COMMENTARY

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Imperceptible biointerfaces enabled by hydrogel-elastomer-based conductive nanomembranes

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Soft bioelectronics hold immense potential across diverse applications, notably in healthcare, human-machine interfaces, and conformal neural interfaces. A core driving force is the pursuit of high-fidelity, seamless integration between electronic systems and biological tissues, enabling the long-term stable monitoring of biosignals and precise diagnosis and therapy within closed-loop configurations. The past decade has seen transformative growth in this field, yielding numerous novel conformal integration strategies. These include seminal developments such as ultra-thin epidermal electronics [1,2], conformal bioelectronics fabrication or encapsulation using viscoplastic effect [3,4], and a "drop-printing" strategy for damage-free, conformal wrapping of bioelectronic interfaces through dynamic stress release [5]. However, a fundamental trade-off in the clinical translation of bioelectronics lies between practical handleability *ex vivo* (pre-implantation) and the demand for mechanical conformability *in vivo* [6]. To realize imperceptible biointerfaces—platforms avoiding mechanical stress or chronic tissue compression—devices must be nanoscale-thin and ultrasoft. Yet, such nanofilms are fragile and difficult to manipulate during conventional microfabrication and transfer steps, impeding their clinical translation and scalability.

Now, writing in *Nature Nanotechnology*, Son, Kim and colleagues [7] report a transformable and imperceptible hydrogel-elastomer adhesive bilayer based on ionic-electronic conductive nanomembranes (THIN) that elegantly resolves the fundamental trade-off between device handleability and mechanical conformability. This work shifts the design paradigm from static mechanical matching to dynamic, stimuli-responsive mechanical decoupling.

THIN is fabricated via an orthogonal solvent spin-coating process, forming a 350-nm-thick bilayer heterostructure, composed of a 90 nm hydrophobic semiconducting elastomer (poly(2-(3,3′-bis(2-(2-(2-methoxyethoxy)ethoxy)ethoxy)-[2,2′-bithiophen]-5)yl selenophene) (P(g2T2-Se)) layer and a 260 nm hydrophilic adhesive hydrogel (catechol-conjugated alginate (Alg-CA)) layer (Figure 1a). This design leverages the dynamic mechanical response of the Alg-CA layer to resolve the conflict between device fabrication and biological application. In the dry state, a high Young's modulus of 1.35 GPa provides structural integrity, ensuring compatibility with standard microfabrication processes. Upon contact with

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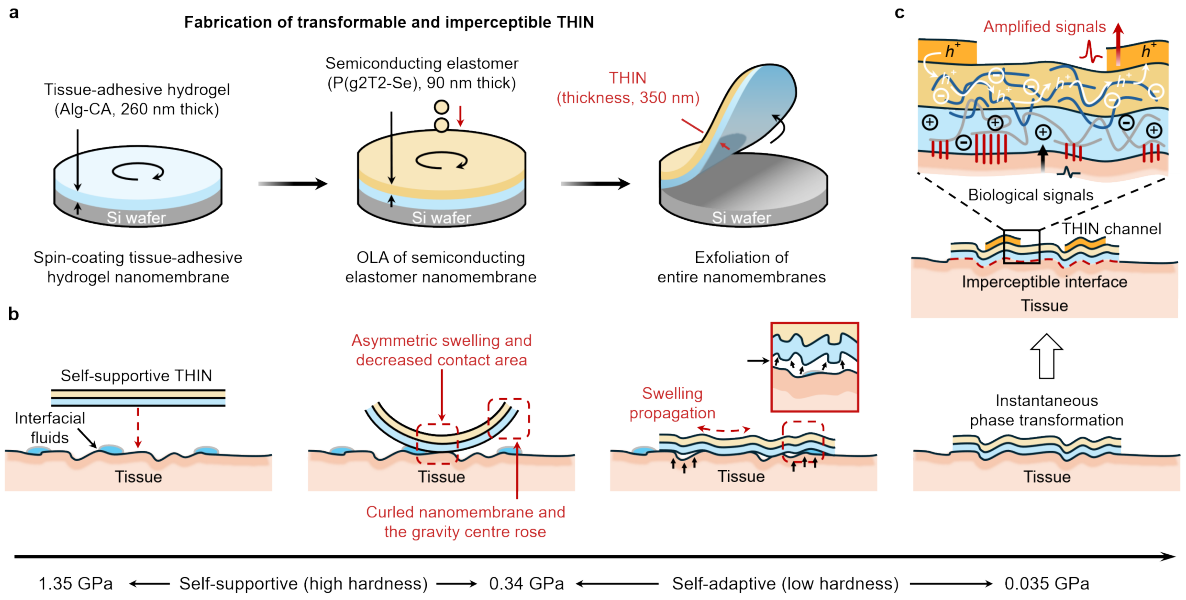


