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Perspective

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The rise of hydrogel transistors

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Abstract

Solid-state silicon transistors have profoundly transformed modern life by enabling a wide array of electronic technologies. The rise of bioelectronics has emphasized the necessity for interfacing transistors with living systems. However, challenges such as mechanical incompatibility, disparities in charge carrier types and differences in form factors present significant barriers to seamless integration. Recent advances in hydrogels have led to the development of hydrogel transistors, which merge the unique properties of hydrogels with transistor functionality, offering a solution to overcome these mismatches. This Perspective highlights hydrogel transistors, their biomimetic features and methods for their fabrication and characterization. We envision how hydrogel transistors, by evolving from conventional 2D thin-film electronics to 3D gel electronics, expand the device toolbox, enabling next-generation 3D, programmable and living bioelectronics.

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Introduction

The year 2025 marks the 100th anniversary of the transistor. Invented by Julius Edgar Lilienfeld in 1925, transistors have become the foundation of modern nanoelectronics and microelectronics[1,2]. In 1947, John Bardeen, Walter Brattain and William Shockley demonstrated the Germanium point-contact transistor at Bell Laboratories, sparking a period of explosive development[3] that included the bipolar junction transistor[4,5], the metal-oxide–semiconductor field-effect transistor (FET)[6], the organic FET[7,8] and the organic electrochemical transistor (OECT)[9,10]. These transistors laid the foundation for the modern electronics industry, enabling functions such as signal amplification[11], logic operations[12–15] and artificial intelligence[16,17].

Transistors are typically three-terminal semiconductor devices containing a gate electrode that modulates the conducting state of the semiconductor channel, which is sandwiched between source and drain electrodes[18]. The amplification capabilities of transistors can help enhance the signal-to-noise ratio of biosensors[11,19] (Fig. 1a). The growing bioelectronic need for recording and processing bio-signals has propelled the use of transistors to interface living systems and improve signal quality[20]. However, inherent mismatches exist between conventional transistors and living systems, such as mechanical mismatch (hard surface versus soft surface)[21–23], charge carrier mismatch (electronic signals versus ionic signals)[24,25], material mismatch (inorganic material versus organic material)[26,27] and dimension mismatch (2D versus 3D)[28–30]. These mismatches have hindered the seamless integration of transistors with living systems[31,32].

Hydrogels are 3D, wet, soft polymeric materials heavily swollen with water[33]. They are promising biomaterials owing to their ability to form an intimate interface with living systems. Their soft, elastic and water-abundant nature mimics the mechanical and chemical environment of biological systems[34]. For example, the 3D polymer network of hydrogels features tunable physico-chemical properties that are needed to satisfy the specific requirements for tissue-engineering applications[33,35]. Microfabricated hydrogels have been widely used in bioelectronics and medical applications[36–39]. Hydrogels have also been functionalized with conductive components for bioelectronics applications. For instance, hydrogel networks have been blended with metal nanowires (such as silver and gold[40–42]), carbon nanotubes[43], graphene[44] and conducting polymers, such as poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS)[45], polypyrrole[46] and polyaniline[47]. The state-of-the-art conductive hydrogels feature conductivities between 10^2 and 10^3 S cm^{-1}, while maintaining a tissue-like modulus and stretchability[48–51].

Although high conductivity is achieved in conductive hydrogels, they have lacked semiconducting properties, limiting their use to passive applications without amplification or the ability to regulate electron flow for logic functions[52]. To leverage the potential of hydrogels for active bio-interfacing, they have been assembled into transistor architectures (Fig. 1b). In the early stages, hydrogels were limited to use as supplementary components, such as non-fluid electrolytes[18,53,54], to assemble transistors. Since then, hydrogel-based semiconductors have been developed[19,55–57], enabling their direct use as the channel material to create true hydrogel transistors for signal processing and amplification. This breakthrough also opens opportunities to develop fully hydrogel-based transistors for a wide range of bioelectronics applications.

Despite the advances of hydrogel transistors, this field is still in its infancy and lacks comprehensive resources to guide newcomers to the field. This Perspective highlights hydrogel transistors. We first define the different types of hydrogel transistors and outline their development roadmap. Next, we explore their fabrication techniques, characterization methods and unique form factors. Finally, we envision how hydrogel transistors, capable of operating at the macroscale and cell loading, can start new research directions of 3D programmable and living bioelectronics, extending the capability of traditional silicon transistors.

Hydrogel transistors

As defined by the International Union of Pure and Applied Chemistry (IUPAC), a hydrogel is, first and foremost, a gel — a non-fluid colloidal or polymer network that is swollen throughout its entire volume by a fluid; and the fluid that swells the polymer network is water[58]. In the context of hydrogel transistors discussed in this Perspective, we mainly refer to hydrogels that are used as semiconductor channel materials.

According to the IUPAC definition, organic thin-film transistors, including those based on semiconducting molecules or polymers such as PEDOT:PSS[59], poly(benzimidazobenzophenanthroline):poly(ethylen eimine)[60], poly(benzodifurandione)[61] and poly(pyridinium phenylene)[19] can all, technically, be regarded as hydrogel transistors if they swell throughout their entire volume in the presence of water. Nevertheless, those thin-film devices are typically less than 1-μm-thick and their swelling properties are limited, normally less than 50%, owing to the high degree of cross-linking required to achieve the crystallization necessary for good semiconducting performance[62]. Consequently, Young's modulus ranges from megapascals to gigapascals — much higher than the kilopascal-scale modulus of biological systems[63,64]. So, although these organic transistors can generally be categorized as hydrogel transistors, they fail to leverage the desired properties of emerging tissue-compliant hydrogels (such as kilopascal-scale modulus[49], greater thicknesses and high stretchability[65]) and fall short of addressing the multidimensional mismatches with living systems. Accordingly, we define a hydrogel transistor as a thick-gel transistor (TGT) in contrast to the thin-film transistor (TFT). TFTs are made by depositing thin semiconducting layers onto rigid substrates, with planar (surface-to-surface) interfaces and micro-scale thicknesses (typically less than 1 μm). TGTs, by contrast, are freestanding devices made from soft semiconducting materials with a 3D network structure. Their bulk (volume-to-volume) interfaces enable efficient 3D charge transport, and their thickness is capable of scaling from micro- to macro-scale (exceeding 100 μm, the boundary between micro- and macro-scale), allowing seamless integration with dynamic living systems.

