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Research Highlight

Permeable three-dimensional liquid metal integrated circuits reshaping the next generation of wearable electronics

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Wearable electronics are becoming a critical technology in the field of health monitoring. Continuous *in situ* monitoring of physiological information is of great value for preventing and treating high-incidence diseases such as cardiovascular diseases, gastrointestinal diseases, dermatological issues, and neonatal conditions [1–4]. However, most flexible wearable sensing devices inevitably need to be connected to extra acquisition equipment and integrated circuits (IC) [5], which do not adequately meet the needs for comfortable wear. Ideal flexible wearable electronics require stretchable and lightweight backend circuits, and related research is still in its early stages [6–8]. Commercial flexible printed circuit boards (FPCBs) use polyimide instead of rigid substrates to withstand limited bending but cannot be stretchable. Emerging silicon-based elastomer circuits face issues such as unstable interfaces between rigid components and stretchable substrates, and excessive device thickness due to multilayer stacking. Moreover, the above electronic systems lack permeability, making them prone to causing discomfort and skin inflammation in practical applications [9]. In contrast, the concept of permeable electronics provides a new solution to these limitations, bringing new opportunities to the field of flexible electronics.

Recently, Prof. Zheng's group and Prof. Yu's group [10] collaborated to develop a permeable, three-dimensional integrated electronic skin (P3D-eskin) based on nanofiber mat substrates and liquid metal (LM) circuits. As shown in Fig. 1a, the P3D-eskin combines high-density electronic components with stretchable poly (styrene-*block*-butadiene-*block*-styrene)-based fiber mats through LM wires and a clever design of hybrid liquid metal (hLM) solders. The integration achieves complex system-level functions, including the collection, processing, and analysis of physiological signals, and communication with mobile devices. The realization of system-level integration greatly enriches the application scenarios of wearable sensing devices.

A crucial challenge for such a system is achieving a robust electrical connection between soft, ultrastretchable LM circuits and rigid electronic chips. To address this challenge, the authors utilized two different LM inks, pristine LM and oxidized LM (oLM), to prepare an hLM solder for use as the interfacial joint, as shown in the electrical interface schematic (Fig. 1b). The hLM solder combines the wettability advantages of oLM and the stretchability advantages of LM, enabling reliable connections between pins of rigid electronic components and flexible LM circuit traces under strains up to 1500% (Fig. 1c). Furthermore, in order to improve system integration, the pristine LM is employed to form stretchable vertical interconnect accesses (VIAs). These VIAs enable circuit connections between multilayer fiber mats, achieving 3D IC designs. As proof of concept, the authors demonstrated a P3D-eskin device with LED indicators that showed stable functionality under a large strain of 550% (Fig. 1d). The ability to withstand such high strain expands the potential applications, such as the development of implantable soft robotics and biomimetic intelligent devices, which may demand extreme deformability to adapt to various environments and perform complex tasks.

While reproducing the functions of conventional IC, the P3D-eskin also exhibits high long-term biocompatibility, attributed to its excellent air and moisture permeability (Fig. 1e). The air and moisture permeability of the P3D-eskin are up to 177 mm s^{-1} and 676 g m^{-2} d^{-1}, respectively, which are 3 times and 22 times higher than medical wound dressings (Fig. 1f). As a result, the P3D-eskin did not induce any skin inflammation during a week-long on-skin attachment test. In contrast, the control group, a PDMS-based stretchable electronic skin, exhibited low air and moisture permeability (<50 g m^{-2} d^{-1}), leading to skin erythema quickly.

Ensuring excellent air and moisture permeability, the P3D-eskin also demonstrates stable encapsulation and waterproofness. On the one hand, good waterproofness allows the device to function normally even when immersed in water and artificial sweat. In this way, the wearers of P3D-eskin do not have to worry about excessive sweating during exercise affecting signal acquisition. On the other hand, the reliable encapsulation of P3D-eskin ensures that LM circuits do not leak even under 50 kPa pressure, leaving no LM residue on the skin after testing. These characteristics lay a solid foundation for the practical application of P3D-eskin system.

Based on the P3D-eskin platform, combined with a Bluetooth Low Energy (BLE) built-in MCU, the authors developed a wireless transcutaneous electrostimulation and electrophysiological sensing system, as shown in Fig. 1g. The system is capable of communicating with mobile devices within a 15 m range. Using the P3D-eskin applying electrostimulations for a rat's biceps femoris muscle, the real-time electromyography (EMG) signals

