2501752.
- [4] G. Dijk.; J. Pas.; K. Markovic.; J. Scancar.; R. P. O'Connor. PEDOT:PSS-coated platinum electrodes for neural stimulation. *APL Bioeng*, 2023, 7(4), 046117, DOI: 10.1063/5.0153094.

- [5] D. Kuzum.; H. Takano.; E. Shim.; J.C. Reed.; H. Juul. Transparent and flexible low noise graphene electrodes for simultaneous electrophysiology and neuroimaging. *Nat Commun*, 2014, 5, 5259, DOI: 10.1038/ncomms6259.
- [6] A.S. Pranti.; A. Schander.; A. Bödecker.; W. Lang. PEDOT: PSS coating on gold microelectrodes with excellent stability and high charge injection capacity for chronic neural interfaces. *Sensors and Actuators B: Chemical*, 2018, 275, 382-393, DOI: 10.1016/j.snb.2018.08.007.
- [7] T.D.Y. Kozai.; A.S. Jaquins-Gerstl.; A.L. Vazquez.; A.C. Michael.; X.T. Cui, "Brain Tissue Responses to Neural Implants Impact Signal Sensitivity and Intervention Strategies. *ACS Chem. Neurosci.*, 2015, 6(1), 48-67, DOI: 10.1021/cn500256e.
- [8] L. Luan.; J. T. Robinson.; B. Aazhang.; T. Chi.; K. Yang.; X. Li.; H. Rathore.; A. Singer.; S. Yellapantula.; Y. Fan.; Z. Yu.; C. Xie. Recent Advances in Electrical Neural Interface Engineering: Minimal Invasiveness, Longevity, and Scalability. *Neuron*, 2020, 108(2), 302-321, DOI: 10.1016/j.neuron.2020.10.011.
- [9] J.J. Jun et al. Fully integrated silicon probes for high-density recording of neural activity. *Nature*, 2017, 551(7679), 232-236, DOI: 10.1038/nature24636.
- [10] K.A. Ng.; E. Greenwald.; Y.P. Xu.; N.V. Thakor. Implantable neurotechnologies: a review of integrated circuit neural amplifiers. *Med Biol Eng Comput*, 2016, 54(1), 45-62, DOI: 10.1007/s11517-015-1431-3.
- [11] K. Kostarelos.; M. Vincent.; C. Hebert.; J. A. Garrido. Graphene in the Design and Engineering of Next-Generation Neural Interfaces. *Advanced Materials*, 2017, 29(2), 1700909, DOI: 10.1002/adma.201700909.
- [12] V. Viswam.; M. E. J. Obien.; F. Franke.; U. Frey.; A. Hierlemann. Optimal Electrode Size for Multi-Scale Extracellular-Potential Recording From Neuronal Assemblies. *Front. Neurosci.*, 2019, 13(385), DOI: 10.3389/fnins.2019.00385.
- [13] Y. Lu.; H. Lyu.; A. G. Richardson.; T. H. Lucas.; D. Kuzum. Flexible Neural Electrode Array Based-on Porous Graphene for Cortical Microstimulation and Sensing. *Sci Rep*, 2016, 6(1), 33526, DOI: 10.1038/srep33526.
- [14] D. Viana et al. Nanoporous graphene-based thin-film microelectrodes for in vivo high-resolution neural recording and stimulation. *Nat. Nanotechnol.*, 2024, 19(4), 514-523, DOI: 10.1038/s41565-023-01570-5.
- [15] G.A. Katirtsidis.; X. Illa.; N. Ria.; E. del Corro.; E. Masvidal Codina.; J.A. Garrido. Long-Term Stable Neural Interfaces with Nanoporous Graphene Electrodes and Hybrid Polyimide-Aluminium Oxide Encapsulation. *Small Methods*, 2025, 9(12), e01720, DOI: 10.1002/smt.202501720.
- [16] S. Ahmadi Seyedkhani.; A. Irajizad, R. Mohammadpour, M. Taghipoor, and M. Vafaiee. Novel Brain-Inspired Hierarchical Micro-Nanostructured Poly(3,4-ethylenedioxythiophene)/Polydopamine Neural Interface on Titanium Nitride Electrodes for Electrophysiological Signal Recording. *ACS Appl. Bio Mater.*, 2025, 8(10), 9332-9345, DOI: 10.1021/acsabm.5c01451.
- [17] S.D. Angelov.; C. Rehbock.; V. Ramesh.; H.E. Heissler.; M. Alam.; S. Barcikowski.; K. Schwabe.; J.K. Krauss. Coating of Neural Electrodes with Platinum Nanoparticles Reduces and Stabilizes Impedance In Vitro and In Vivo in a Rat Model. *Coatings*, 2024, 14(3), 352, DOI: 10.3390/coatings14030352.