State-of-the-art hydrogel transistors aim to develop devices entirely made of gel materials, with channels featuring hydrogels that possess mixed ion–electron conductivity, enabling ion-to-electron conversion through reversible electrochemical processes. A key objective is to achieve kilopascal-scale softness in the semiconductor channel for tissue-level compatibility while maintaining substantial channel thicknesses to ensure mechanical robustness for free-standing features[55,57]. This requires advanced molecular, polymer and supramolecular processing to impart semiconducting properties to macroscopic bulk gels, which was previously unattainable until the report of 3D hydrogel semiconductors[30]. One approach involves the deliberate construction of 3D micropores within semiconducting polymers to serve as water reservoirs[66]. These reservoirs can greatly enhance the swelling ratio, by as much as 1,000%, with excellent reversibility[30] — far exceeding the capabilities of hydrophilic semiconducting polymers. However, these materials are often fragile and lack stretchability. Another strategy employs a multi-network supramolecular system, where the semiconducting network is complemented with other supporting polymer

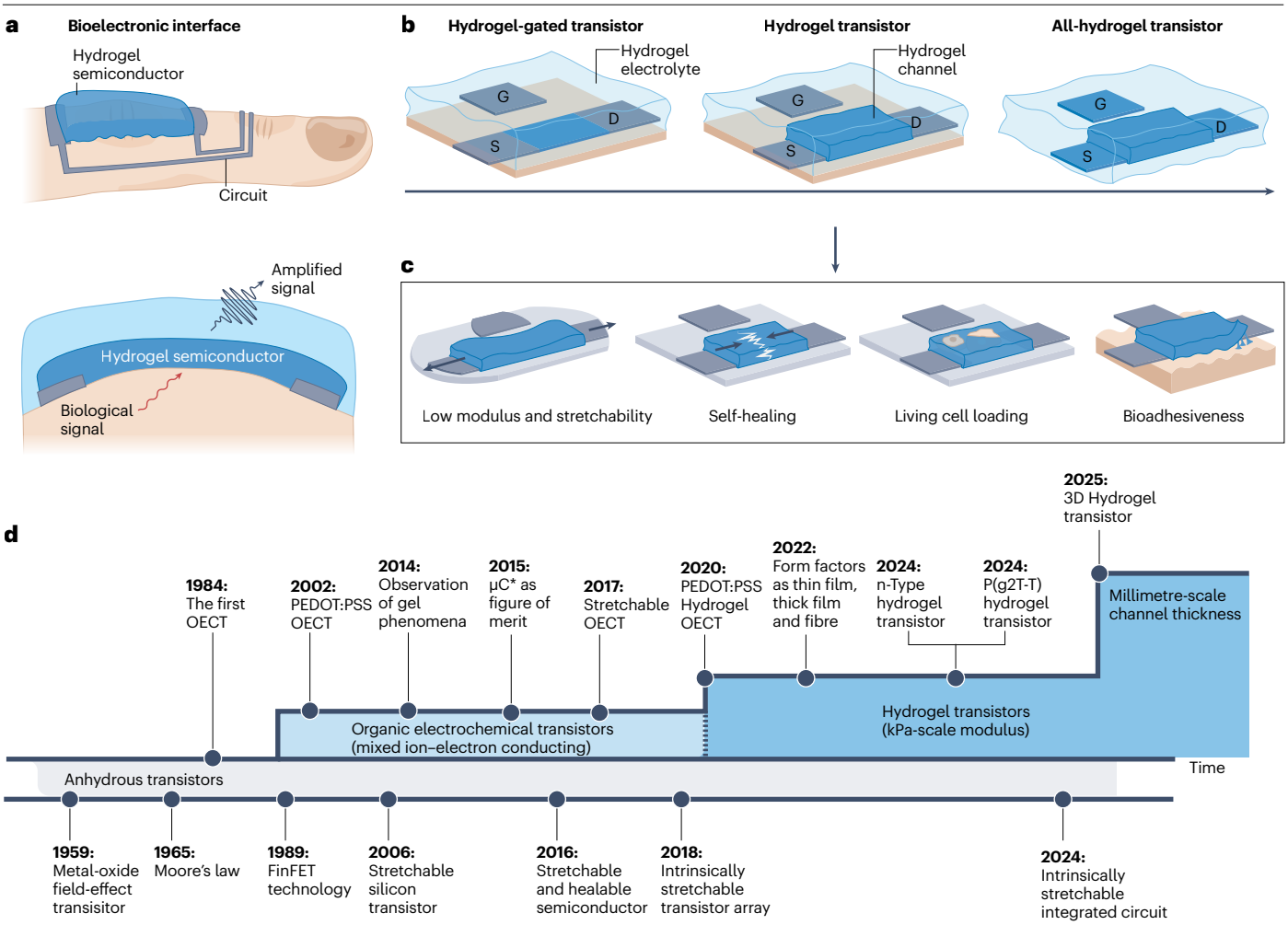


Fig. 1 | Hydrogel transistors provide exclusive opportunities to fill gaps between transistors and living systems. a, A hydrogel transistor interfaces with a living system with tissue-like softness. It translates ionic biological signals into amplified electronic signals. **b**, Hydrogel transistors have evolved from hydrogel-gated transistors (previous generation) to hydrogel semiconductor transistors (current generation), and are advancing towards fully hydrogel-based transistors (next generation). **c**, Hydrogel transistors demonstrate a broad range of biomimetic properties, such as a low modulus and high stretchability, self-healing behaviour, the capacity to support living cells as a living transistor and bioadhesiveness. **d**, Transistor technologies have developed from the early anhydrous germanium point-contact transistor to the organic electrochemical transistor (OECT), and currently to hydrogel transistors. This progression not only marks a shift in material systems and operational environments but also reflects a dimensional transformation, with the thickness of the channel evolving from nano-scale and micro-scale thin films to the millimetre-scale bulk gels in hydrogel transistors, enabling 3D, hydrated and programmable bioelectronic interfacing. Major milestones are indicated along the timeline: 1959 (ref. 6), 1965 (ref. 3), 1984 (ref. 10), 1989 (ref. 128), 2002 (ref. 67), 2006 (ref. 129), 2014 (ref. 130), 2015 (refs. 112,117), 2016 (ref. 131), 2017 (ref. 53), 2018 (ref. 132), 2020 (ref. 55), 2022 (refs. 56,69,71), 2024 (refs. 15,19,57) and 2025 (ref. 30). D, drain electrode; G, gate electrode; PEDOT:PSS, poly(3,4-ethylenedioxythiophene) polystyrene sulfonate; S, source electrode.

networks via non-covalent interactions[19,55–57]. In this configuration, the semiconducting network contributes to the hydrogel's semiconducting properties, whereas the supporting polymer network provides additional tissue-like properties, such as stretchability, needed for compatibility with biological systems.

Hydrogel transistors based on multi-network hydrogel semiconductors have recently achieved notable success in combining a low modulus and stretchability[55,57] (Fig. 1c). The improved mechanical properties are essential for establishing intimate and robust tissue interfaces. Additionally, these transistors are able to retain function at greater channel thicknesses compared with thin-film semiconductors, mainly because, first, the multi-network structure allows more material components to be hosted and, second, their micropores contribute to a superior swelling capacity[30]. Therefore, the channel thickness can easily be on the scale of micrometres to millimetres, corresponding to a macroscopic transistor[30], which opens a new technological pathway distinct from conventional transistors (Box 1). This unique feature provides 3D capacity for cell loading and offers easier manipulation in a free-standing form, opening new opportunities for interfacing with macroscale biological systems.

