Organic neuromorphics

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Soft organic electrochemical neurons operating at biological speed

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Organic electrochemical neurons respond to brain signals in real time, firing at biologically relevant speeds. Their flexibility and low power use could enable soft, implantable systems for closed-loop neuromodulation and future brain–computer interfaces.

Our brains are event-driven machines. Neurons remain silent most of the time, conserving energy until an event occurs — a sound, a thought, or a seizure. Mimicking this efficiency in electronics has long challenged researchers developing implants and brain–computer interfaces. Traditional silicon chips are powerful at computation, but their rigidity, heat generation, and high energy use make them unsuitable for long-term implantation. Writing in *Nature Sensors*, Fabiano and colleagues[1] now show that soft organic materials can match the speed and energy efficiency of neurons while communicating through ionic signals, the brain's native language. This advance marks an important milestone in moving organic devices beyond experimental prototypes toward practical, real-time neural interfaces.

Existing silicon-based neural implants, despite their computational precision, often provoke unwanted tissue responses, including inflammation and scarring. Their milliwatt-scale power budgets also degrade over time, diminishing performance and continuous operability. Consequently, fully wireless, battery-free platforms remain out of reach[2]. In contrast, organic mixed ionic–electronic conductors (OMIECs) couple electronic circuitry directly to the chemical environment of cells via concurrent ion–electron transport. With low-voltage operation (0.1–0.7 V) and patternability on flexible substrates, OMIECs conform mechanically to the brain surface.

OMIEC-based organic electrochemical transistors have already been used for biosensing and signal amplification, but they have not been fast enough to mimic biological neurons. Recent advances in materials and device architectures have improved their performance to achieve firing frequencies of around 140 Hz, yet this remains insufficient compared with the broad firing bandwidth of mammalian neurons (0.5–1,000 Hz), and the devices continue to consume nanojoules to even microjoules of energy per spike[3]. To overcome these limitations, Fabiano and colleagues shortened the transistor channel length from 42 μm to 3.6 μm to minimize the capacitance that delays switching, and combined the p-type polymer glycolated polythiophene P($g_3$2T-TT) with the n-type polymers poly(benzimidazobenzophenanthroline) (BBL) or glycolated, fluorinated benzodifurandione-based poly(p-phenylene vinylene) (FBDPPV-OEG) to build complementary circuits and fabricate leaky integrate-and-fire organic electrochemical neurons (OECNs) that respond within approximately 1 ms, operate below 0.7 V (safely below the 1.23 V electrolysis threshold of water), and fire across the mammalian frequency range (the energy per spike is about 40 pJ and the maximum firing rate reaches 1.1 kHz).

The OECNs are event-driven, staying silent until input derived from local field potentials accumulates and raises the membrane voltage above the firing threshold. When triggered, the circuit emits a sharp electrical pulse within ~6 ms, which is then used to immediately stimulate another part of the neural network. Processing directly occurs in analog form, without digital conversion, reducing latency and power use. In laboratory experiments (Fig. 1), OECNs were integrated into a closed-loop system that detected epileptic discharges in the hippocampus of rats and sent timed stimulation to the medial prefrontal cortex. Compared with silicon-based detectors, the organic neurons identified pathological signals more accurately while using far less power. Stimulation suppressed abnormal spindle oscillations in the 10–15 Hz range, demonstrating real-time neuromodulation in a living brain. Built on 5 μm-thick parylene C films, their softness enables bending and stretching with the brain, reducing mechanical stress and preventing inflammation. The researchers also created a 10 × 10 array of 100 OECNs, each about 1 mm^2, firing at an average frequency of 400 Hz, showing that the design can be scaled without losing speed or consistency. Together, these properties point to a new generation of neural interfaces that combine high performance with long-term comfort and biocompatibility.

Beyond epilepsy, there is potential for expansion into other areas of neurotechnology. Event-driven systems could transform how medical implants interact with the body. Instead of streaming vast volumes of data to external processors, future devices might sense, interpret, and respond autonomously in real time. Such systems could recognize early signs of seizures, tremors, or heart arrhythmias and deliver corrective stimulation within milliseconds, before symptoms fully emerge. The same principles could inspire neuromorphic computers that process information through spikes and timing rather than binary logic, offering a more efficient brain-like computation.

This work also reflects a philosophical shift. For decades, engineers have tried to force rigid silicon to coexist with soft tissue. Now the design logic is reversed. Devices are being crafted to behave more like living systems, using ions instead of electrons, operating in analog rather than digital, and adapting dynamically to their surroundings. The boundary between biology and technology becomes less a wall and more a membrane through which information flows both ways. These organic neurons show that computation can arise directly from material properties rather than software, suggesting a new form of 'physiological computing' where physics, chemistry, and biology work together.

Translating these soft organic neurons from the laboratory to clinical use faces several engineering challenges. Sterilization is among the most critical: implantable organic devices must endure heat, humidity, and chemical stress while maintaining electrical stability. Yet the polymers and electrolytes that make these devices soft and biocompatible

