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Building fast artificial nerves using vertical architectures

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Vertical organic electrochemical transistors with gradient-intermixed bicontinuous structures can emulate artificial nerves, showing high-frequency sensing, processing and memory functions.

Interfacing electronics with biological neural systems is important for the development of neuroscience, neurological treatments and brain–machine interfaces. In pursuit of optimal functional integration of electronics and neural systems, electronic devices have been designed that can mimic neural functions (Fig. 1a). These artificial nerves can respond to and generate neural-like spiking signals, while showing short-term or long-term memory characteristics[1,2]. Different devices can be used to build artificial nerves, but n-type organic electrochemical transistors (OECTs) are potentially an ideal option owing to their neuron-like dynamics, response to positive-voltage neural action potentials and mechanical softness. However, n-type OECTs typically show limited device capabilities. Writing in *Nature Electronics*, Wei Ma and colleagues now report that n-type OECTs with a vertical structure can be used to create artificial nerves with fast response speed and long retention[3].

OECTs are used in technologies such as biosensing and neuromorphic computing[4]. Unlike conventional field-effect transistors, OECTs rely on gated electrochemical doping reactions in the channel, which provides high amplification of signals coupled to the gate, and retention of the instantaneous doping state in the channel. To interface OECTs with neural systems, both p-type and n-type devices are, ideally, needed. However, compared with p-type OECTs, n-type devices suffer from lower response speed, smaller transconductance (the changing ratio of drain current versus gate voltage) and worse operational stability[5,6]. This is due, in particular, to the lower mobility of electrons in organic mixed ion–electron conductors compared with holes, which is the result of stronger trapping effects on electrons.

The researchers — who are based at Xi'an Jiaotong University, Technical University of Munich, Deutsches Elektronen-Synchrotron DESY and KTH Royal Institute of Technology — developed a vertical n-type OECT with a gradient-intermixed bicontinuous structure that enhances both electron and ion transport, as well as the ion storage properties. The gradient-intermixed bicontinuous structure is formed in the vertical channel of the n-type OECT by depositing a hydrophilic polymer (branched polyethyleneimine) onto the surface of a model n-type semiconducting polymer (poly(benzimidazobenzophenanthrolinedione)). The polyethyleneimine diffuses into the n-type semiconductor, forming interpenetrated microstructures (Fig. 1b). The polyethyleneimine enhances ion transport into the layer and also provides doping effects to the n-type semiconductor that help mitigate the trapping effects that restrict electron transport. At the same time, the packing structure of the semiconducting polymer, which offers ion-storage capabilities, remains unchanged and thus non-volatile behaviour is ensured.

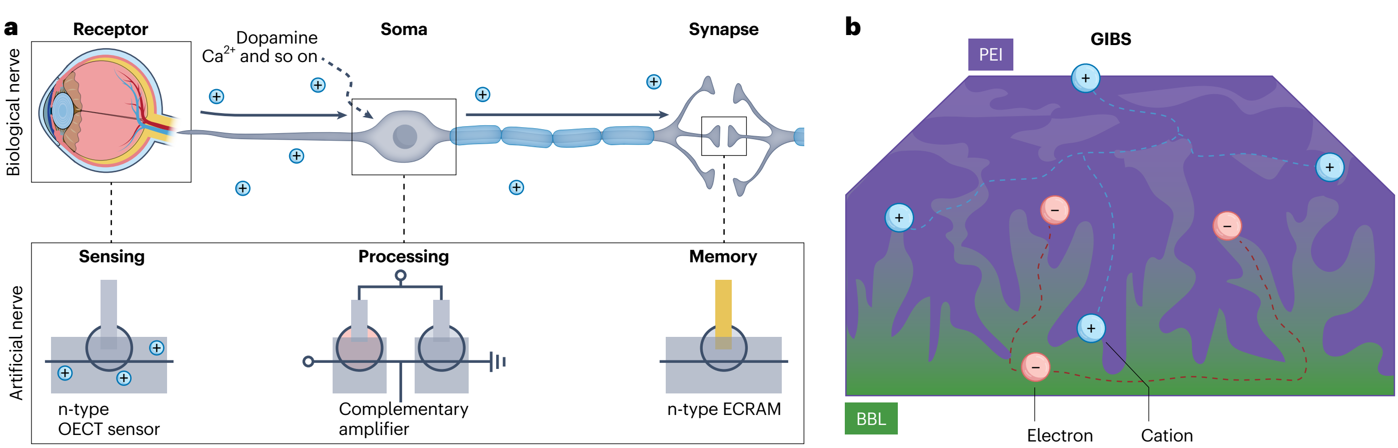

Fig. 1 | An artificial nerve based on vertical OECTs. a, Comparison between biological and artificial nerves. Biological nerves are composed of receptors for signal sensing, soma/neurons for signal processing, and synapse information storage/memory. Analogous to the biological nerve, artificial nerves are composed of a sensing receptor, a processing unit and an electrochemical random-access memory (ECRAM) unit. All the parts of the artificial nerve are based on n-type (shaded in grey) and p-type (shaded in red) OECTs. **b**, The OECTs have a vertical channel fabricated from a hydrophilic polymer (branched polyethyleneimine; PEI) and an n-type semiconducting polymer (poly(benzimidazobenzophenanthrolinedione; BBL) with a gradient-intermixed bicontinuous structure (GIBS) that improves volatile and non-volatile OECT performance. Figure adapted from ref. 3, Springer Nature Limited.

Ma and colleagues show that the vertical OECTs offer a fast volatile response of 27 µs. They also demonstrate that the bicontinuous design strategy can be applied to high-performance p-type polymers with similar effects. To illustrate the wider capabilities of the approach, they construct a complementary amplifier by combining the vertical n-type OECT with a performance-matched p-type OECT, demonstrating a high gain of 250 V/V and a high cut-off frequency of 1.5 kHz. The complementary amplifier building block was then used to build an axon-hillock spiking neuron circuit to emulate the soma of a nerve system. The fast circuit response provides a high firing rate of approximately 50 Hz when supplied with an input current of 100 µA, a firing rate that is 5 times higher than previous OECT-based axon-hillock circuits[7,8].

The team also illustrated the improved non-volatile performance of the OECTs, demonstrating an approximately 2,000 times improvement in the tuning pulse width compared with their counterparts without branched polyethyleneimine, while maintaining retention times of 10^3 s. As a result, the n-OECT can be used to form a synaptic device that is integrated with the axon-hillock circuit, providing a connected soma and synapse neural circuit. In this system, each spiking event enhances the downstream synaptic weight, forming a memory that leads to an increased excitatory post-synaptic current output. By integrating a vertical OECT that detects light and chemical modulation with the complementary amplifier structure and the synaptic OECT, the researchers also constructed a chemical-modulated artificial nerve on a flexible polydimethylsiloxane substrate. To illustrate its capabilities, the synaptic current output was connected to the muscle tissue of mice. The simultaneously light- and ion-concentration-controlled stimulation function results in a more realistic afferent nerve operation compared with devices with only one input signal.

Further advancements in several key aspects will be needed to deliver practical neural interfaces. First, device miniaturization and scalable fabrication will be crucial to enhance resolution and to communicate with and stimulate a large number of nerves and other neuron structures[6]. Second, expanded chemical sensing functionality – which includes other neurotransmitters and neuromodulators such as glutamate, dopamine and norepinephrine[9] – will be needed to deliver multi-modal communication with neural systems. Third, location shifting between devices and neurons will need to be minimized – through, for example, tissue-adhesive properties[10] – and immune reactions suppressed to create long-term stable interfaces.

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Competing interests

The authors declare no competing interests.