The rise of hydrogel transistors

Hydrogel transistors evolved from OECTs[9,10], which are considered flagship devices in the transdisciplinary field of organic bioelectronics

Box 1 | Technology transfer of hydrogel transistors

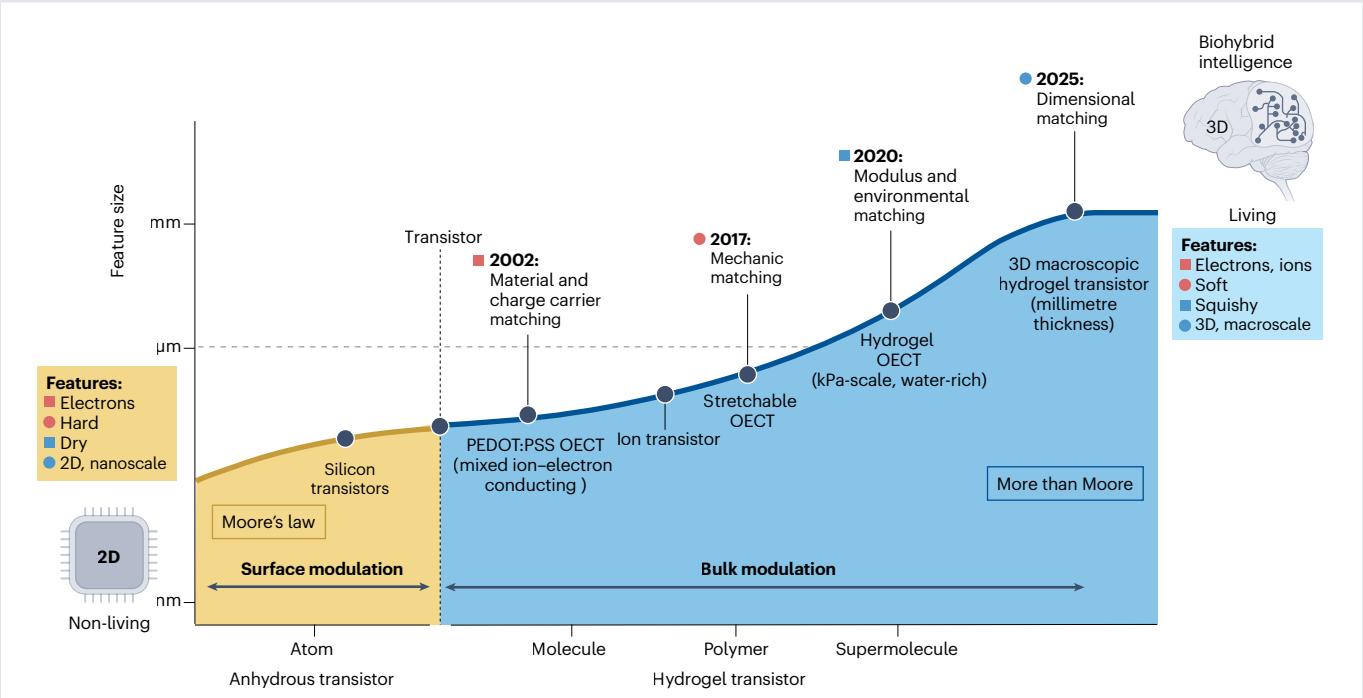
Conventional transistors, which are dry, rigid and non-living, have improved computing power by becoming smaller and operating within limited 2D spaces. This strategy of miniaturization has enabled the packing of more transistors into very large-scale integration systems. However, this approach is slowing down as Moore's law reaches its limits[133].

In contrast, hydrogel transistors, which are water-rich, soft and living, take a complementary approach. They enhance computing power without the need for miniaturization. Instead, they overcome the dimensional limitations of conventional transistors, enabling the integration of electronic devices with biological systems to enable 3D and programmable bioelectronics. This 'More than Moore' strategy[134] facilitates the development of brain-inspired intelligent systems that, despite being larger in size, remain highly efficient and powerful in computational performance.

The figure highlights the evolution of hydrogel transistors and their progressive advancements (highlighted by leader line) in simultaneously addressing critical mismatches — charge carrier, mechanical and dimensional mismatches — on the path towards practical bioelectronic integrations.

In 2002, poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS)-based organic electrochemical transistors (OECTs) introduced mixed ion–electron conduction, enabling stable operation of organic transistors in aqueous environments and resolving the material and charge carrier mismatch between transistors and living systems[67]. By 2020, the development of kilopascal-scale hydrogel OECTs tackled modulus constraints, overcoming the modulus and environmental mismatch with biological tissues[55]. Most recently, in 2025, hydrogel OECTs broke through thickness limitations with the introduction of 3D millimetre-thick channel designs, enabling cell loading and addressing the dimensional mismatch[30].

By overcoming these multidimensional mismatches, hydrogel transistors are paving the way for brain-inspired hybrid intelligence systems that seamlessly combine the efficiency of electronics with the unparalleled capabilities of biological systems.



involving organic electronics, electrochemistry and microelectronics (Fig. 1d). OECTs are iontronic transistors in which the modulation of channel conductance is achieved through ion injection from the electrolyte and reversible electrochemical reactions within the semiconducting polymer. The first OECT, developed in 1984 (ref. 10), used the conducting polymer polypyrrole as the channel material. However, OECTs were not widely adopted in bioelectronics until 2002, when the semiconducting polymer PEDOT:PSS was introduced as the channel material[54,67], which greatly improved device stability in both air and water.

Hydrogel transistors were developed as part of the effort to create stretchable OECTs[53,68], with a particular focus on designing low-modulus and stretchable semiconducting polymers for these devices. Towards this goal, in 2020, the first hydrogel semiconductor with a Young's modulus as low as 1 kPa was synthesized by mixing a PEDOT:PSS suspension with 4-dodecylbenzenesulfonic acid (DBSA)[55]. By optimizing structural and processing controls, efficient ion-to-electron conversion within the hydrogel was achieved. To further enhance the mechanical stretchability of the hydrogel semiconductor while maintaining its low modulus, a multi-network polymer approach was adopted, blending the π-conjugated PEDOT:PSS hydrogel with a secondary stretchable hydrogel network, polyacrylamide (PAAm). The resulting hydrogel semiconductor exhibited a modulus range of

1–100 kPa and a stretchability of up to 50%, and by processing it into the form of a fibre (Fig. 2a) a hydrogel transistor with an on–off ratio of 100 was demonstrated[55]. This represented the first observation of semiconducting behaviour in hydrogels.

