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Planar to shape-adaptive electronics: Based on liquid metal circuits printed on thermoplastic films

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With the rapid development of intelligent electronics technology, electronic devices are gradually evolving from traditional rigid structures towards flexibility, stretchability, and three-dimensional (3D) structures. These are widely used in wearable health monitoring, biomedical electronics, and intelligent sensing, capable of recording physiological signals such as body temperature, blood pressure, pulse, strain, and infrared radiation in real time. In practical applications, these electronic systems typically need to achieve close contact with complex 3D curved surfaces. For example, wearable medical devices need to integrate sensing and control circuits on flexible structures and be stably attached to the human skin surface. Therefore, electronic devices not only need to possess good flexibility but also maintain stable electrical performance and good mechanical compatibility in complex curved surface environments.

The mainstream microelectronic manufacturing technology is still based on traditional planar micromachining technology. These technologies have achieved great success in the field of integrated circuits However, this technology is prone to stress concentration when processing on irregular 3D curved surfaces, which can lead to conductive layer fracture and device failure.[1] To solve this problem, researchers have proposed various flexible electronic and stretchable electronic technologies.

The first is direct 3D molding (such as 3D printing, laser direct writing, and in-situ growth). This method can directly construct 3D functional structures, but it relies on special high-end equipment and the process is complex. It is only applicable to a few printable or induced growth material systems, and the ink rheological properties make it difficult to guarantee the adhesion and line uniformity on complex curved surfaces.[2] The second is a planar transfer/deformation scheme (including inkjet printing, transfer printing, etc.). This method is compatible with planar processes and is easy to batch, but the conformal capability is insufficient. Inkjet printing is prone to uneven spreading and difficult to control the morphology on curved surfaces; transfer printing is prone to bubble wrinkles and alignment deviations, and the cost is high; the film deformation is limited by the material's fracture elongation rate and is only applicable to small curvature curved surfaces, which is difficult to adapt to high steep irregular curved surfaces.