- [18] A. M. Sodagar.; Y. Khazaei.; M. Nekoui.; M. Shaeri. Real-time, neural signal processing for high-density brain-implantable devices. *Bioelectron Med*, 2025, 11(1), 17, DOI: 10.1186/s42234-025-00177-6.
- [19] A. Lakunina et al. Neuropixels Opto: Combining high-resolution electrophysiology and optogenetics. *Neuroscience*, 2025, DOI: 10.1101/2025.02.04.636286.
- [20] W.A. Pawlak.; N. Howard. Neuromorphic algorithms for brain implants: a review. *Front. Neurosci.*, 2025, 19, 1570104, DOI: 10.3389/fnins.2025.1570104.
- [21] N.A. Steinmetz et al. Neuropixels 2.0: A miniaturized high-density probe for stable, long-term brain recordings. *Science*, 2021, 372(6539), eabf4588, DOI: 10.1126/science.abf4588.
- [22] T. Jung et al. A wireless subdural-contained brain–computer interface with 65,536 electrodes and 1,024 channels. *Nature Electronics*, 2025, 8(12), 1272-1288, DOI: 10.1038/s41928-025-01509-9.
- [23] D. Kudithipudi et al. Neuromorphic computing at scale. *Nature*, 2025, 637(8047), 801-812, DOI: 10.1038/s41586-024-08253-8.
- [24] G.A. Katirtsidis.; X. Illa.; N. Ria.; E. Del Corro.; E. Masvidal Codina.; J.A. Garrido. Long - Term Stable Neural Interfaces with Nanoporous Graphene Electrodes and Hybrid Polyimide- Aluminium Oxide Encapsulation. *Small Methods*, 2025, 9(12), e01720, DOI: 10.1002/smt.202501720.
- [25] S. Park, et al. Mechanically Robust and Anti-Biofouling Hybrid Encapsulation via Layered Organic-Liquid Interfaces for Implantable Devices. *Small*, 2026, e10949, DOI: 10.1002/sml.202510949.
- [26] T. Jung et al. A wireless subdural-contained brain–computer interface with 65,536 electrodes and 1,024 channels. *Nat Electron*, 2025, 8(12), 1272-1288, DOI: 10.1038/s41928-025-01509-9.
- [27] K. Nanbakhsh.; M.V. Gompel.; R. Ritasalo.; A. Gollhardt.; D. Horváth.; K. Tóth.; D. Meszéna.; I. Ulbert.; W. Serdijn.; V. Giagka. An In Vivo Biostability Evaluation of ALD and Parylene-ALD Multilayers as Micro-Packaging Solutions for Small Single-Chip Implants. *Small*, 2025, 21(16), 2410141, DOI: 10.1002/sml.202410141.
- [28] D. Kudithipudi et al. Neuromorphic computing at scale. *Nature*, 2025, 637(8047), 801-812, DOI: 10.1038/s41586-024-08253-8.
- [29] M. Sharifshazileh.; K. Burelo, J. Sarnthein.; G. Indiveri. An electronic neuromorphic system for real-time detection of high frequency oscillations (HFO) in intracranial EEG. *Nat Commun*, 2021, 12(1), 3095, DOI: 10.1038/s41467-021-23342-2.



© 2026 by the author(s); licensee International Technology and Science Publications (ITS), this work for open access publication is under the Creative Commons Attribution International License (CC BY 4.0). (<http://creativecommons.org/licenses/by/4.0/>)