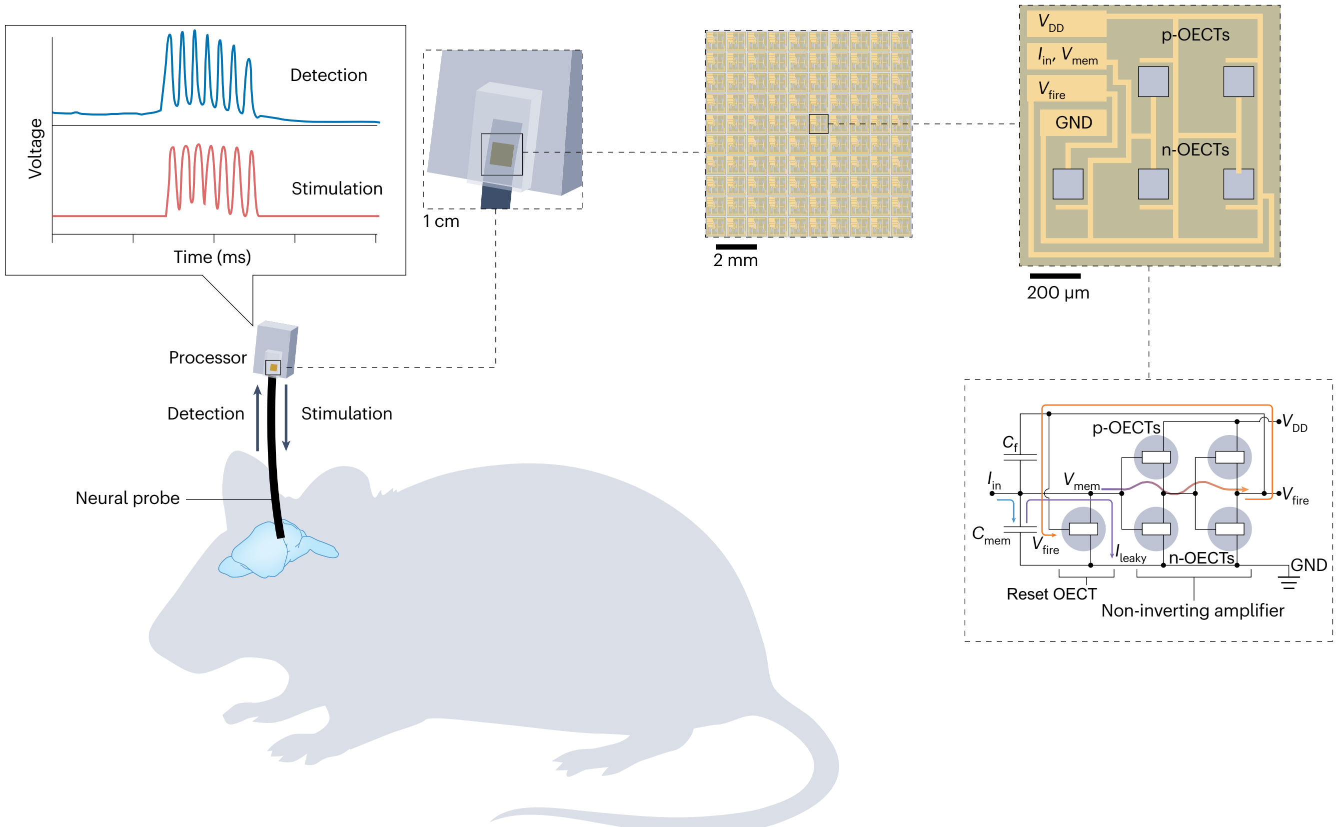

Fig. 1 | Closed-loop neuromodulation with soft organic electrochemical neurons. Left: schematic of an event-driven closed-loop system in which a neural probe implanted in the hippocampus records local field potentials. These physiological signals are converted into an input current (I_{in}) and fed to organic electrochemical neurons (OECNs). The OECNs integrate I_{in} on the membrane capacitor until the membrane voltage (V_{mem}) crosses the firing threshold, at which point they generate output voltage spikes (V_{fire}) that trigger time-locked stimulation pulses delivered to the medial prefrontal cortex, providing the stimulation output of the system. Right: a complementary p- and n-type organic electrochemical transistor (OECT) processor fabricated on a 5-μm-thick parylene C film, implementing leaky integrate-and-fire circuitry for low-power, real-time neuromodulation. V_{DD}, supply voltage; GND, ground; C_f, feedback capacitor; C_{mem}, membrane capacitor; p-OECT, p-type OECT; n-OECT, n-type OECT. Adapted from ref. 1, Springer Nature Ltd.

are also highly sensitive to heat and oxidation. Progress will depend on designing materials that can tolerate standard sterilization conditions such as steam, ethylene oxide, or γ-irradiation, without losing their electrical or mechanical integrity[4–6]. Architectural advances are also essential. Planar transistor layouts, while simple and reliable, limit speed and scalability; vertical or three-dimensional geometries[7–10] could shorten channel lengths, push switching frequencies beyond ten kilohertz, and enable denser arrays of artificial neurons on flexible substrates. As these systems scale to thousands of interconnected units, maintaining synchronization and filtering out biological noise will require new circuit designs and adaptive algorithms. Yet these are engineering challenges rather than conceptual barriers.

From a clinical perspective, long-term operation in physiological environments can gradually degrade organic device materials and alter their spiking characteristics. Implanted systems may also trigger immune responses and glial encapsulation, increasing impedance and compromising signal fidelity. Chronic implantation further poses additional challenges for mechanical robustness and packaging. Addressing these issues will be essential for the safe and reliable clinical translation of soft organic neuron technologies. The essential proof has already been made: soft organic materials can now approach the speed and energy efficiency relevant to neural signalling, bringing us closer to truly bio-integrated electronics.

A decade ago, organic electronics were dismissed as too sluggish for neural computation. Today they can detect, decide, and act on brain activity in real time, all within a sheet of polymer only a few micrometres thick. The message is clear: electronics no longer have to impose their logic on biology. Instead of forcing the brain to adapt to hard digital machines, we can now build machines that think and respond more like the brain itself — soft, efficient, and alive with spikes of meaning.

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Competing interests

The authors declare no competing interests.