Later, the on–off ratio of hydrogel transistors was boosted to 10^3 through the controlled synthesis of a double-network hydrogel based on PEDOT:PSS and PAAm[56]. Other hydrogel networks, such as poly(2-acrylamido-2-methyl-1-propanesulfonic acid) (PAAMPSA), were explored and a hydrogel transistor array exhibited a similar 10^3 on–off ratio and an average transconductance up to 13 mS (ref. 69). Hydrogel transistors using poly(vinyl alcohol) (PVA) and PEDOT:PSS have been reported, where Raman spectroscopy analyses indicated that the ionic transport through the swollen hydrogel was clearly different from the transport in a thin film[70]. It was later demonstrated that, despite a relatively low on–off ratio, it was possible to develop a semiconducting hydrogel with only PEDOT:PSS by adding a choline-based ionic liquid during processing[71].

Other types of hydrogel transistors have also been reported. An n-type semiconducting hydrogel was reported based on the redox-active and hydrophilic semiconducting polymer, which shows good electron mobilities, enabling the fabrication of complementary logic circuits and signal amplifiers[19]. A solvent exchange strategy for polymer integration in hydrogels has enabled the incorporation of the poly(3,3′-bis(2-(2-(2-methoxyethoxy)ethoxy)ethoxy)2,2′:5′,2″-terthiophene) (p(g2T-T)) polymer into a hydrogel matrix formed from acrylic acid, resulting in a soft, biocompatible material with excellent semiconducting performance[57] (Fig. 2b,c).

Material strategies for hydrogel transistors

Hydrogel semiconductors are electroactive materials, serving as the channel of transistors. They play a central role for signal processing and amplification by enabling mixed ion–electron transport and conversion within the hydrogel. Unlike conventional organic semiconductors, which are typically composed of a single polymer network, hydrogel semiconductors require the integration of multiple polymer networks, each engineered to perform a specific function. These networks typically include a semiconducting network, a supporting network and additives[55,68] (Fig. 3). Achieving optimal semiconducting properties requires not only that the concentrations of these polymer networks are balanced but also that the processing conditions are carefully controlled. Both affect the phase formation of the semiconducting network and fine-tuning of the hydrogel's porosity, which are critical for efficient ion and electron transport, as well as ion-to-electron conversion[30]. Finally, the manufacturing approach determines the form factor of hydrogel transistors, such as films[14,72,73], hydrosponges[29,74], fibres[71] and meshes[75], enabling them to meet the specific requirements of various bioelectronic applications (Fig. 3b).

The following considerations are crucial when developing hydrogel semiconductors for hydrogel transistors.

First, it is essential to select an air and water-stable π-conjugated polymer network — for example, using redox-active polymers with reversible electrochemical reactions, such as PEDOT:PSS, or semiconductor fillers whose conductivity can be modulated electrostatically, such as graphene, metal oxides or semi-metallic polymers[76]. These materials should demonstrate stability under various conditions, including prolonged exposure to water, air and complex biological environments[77]. Maintaining stability ensures that the semiconducting polymer retains its functionality during hydrogel assembly and in practical applications.

Second, the semiconducting polymer must be capable of forming an independent 3D network. This can be achieved via reversible supramolecular interactions, such as π–π stacking, electrostatic coupling or non-reversible covalent bonding[55,56]. Establishing a robust 3D semiconducting network ensures its viability across different phases and material forms. This property is a fundamental requirement for tissue-like functionality in hydrogels and practical applications in bioelectronics.

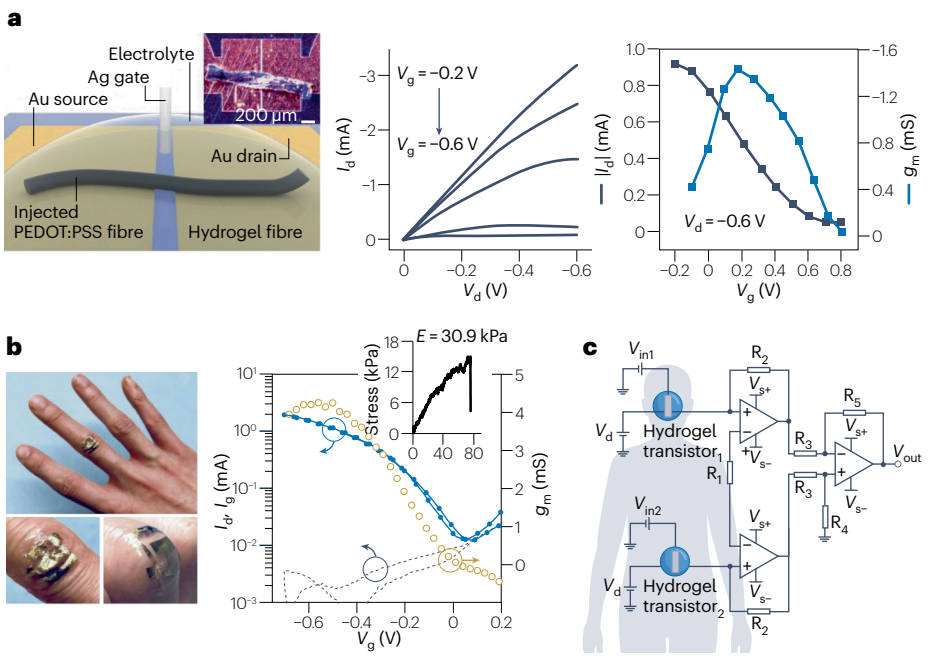


Fig. 2 | Hydrogel transistors and circuits for practical bioelectronic applications. **a**, Hydrogel-fibre semiconductor transistors and their output and transfer characteristics. **b**, Hydrogel transistors form a highly conformable interface with a bending human finger, demonstrating semiconducting properties by the transfer curve and a low modulus of 30.9 kPa. **c**, Hydrogel transistors can use operational amplification circuits for on-body signal amplifying. E, Young's modulus; g_m, transconductance; I_d, drain current; I_g, gate current; PEDOT:PSS, poly(3,4-ethylenedioxythiophene) polystyrene sulfonate; R, resistor; V_d, drain voltage; V_g, gate voltage; V_{in1}, V_{in2}, input bio-signals; V_{s+}, non-inverting input voltage of amplifier; V_{s-}, inverting input voltage of amplifier; V_{out}, output voltage. Part **a** reprinted with permission from ref. 55, Wiley-VCH, Part **b** is reprinted with permission from ref. 57, AAAS.