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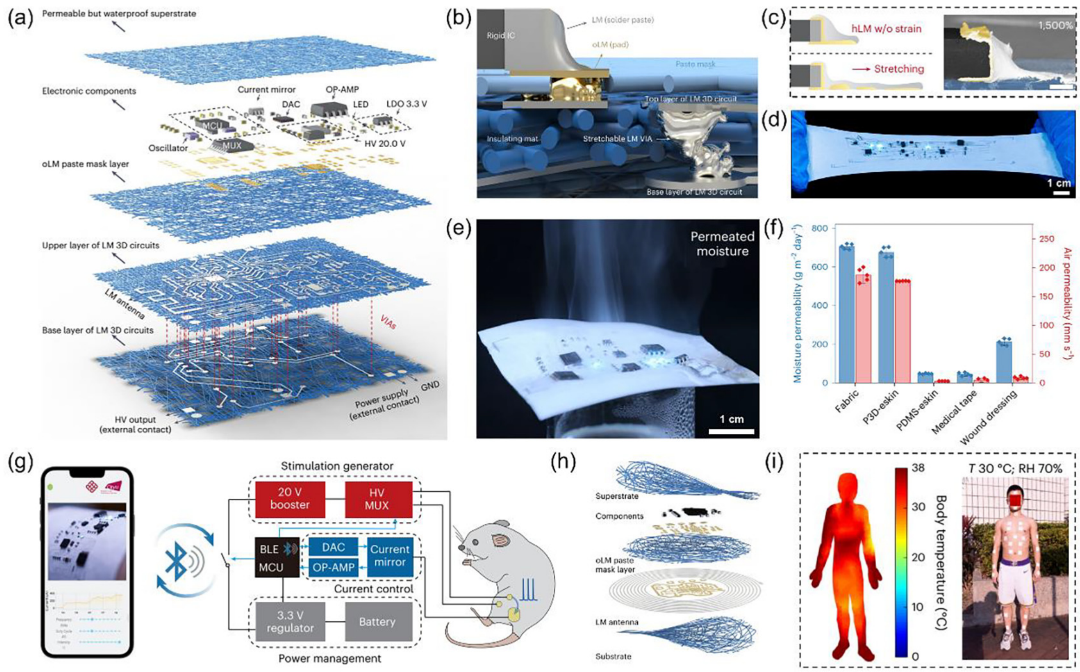

Fig. 1. (Color online) Wearable P3D-eskin system [10]. (a) Exploded schematic of P3D-eskin. LM microelectrodes are used to connect the soft fiber mat substrate and the rigid electronic components. VIAs provide electrical connections between layers, highlighted by dashed lines. MCU, microcontroller unit. MUX, multiplexer. DAC, digital–analogue converter. OP-AMP, operational amplifier. LED, light-emitting diode. HV, high-voltage. LDO, low-dropout regulator. (b) Schematic of the 3D electrical connection and interfaces. The oLM serves as the contact pads, while LM serves as the in-plane interconnects, VIAs and additional contact paste. (c) Schematic and SEM image showing the electrical interfaces of hLM solder. Scale bars, 200 μm. (d) Digital image demonstrating the P3D-eskin maintaining stable electrical performance when stretched by 550%. (e) Digital image showing the permeability of the P3D-eskin. (f) Air and moisture permeability comparison of P3D-eskin, PDMS-eskin, wound dressing, medical tape and cotton fabric. PDMS, polydimethylsiloxane. (g) Block diagram of the wireless electrostimulation and sensing system with a mobile app. The system delivers electrical stimulations to a rat's bicep femoris and records the corresponding electromyography signals. BLE, Bluetooth Low Energy. (h) Exploded schematic of battery-free P3D-eskins. The system included a stretchable LM antenna and integrated microcircuits for near-field communication. (i) Thermal imagery showing body temperature distribution on an adult using 40 battery-free P3D-eskin arrays. Reprinted with permission from Ref. [10], Copyright © 2024 Springer Nature.

from adjacent areas could be recorded. The EMG signals responded to stimulation currents with different frequencies, matching well with the stimulation input, which fully verifies the system-level integration capabilities of the wireless P3D-eskin.

Furthermore, the authors further constructed a battery-free P3D-eskin system using near-field communication (NFC) technology. A representative device structure is shown in Fig. 1h. The patterned LM antenna, which replaced the conventional copper coils, exhibited good stability in quality factor, phase, and impedance under various strain conditions and working distances. Based on this battery-free design, the authors fabricated a lightweight distributed temperature-sensing P3D-eskin array for continuously recording the temperature of different body positions during daily activities (Fig. 1i). Compared with PDMS-eskin, the P3D-eskin had less thermal impact and reflected more realistic skin situations, with smaller thermal artifacts and less signal fluctuation.

In summary, the P3D-eskin represents a breakthrough in the structural design and functional integration of wearable electronics, showing significant potential in personalized health monitoring. The research groups led by Prof. Zheng and Prof. Yu have successfully broken through the limitations of traditional wearable devices in terms of comfort and functionality by developing the P3D-eskin system with excellent permeability and stable wireless communication capabilities. Through high-density 3D integration of electronic components and the ingenious design of hLM solder, the stretchable P3D-eskin achieves complex functions of commercial FPCBs. The prepared P3D-eskin system showcases high performance and stability in electrostimulation and electrophysiological sensing, demonstrating its broad application prospects in the field of individualized medicine. Furthermore, the combination of P3D-eskin with NFC technology sparks convenient-to-use, thereby expanding the range of application scenarios. The permeable, soft, and powerful electronic skin not only provides a new solution for daily health management but also points the way for the future development of smart wearable devices.

It is worth noting that there remains room for further research into permeable IC. The current complexity of the P3D-eskin manufacturing process may hinder its scalability. As the field of permeable electronics evolves, automated manufacturing technologies, which can improve both process reliability and production efficiency, may be realized. Moreover, while this study demonstrates the stability of the P3D-eskin in daily application, future studies need to explore the performance of these integrated devices in harsh environments, such as high humidity and extreme temperatures. Ensuring the robustness and reliability of the device under various conditions will be crucial for driving this technology towards practical applications. With ongoing technological advancements, we anticipate the P3D-eskin platform to bring enhanced well-being to human health management and smart living.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

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