Figure 1 Fabrication, self-adaptation, and biosignal monitoring mechanisms of THIN. (a) Schematic of the fabrication process for THIN, where OLA denotes orthogonal-layered assembly. (b) Schematic of the possible mechanism of self-adaptation of THIN on a moisturized tissue. (c) Direct conformal adhesion is achieved by a thin channel and a wet tissue surface. Adapted from Ref. [7]. Copyrighy 2025, Springer Nature Limited.

physiological fluids, the hydrogel layer rapidly hydrates, triggering an instantaneous "rigid-to-soft" phase transition, where the modulus plummets to 0.035 GPa, resulting in an extremely low bending stiffness (Figure 1b). This mechanical softening enables the THIN-based device to spontaneously establish seamless conformal contact with complex tissues featuring microscale curvatures (<5 μm), effectively eliminating interfacial gaps and stress concentrations and thereby enabling nearly imperceptible integration.

Besides the mechanical design, the authors also optimized the electrical performance of the semiconducting elastomer. The authors synthesized a novel semiconducting elastomer, P(g2T2-Se), by substituting sulfur atoms in P(g2T2-T) with selenium (Se) atoms. This selenium-substitution strategy enhanced the π-π stacking between polymer chains and increased the material's crystallinity, thereby optimizing its mixed ion-electron conduction efficiency. Consequently, the organic electrochemical transistor (OECT) devices integrated with THIN achieved record-breaking performance: μC^* (μ, charge-carrier mobility; C^*, volumetric capacitance) as high as 1034 F cm^{-1} V^{-1} s^{-1}. In addition to the superior electrical properties, the nano-scale functional layers shorten the effective distance between THIN-OECT and the tissue, accelerating mixed ion-electron conduction. This synergistic effect enables high-gain amplification of weak signals directly at the bio-interface, enhancing signal acquisition accuracy and the signal-to-noise ratio (Figure 1c). Furthermore, the resulting THIN-OECT demonstrated exceptional mechanical and electrical stability. The device remained fully functional under a tensile strain of up to 200%. Electrically, it exhibited remarkable reliability: an impedance of 138.4 ± 1.53 Ω at 1 kHz, an on/off ratio >3600, and a sustained stability over 20000 cycles. The THIN-OECT demonstrates its applicability in complex biological environments through stable adhesion and signal integrity, enabling high-precision monitoring of diverse physiological signals, including epicardial electrograms (EGM), electromyograms (EMG), and electrocorticograms (ECoG).

The introduction of THIN represents a major advance in soft bioelectronics. However, several challenges

remain on the path to clinical translation. The adhesive stability of THIN in dynamic biological environments requires long-term assessment over months or years. Scaling the orthogonal solvent spin-coating process to large-scale, low-cost manufacturing while guaranteeing defect-free uniformity remains a significant engineering bottleneck. Moreover, precise integration technologies are needed to incorporate THIN into complex multifunctional circuits and wireless systems without introducing mechanical loads from rigid interconnects. Despite these hurdles, the instantaneous rigid-to-soft transition effectively addresses the conflict between handleability and conformability. It opens a clear path for the next generation of truly imperceptible bioelectronic interfaces.

Conflict of interest

The authors declare no conflict of interest.

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