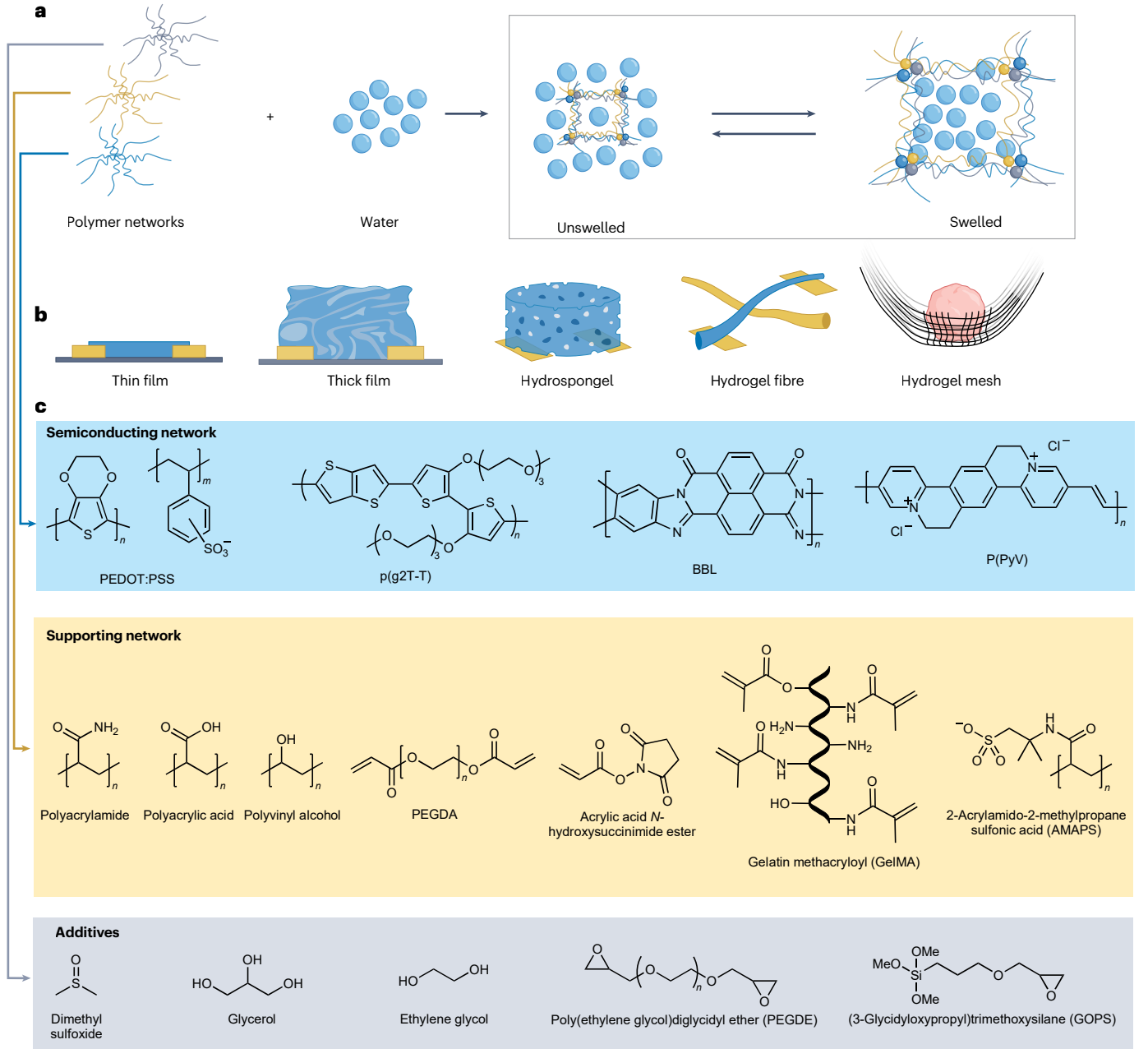


Fig. 3 | Material strategies towards hydrogel transistors and tissue-like properties. a, Network design of a hydrogel semiconductor involving a semiconducting network, a supporting network and additives. **b**, Diverse form factors of hydrogel transistors. **c**, Typical semiconducting networks involve organic semiconducting polymers, such as poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) and poly(3,3′-bis(2-(2-(2-methoxyethoxy) ethoxy)ethoxy)2,2′:5′,2″-terthiophene) (p(g2T-T)). The supporting networks such as polyacrylamide (PAAm) impart hydrogel with mechanical properties such as softness and stretchability. Additives are incorporated to tune the physicochemical properties of the hydrogel, for example, DMSO can be used to enhance the electronic conductivity of PEDOT:PSS.

Third, the resulting multi-network hydrogels must be capable of supporting efficient ion and electron transport, as well as effective ion-to-electron conversion[78–80]. These characteristics are essential for modulating the hydrogel's redox properties, allowing for precise tailoring of its semiconducting performance to suit various bioelectronic applications.

Biomimetic features of hydrogel transistors

By harnessing the tissue-like properties of hydrogels, hydrogel transistors create a seamless interface with living systems[33]. Integrating hydrogel-specific attributes into transistors imparts them with unprecedented capabilities, including mechanical conformability, self-healing, responsiveness to stimuli, actuation and even living

functionalities. These biomimetic features effectively bridge the gap between traditional transistors and the intricate dynamics of biological tissues.

Mechanical conformability

The exceptional mechanical properties of hydrogels, particularly their kilopascal-scale low modulus, enhance the mechanical compliance of hydrogel transistors. Mechanical conformability refers to a material's ability to adapt or conform to curved or irregular surfaces. It is inversely related to bending stiffness – materials with lower bending stiffness are more conformable[81]. The bending stiffness (B) of a material depends on its Young's modulus (E), as given by the following equation[82]:

$$B = \frac{Eh^3}{12(1-\nu^2)},$$

where h is the elastic thickness and ν is Poisson's ratio. Transistors assembled using materials with a low modulus are more conformable because their bending stiffness is reduced.

When a secondary stretchable hydrogel network is introduced, to form a double network with the semiconducting network, these hydrogel transistors can gain additional stretchability and, hence, mechanical robustness without compromising their low modulus[65,83,84]. The combination of mechanical compliance and robustness is essential for minimizing tissue damage and reducing motion artefacts at device–tissue interfaces, ensuring prolonged and reliable integration with biological systems.

In addition, hydrogel transistors, benefiting from their greater thickness scalability[30], adopt diverse form factors that are difficult to achieve using conventional thin-film transistors. Their mechanical robustness enables them to exist in free-standing forms, such as fibres[71], meshes[85] or hydrospongel structures[29].

Self-healing ability

Hydrogels can endow transistors with self-healing capabilities that closely mimic the natural repair processes of biological tissues, thus improving their lifespan for prolonged use[86]. This self-healing ability is achieved by introducing dynamic bonds within multi-networked hydrogels, and can be designed to be autonomous, without the need for external intervention.

Bioadhesiveness

Hydrogels can be designed with unique bioadhesive properties, to achieve strong adhesion between transistors and biological tissues[87,88]. Similar to self-healing, improved adhesion can be realized by introducing dynamic bonds within the hydrogel, which then form ionic bonds with the ionic species on targeted surfaces[44,89]. Additionally, microstructures can be created to serve as suckers or drains to further improve adhesion forces[90]. These combined approaches have been validated to achieve strong underwater adhesion[91,92], a highly desirable characteristic for interfacing with wet biological systems.

