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Research Highlight

A plug-and-play interface technology: boosting simple but robust stretchable device assembly

Chunya Wang

State Key Laboratory of Heavy Oil Processing, College of Carbon Neutrality Future Technology, China University of Petroleum (Beijing), Beijing 102249, China

Stretchable electronic devices are mechanically compatible with curvilinear contours and can accommodate mechanical deformations. They are emerging with great potentiality in applications that cannot be realized by conventional rigid electronics, such as wearable high-fidelity health monitoring and soft robotics [1,2]. To achieve complex functionality, stretchable devices are generally composed of three individual functional components, that is, soft modules that match the mechanical requirements, rigid modules that contain Si-based microelectronics, and encapsulation modules that provide protection for the device. These various modules are typically assembled into stretchable devices using commercial conductive pastes such as silver pastes and adhesive anisotropic conductive films (ACF). In such case, the modular connection points are the weakest parts of a stretchable device because of the mechanical mismatch between the modules and pastes, which leads to the limited robustness of the device and constrains the function of the device under mechanical deformations [3].

To solve this challenge about the weak modular connection, various attempts have been made, including the development of all-soft electronics (without rigid Si-based components) [4], and the development of paste substitutions such as liquid metal, conductive polymer/hydrogel composite [5–7]. A convenient approach for robustly connecting modules assembled in stretchable devices is still highly needed. Very recently, Xiaodong Chen and his colleagues [8] proposed an innovative interface strategy, which can reliably assemble soft, rigid and encapsulation modules into a robust stretchable electronic system in a Lego-like way without the use of pastes. The interface that they named a biphasic, nano-dispersed (BIND) interface, was prepared by thermally evaporating Au nanoparticles onto a self-adhesive stretchable thermosplastic elastomer (SEBS) to form interpenetrating nanostructure inside the SEBS matrix (the depth of the interpenetrating layer: ~90 nm), which showed the exposed Au and SEBS on the surface and interpenetrating continuous Au nanoparticles inside the matrix (Fig. 1a).

The formation of the BIND interface could be depicted by a biphasic network growth model which was built based on experimental data and molecular dynamics simulations. Such growth model describes the nanomechanics process of the complete transformation of a flux of Au atoms from the gas phase into the biphasic, nano-dispersed structure in the interface, during the thermal deposition. Such growth model can be analyzed with three stages: (1) beginning, in this stage, a flux of gas phase Au atom with high momentum was emitted from the heated source and approaching the softened SEBS substrate; (2) nucleation, in this stage the high-momentum Au atoms penetrate a few nanometers deep into the softened SEBS surface and form sub-nanometer independent nuclei below the surface; (3) growth, in this stage these Au nuclei grow into ~20 nm nanoparticles and penetrate to ~90 nm deep into the SEBS surface, and over time, eventually coalesce with each other to form interpenetrating nanostructure in the BIND interface.

Owing to the interfacial nanostructure which could simultaneously provide mechanical and electrical connection, modules with the BIND interface can form reliable and robust BIND connections in less than 10 s by simply finger pressing (Fig. 1a, right). The exposed self-adhesive SEBS in the interface provides the mechanical strength of the connection induced by the partial polymer welding, and the exposed metal nanoparticles provide the electrical conductivity of the connection, which makes the BIND connections much more robust in both mechanical and electrical aspects than paste connections. To be specific, soft–soft modules joined by the BIND interface showed 180% electrical stretchability which was nearly three times greater than the connection with commercial pastes (~45%), and 600% mechanical stretchability which was nearly ten times greater than the commercial paste connection (~60%). soft–rigid connections with the BIND interface also showed much higher electrical (~200%) and mechanical (~800%) stretchability than conventional connections via commercial pastes.

Such BIND interface can meet various connection requirements for constructing complex stretchable devices with mechanically compliant modular connections. As demonstration, they developed stretchable implantable *in vivo* neuromodulation devices with BIND connections for the stimulation and recording of subcutaneous compound muscle action potential from the peroneus longus muscle in a rat leg (Fig. 1b) and for recording the electrocorticography (ECoG) from the rat cerebral. Owing to the intimate contact between the ultrathin module and soft cortex, high-quality ECoG signals could be recorded by the as-developed stretchable implantable device, which showed that epileptic rats had larger