A living transistor

The 3D nature of hydrogels and their water-rich composition permit cell loading and proliferation, thereby enhancing the biocompatibility of transistors and enabling cell–transistor fusion[35]. Such a 'living transistor' can accelerate the development of synthetic bioelectronics involving cell–transistor integration[29,93], facilitating the advancement of various living, wearable and implantable bioelectronic devices and logics. Notably, it may also present new opportunities to develop biohybrid neuromorphic hardware for computing applications[94,95].

The ability of hydrogel transistors to achieve a range of channel thicknesses – from nanoscale thin films to millimetre-sized structures – facilitates cell–transistor integration: with greater channel thicknesses, these transistors can support cell growth and proliferation[30]. Such stretchable systems can leverage the programmability of transistors for active control, while also enabling the study of how biomechanical forces influence cell behaviour[96,97], transistor performance[93] and cell–transistor interactions[98,99].

Drug delivery

Hydrogels can provide spatial and temporal control over the release of various therapeutic agents, including small-molecule drugs, macromolecular drugs[100] and cells[33,101]. This can be achieved by tuning the multiscale properties of hydrogels, the rate of drug diffusion within the hydrogel network or the drug–network interactions. Hydrogel transistors can further advance such systems to be programmable[102,103], which is essential for precise closed-loop sensing and delivery.

Dynamic actuation

Controllable volumetric expansion or contraction by a safe, low-voltage stimuli enables hydrogel transistors to gain programmable actuation abilities[104]. These abilities derive from a reversible electrochemical process in semiconducting polymers[105,106], enabling hydrogel transistors to adapt their shape and conform to complex tissue dynamics[107]. This controllable deformation is particularly valuable in neuro-electronics, offering new solutions for minimally invasive, interactive and shape-adaptable bioelectronic interfaces.

Characterization of hydrogel transistors

Hydrogel transistors, based on π-conjugated hydrogel semiconductors, operate as three-terminal OECTs[9]. The state of electronic conductivity of the semiconductor channel (electronic circuit), sandwiched between source and drain electrodes, is electrochemically modulated through a gate electrode that controls ion injection from the electrolyte (ionic circuit)[108] (Fig. 4a). The characterization of OECTs – and thus also of hydrogel transistors – includes, primarily, characterization of output, transfer, transient response and volumetric capacitance.

Output characterization

The hydrogel transistor regulates current flow between the source and the drain under varying gate voltage (V_g) conditions. The output curves in Fig. 4b show the relationship between the drain current (I_d) and the drain voltage (V_d) at different V_g. Saturation occurs when I_d reaches its maximum value for the given V_g and becomes independent of V_d, indicating the pinch-off voltage (V_p) of the channel. This test is critical for understanding the transistor's current-driving capability and overall output performance.

Theoretical models have been developed to understand the operation of OECT devices[109]. In general, if a differential slice, dx, in the vicinity of position x of the channel is considered, then steady-state current flux, J(x), follows the governing equation:

$$J(x) = e\mu_{\text{electron}} p_0 \left[1 - \frac{V_g - V(x)}{V_p}\right] \frac{\mathrm{d}V(x)}{\mathrm{d}x},$$

where V_p is defined as qp_0d / c_d, e is elementary charge, $\mu_{electron}$ is the electron (or hole) mobility, p_0 is the initial electron (or hole) density in the organic semiconductor before the application of V_g, c_d is capacitance per unit area and $V(x)$ is the spatial voltage profile. The equation can be simplified for different regimes of behaviour following the Bernards–Malliaras model[109], or the Friedlein–McLeod model[110] and the Kaphle–Lüssem model[111] if considering the dependence of mobility on carrier density.

Transfer characterization

Transfer characterization provides crucial insights into the transistor's switching, amplification and memory behaviour. To understand

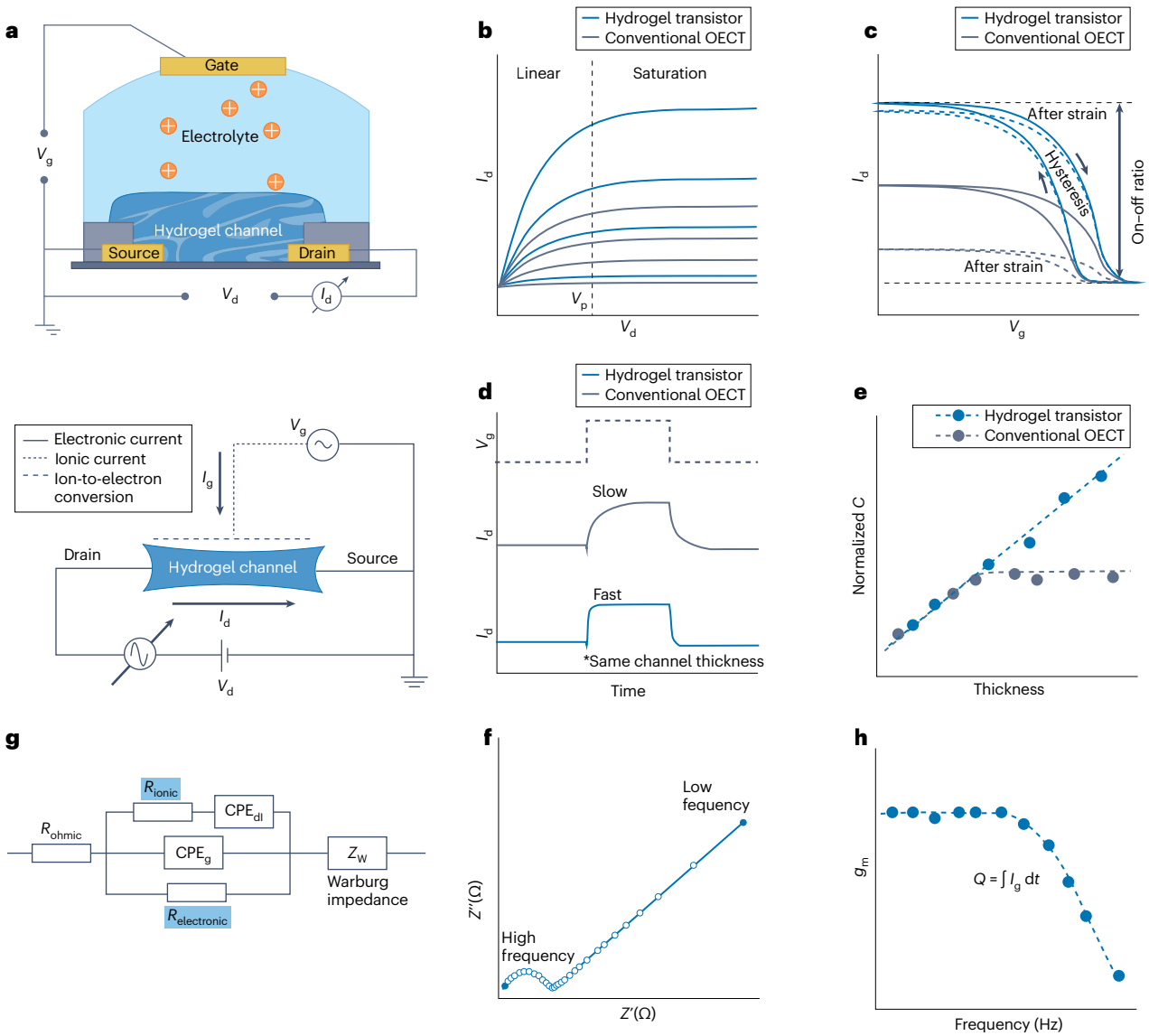


Fig. 4 | Characterization of hydrogel transistors. a, Hydrogel transistors operate in the three-terminal configuration (source, drain and gate electrodes). The flow of electrons through the hydrogel semiconductor channel is modulated by ionic currents from the gate. This ion-to-electron conversion enables the transistor to amplify ionic signals, effectively converting small ionic inputs into larger electronic outputs. **b**, Output curves. The hydrogel transistor can obtain higher current due to its increased thickness. **c**, Transfer curves. The hydrogel transistors can maintain their transfer characteristics even under strain, benefiting from their combined low modulus and stretchability. **d**, Transient curves. Hydrogel transistors, under the same channel thickness, can respond faster due to their porous structure, which facilitates ion transport. **e**, The hydrogel semiconductor channel can maintain the capacitance–thickness linearity at greater thickness, benefiting from the facilitated ion transport. **f**,**g**, The ionic and electronic transport properties in hydrogel semiconductors can be evaluated with electrochemical impedance spectroscopy (**f**) and fitting the data to equivalent circuits (**g**). **h**, The ion-to-electron conversion efficiency can be evaluated by analysing the proportionality between transconductance (g_m) and the injected ionic charge from the gate (Q); failing to maintain the proportionality may indicate deteriorated conversion. C, capacitance; CPE_{dl}, double-layer capacitive phase element; CPE_g, geometric capacitive phase element; I_d, drain current; I_g, gate current; OECT, organic electrochemical transistor; $R_{electronic}$, electronic resistance; R_{ionic}, ionic resistance; R_{ohmic}, ohmic resistance; V_d, drain voltage; V_g, gate voltage; V_p, pinch-off voltage; Z', real part of the impedance; Z'', imaginary part of the impedance; Z_w, Warburg impedance.

transistor switching behaviour – such as the on–off ratio – it is critical to assess how effectively V_g controls the current flow in the hydrogel channel. The transfer curves in Fig. 4c show the relationship between I_d and V_g at a fixed V_d. By sweeping V_g, the transistor's on–off ratio and threshold voltage can be obtained[109,112]. Transfer curves are also critical for evaluating transconductance (g_m), which measures the amplification capability of the transistor; g_m is extracted from the transfer curve using the following equation[113]:

$$g_m = \frac{\partial I_d}{\partial V_g}.$$

A high transconductance indicates efficient gate modulation of the channel current, and is essential for amplification applications.

The hysteresis in the transfer curve (Fig. 4c) reflects the memory effects of the transistor, where the current response depends on the history of the applied V_g (refs. 114,115). This is particularly relevant for neuromorphic and memory-related applications[16,32].

Transient characterization

Transient characterization provides insight into the dynamic performance of the hydrogel transistor, evaluating the transistor's frequency response and neuromorphic behaviour[16,116]. Figure 4d shows the time-dependent response of I_d to changes in V_g. Short-term responses reflect the switching speed[109], whereas long-term responses indicate memory or adaptation capabilities in neuromorphic applications[116]. This test is critical for understanding how quickly a hydrogel transistor can respond to input signals and for mimicking biological processes, making it essential for wearable and bioelectronics applications[32].

Volumetric capacitance characterization

The ability of the hydrogel channel to modulate charge throughout its thickness is critical for maintaining bulk transport, and the performance of hydrogel transistors with varying channel dimensions must be understood to ensure their effective operation in bioelectronic systems. The volumetric capacitance evaluates the channel's thickness limit, below which capacitance (C) maintains a linear relationship with channel thickness[117,118] (Fig. 4e). This capacitance can be measured using electrochemical impedance spectroscopy[119] (Fig. 4f), with values extractable via a Randles equivalent circuit[120] and its variants[49] (Fig. 4g).

Ions, electrons and ion-to-electron conversion

A quantitative measure of ion and electron transport in the hydrogel channel is required to gain insight into the hydrogel transistor's electrical performance. In ionic conductors, the charge carriers are ions – either negatively charged anions or positively charged cations. The hydrogel usually forms a porous structure where the diffusion coefficient of ions is smaller than the diffusion coefficient for the same ion in water. It needs to be adjusted for the size and topography of the pores as given by:

$$D = D_0 \frac{\varepsilon}{\tau},$$

where D is the diffusion coefficient in a porous network, D_0 is the diffusion coefficient in liquid, ε is porosity and τ is tortuosity[121,122]. Ionic mobility (μ_{ion}) is the drift velocity of an ion per unit electric field. The Einstein–Smoluchowski equation is widely used to infer μ_{ion} from the ionic diffusion coefficient:

$$\mu_{ion} = \frac{qD}{k_B T},$$

where μ_{ion} is dependent on the charge of the ion (q), diffusion coefficient (D), Boltzmann constant (k_B) and temperature of the system (T). The conductivity (σ_{ion}) of an ionic conductor is the sum of the contributions from all charge carriers, as expressed by the following equation[123]:

$$\sigma_{ion} = \sum_i n_i |z_i| e\mu_{ion},$$

where σ_{ion} is contributed by each mobile ion species (i). For the ith ion, z_i is the absolute value of the charge and n_i is the charge carrier density. According this equation, the σ_{ion} value of a hydrogel depends on both the properties of the ionic conductor, such as the charge carrier density, and the properties of the charged species, such as their mobility. The assumption is that a hydrogel will be charge neutral, so a fixed charge in the polymer backbone will result in the same amount of mobile charge that can contribute to the ionic conductivity[123].

The $\mu_{electron}$ value can be obtained through transfer characterization[109], transient characterization[109], electrochemical impedance spectroscopy[112] and small-signal analysis[124]. According to the Bernards–Malliaras model[109], $\mu_{electron}$ of a hydrogel semiconductor can be evaluated by fitting the transient response of I_d to a constant gate current (I_g):

$$I_d(t, I_g) = I_0 - I_g\left(f + \frac{t}{\tau_e}\right),$$

$$\tau_e = \frac{L^2}{\mu_{electron} V_d},$$

$$-\frac{\partial I_d}{\partial t} V_d = \frac{\mu_{electron}}{L^2} I_g,$$

where a pulse of I_g injects cations, causing a linear change of I_d proportional to the transit time (τ_e) of carriers across a channel of length L. I_0 is the steady-state current baseline, and f is the fraction of I_g that preferentially flows to the drain (as determined by the relative electrochemical state of the source and the drain).