E-mail address: chunyawang@cup.edu.cn

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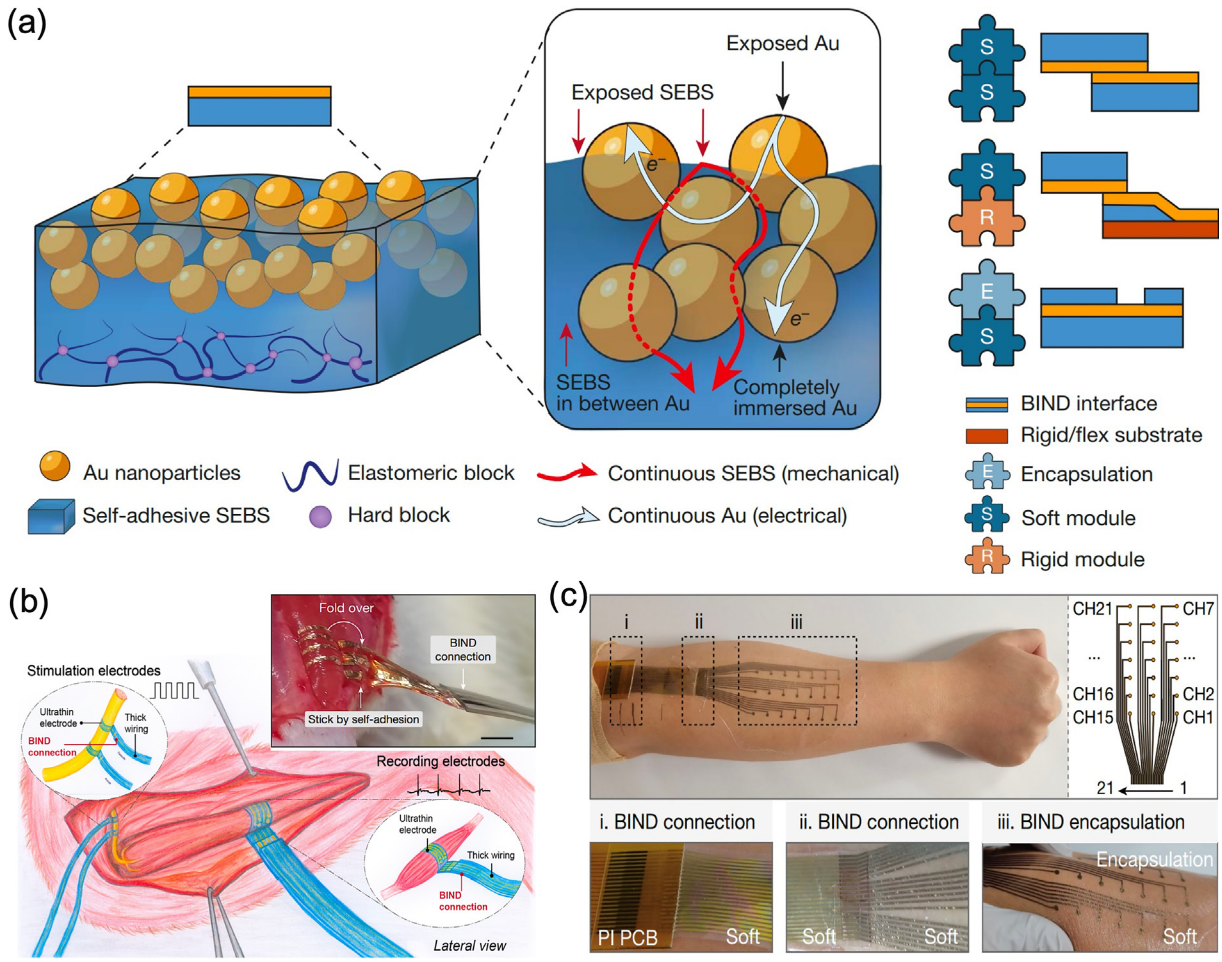

Fig. 1. (Color online) An innovative connection interface for convenient and robust assembly of stretchable electronic devices [8]. (a) Illustration of the BIND interface and the BIND connection between various modules. (b) Schematic and photograph showing the stretchable *in vivo* neuromodulation devices assembled using BIND interface for subcutaneous compound muscle action potential stimulation and recording. Scale bar, 5 mm. (c) Photograph of a 21-channel on-skin EMG electrode array attached on a human arm, and magnified view of BIND connections between rigid, soft, encapsulation modules and soft modules. Figures adapted from Ref. [8] with Copyright © 2023 Springer Nature.

amplitudes and higher power in the ECoG frequency range than healthy rats. By using plug-and-play BIND connections, they also developed a stretchable and complicated 21-channel on-skin electromyography (EMG) electrode array (Fig. 1c). This 21-channel on-skin EMG electrode can be used to map EMG signals induced by various gestures with high quality and good resistance to mechanical interference, and this on-skin electrode could functional well underwater as well as on sweaty skin after exercise. Such on-skin EMG electrode array offers promising options for on-skin human-machine interaction.

This innovative interface technology provides a simple and convenient solution to the long-standing challenge of assembling different functional modules into a stretchable hybrid device with robust electrical-interface connections, which paves the way for many applications involving wearable stretchable devices. And this interface technology makes it possible to build more-complex stretchable devices easily on demand, representing a remarkable landmark for the stretchable electronic field, and being an enlightenment for multidisciplinary researchers. Nevertheless, there is still some limitation for such interface technology. For example, the spatial resolution and electrical conductivity of the BIND connections need to be further improved considering their utilization in low-energy devices and in functions that require high resolution. And the BIND interface and the individual modules are not reusable, because the diffusion of the SEBS molecular segments between the two connected interfaces makes it very challenging to separate the binding interface without damage. Addressing these limitations needs further contribution from multidisciplinary researchers for exploration of novel materials and pioneering strategies.

Conflict of interest

The author declares that she has no conflict of interest.

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Chunya Wang received her Ph.D. degree in Chemistry from Tsinghua University in 2018. Afterwards she joined in Prof. David Kaplan's group at Tufts University, and then worked in Prof. Takao Someya's group as a JSPS fellow at the University of Tokyo. She is now an associate professor at China University of Petroleum (Beijing). Her research interest is designing natural biomaterials into functional biogels and advanced carbon materials for soft bioelectronics and flexible energy devices.