The ion-to-electron conversion efficiency is an exclusive property of hydrogel semiconductors over conventional hydrogels, determining their transistor performance[30]. The conversion efficiency can be evaluated through the fundamental characterizations mentioned above. In the steady state, ion-to-electron conversion can be assessed by measuring the on–off ratio of hydrogel transistors, where a high on–off ratio indicates efficient conversion. In dynamic, frequency-dependent states, conversion efficiency can be evaluated from the response time derived from transient curves, the transconductance, or the subthreshold swing from transfer characteristics, which collectively reflect dynamic ion-to-electron conversion.

The dynamic conversion efficiency can be further evaluated by analysing the relationship between the injected ionic charge from the gate (Q) and g_m (Fig. 4h). For example, in an OECT, Q exhibits similar behaviour to g_m, given by the following equation[113]:

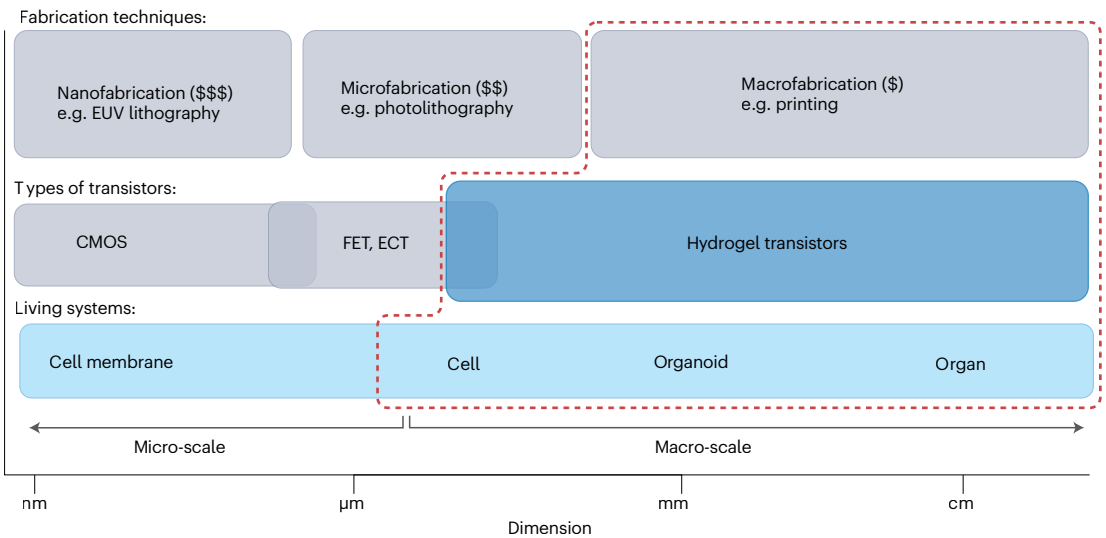
$$g_m \propto Q = \int I_g \mathrm{d}t,$$

Box 2 | Manufacturing of hydrogel transistors

The fabrication of conventional transistors relies heavily on high-cost and complex techniques to achieve functionality. Processes such as photolithography, including extreme ultraviolet (EUV) lithography[135], are fundamental for producing traditional nano-transistors and micro-transistors such as complementary metal-oxide-semiconductor (CMOS)-based field-effect transistors (FETs), electrolyte-gated FETs[18] and electrochemical transistors (ECTs)[9,136] (see the figure). These methods require extreme precision and significant financial investment, which limits accessibility and scalability.

Hydrogel transistors overcome these limitations by maintaining semiconductor properties and functionalities even at greater thicknesses and in bulk forms. This is made possible by the dimensional breakthrough of hydrogel semiconductors, which can function effectively at sizes and thicknesses previously restricted to thin-film semiconductors. This inherent advantage enables hydrogel transistors to be fabricated using more accessible and low-resolution techniques — such as textile manufacturing[137–139] and printing[140–143] — bypassing the need for complex and expensive microfabrication processes.

This shift in fabrication not only reduces costs but also significantly simplifies scalable production, positioning hydrogel transistors as a transformative technology for widespread commercialization and diverse applications.



where the Q is calculated by integrating I_g over time (dt). The above equation signifies that the frequency response of the transistor is dominated by the ion transport process between the electrolyte and the channel. This agreement between g_m and Q occurs because I_d is proportional to the ionic charge injected into the channel. The modulation of V_g leads to a modulation of this charge, and hence g_m is proportional to Q. Failure to maintain proportionality, or decreased proportionality, indicates a deterioration in conversion efficiency of the hydrogel transistor. Quantitatively, the ion-to-electron conversion efficiency can be determined by extracting the redox capacitance from the total measured volumetric capacitance using Dunn's method[125–127].

Conclusion and outlook

We have highlighted the rise of hydrogel transistors as a promising solution to address the longstanding mismatches between conventional transistors and living systems. By leveraging biomimetic features of hydrogels, including low modulus, stretchability, biocompatibility and the ability to function in hydrated environments, these devices overcome the mechanical, structural and functional limitations of traditional inorganic or organic transistors. Their ability to operate at 3D macroscopic scales, combined with low-cost and scalable fabrication techniques, positions them as a transformative technology to enable 3D programmable and living bioelectronics (Box 2).

We have discussed critical advances in materials design, fabrication strategies and device optimization, which provide a foundation for the development of hydrogel-based transistors capable of seamlessly interfacing with biological systems. Challenges remain in material development, fabrication and characterization, and these must be addressed to fully realize the potential of hydrogel transistors for broad bioelectronic applications.

Developing multifunctional semiconducting hydrogels with robust mechanical properties, excellent ion-to-electron conversion, and resilience under complex biological and environmental conditions remains a priority. Future research should focus on designing advanced polymer networks, integrating hierarchical structures, and exploring strategies to enhance response speed and stability without compromising tissue compatibility. Although low-cost and scalable manufacturing methods such as printing have proven effective, achieving precise control over device architecture, response speed and hysteresis at larger scales requires further refinement.

Co-optimization of materials, fabrication processes and operation mechanisms will be essential to meet the diverse demands of

bioelectronic applications. Realizing the full potential of hydrogel transistors will require the development of operando characterization platforms capable of monitoring multiple parameters simultaneously under biologically relevant conditions. These platforms will provide deeper insights into the fundamental mechanisms of hydrogel transistor operation and inform future device design.

Looking ahead, hydrogel transistors provide unprecedented opportunities in emerging fields relevant to 3D, synthetic, programmable and living bioelectronics. For example, in tissue-integrated biosensing, they offer the ability to create tissue-conformable active biosensors for real-time health monitoring and disease diagnosis. In biohybrid systems, they enable direct integration with cells and tissues, paving the way for developing hybrid biocomputing platforms and bioelectronic devices, such as brain–machine interfaces and artificial intelligence-embedded wearables. Furthermore, their adaptability in mimicking biological functions positions them as foundational components for developing biohybrid neuromorphic hardware for bio-integrated artificial intelligence, where electronics and biology merge to create intelligent, living systems.

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Competing interests
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