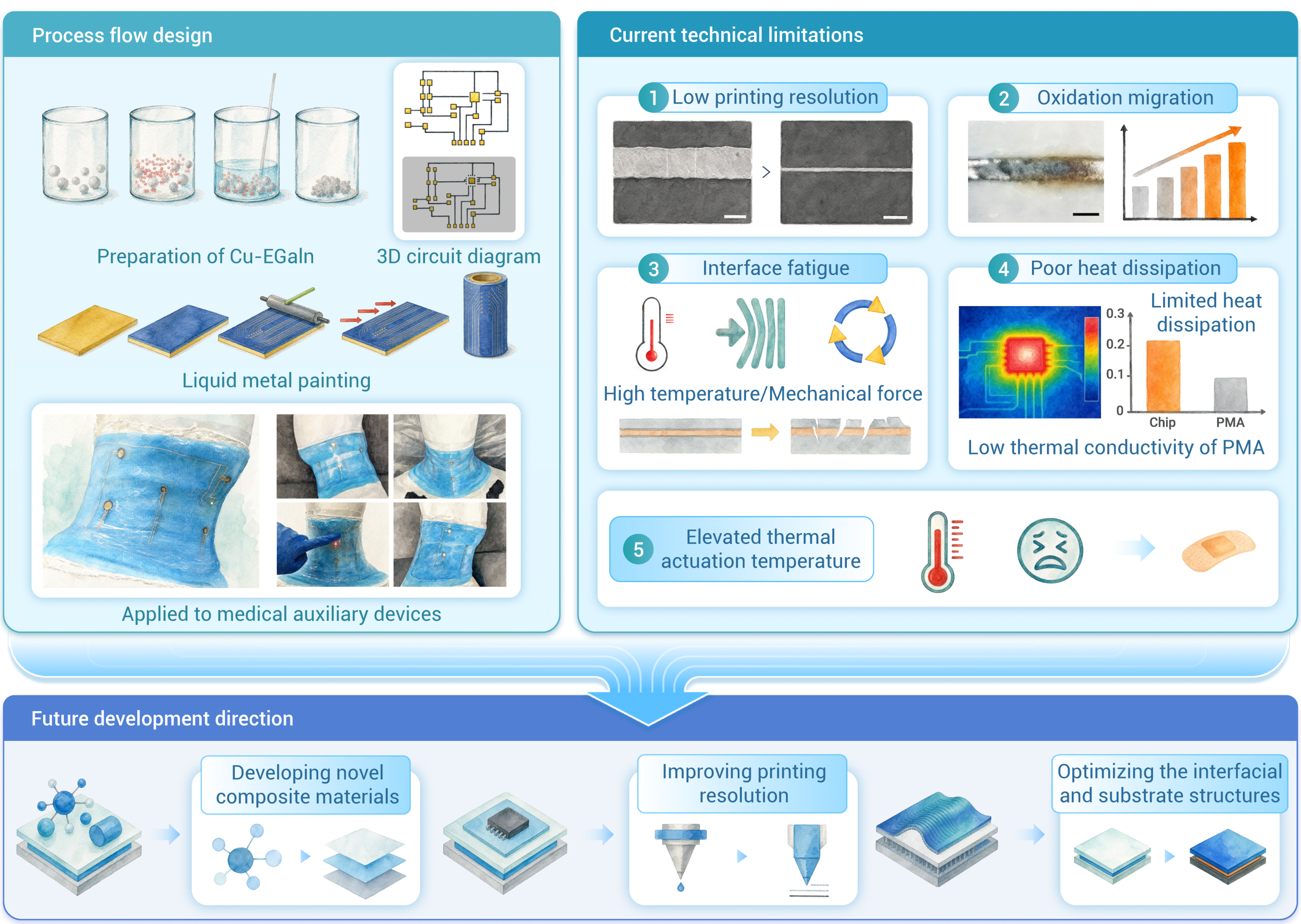

Figure 1. The process flow of shape-adaptive electronic systems, challenges and future development directions.

To address the aforementioned issues, a novel "2D manufacturing to 3D deformation" strategy has emerged. This method inherits the fabrication precision, material compatibility, and batch production advantages of planar processes, while eliminating reliance on specialized functional inks and customized equipment. It is compatible with high-performance material systems used in traditional microelectronic processes, offering significant efficiency and cost advantages. Simultaneously, controllable 3D deformation enables conformal adaptation to large deformation amounts and complex curved surfaces, effectively reducing stress concentration and device failure risks during the bonding process. In multi-layer 3D integration scenarios, this strategy theoretically allows for the interconnection of multi-layer circuits during the planar fabrication stage, followed by overall deformation, achieving superior processing efficiency and alignment accuracy compared to point-by-point molding techniques. However, significant limitations remain: large deformations can easily lead to interlayer delamination and interconnect breakage, and long-term electrical reliability needs further verification; alignment deviations accumulate with the number of stacked layers, making it difficult to meet the demands of high-density integration. This has become a core breakthrough direction for engineering applications.

CONFORMAL ELECTRONICS BASED ON HEAT-SHRINKABLE LIQUID METAL CIRCUITS

Based on the above approach, Jiang et al. proposed a solution: printing liquid metal circuits on thermally shrinkable thermoplastic films and using thermally driven shrinkage to transform 2D circuits into 3D structures, thereby constructing shape-adaptive electronic systems.[3] This method prints semi-liquid metal circuits with copper-doped eutectic gallium-indium alloy (Cu-EGaIn) on pre-stretched thermoplastic films. After heating to the glass transition temperature, the film shrinks, causing the circuit to deform and fit the 3D curved surface (Figure 1). By adding polymethyl methacrylate (PMA), precise transfer is achieved. This composite conductor has the characteristics of electrical and thermal conductivity, stretchability, and self-healing. Under large deformation, its structural and electrical stability is better than that of traditional liquid metals.[4]

Meanwhile, a mechanical model is established via finite element simulation to predict thermally induced shrinkage deformation. Figure 1 in the Jiang's paper shows that by setting the film shrinkage stress through the stiffness equation, the node displacement value can be determined to predict the film shrinkage value. The planar circuit pattern can be inversely designed according to the target 3D structure, thereby realizing controllable construction of 3D electronic architectures. Experimental results show that the fabricated shape-adaptive electronic device maintains a stable structure and acceptable resistance change after 5000 bending and torsional cycles, with a resistance increase of approximately 4% and a resistance value of less than 10 Ω. They can effectively adapt to various complex curved surfaces, providing a reliable and feasible technical route for constructing shape-adaptive flexible electronic systems.

CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Despite the promising application prospects of liquid metal circuits based on heat-shrinkable films, their practical implementation still faces numerous critical challenges (Figure 1). First, the process is limited by equipment performance, resulting in limited printing accuracy and resolution. It can only achieve linewidth preparation at the 100 μm level, which is difficult to meet the processing requirements of high-precision flexible electronic devices. In contrast, advanced preparation technologies such as ultrasonic crushing can achieve high-precision linewidth processing of 0.1–10 μm, with significant accuracy advantages. Therefore, by optimizing the process scheme and introducing advanced processing equipment and technologies to improve printing resolution, the accuracy limitation can be effectively overcome, greatly expanding the application scenarios and scope of this technology. Second, liquid metal is prone to oxidation and migration after long-term use, leading to increased circuit resistance. This is because liquid metal generates an ultrathin oxide layer (Ga_2O_3) in the air to stabilize the surface and support precision molding. However, solid films will increase interfacial flow resistance, weaken the device's real-time reconstruction capability, increase contact internal resistance, and weaken its high conductivity, high thermal conductivity, and high fluidity. Temperature gradients and mechanical stress will also cause metal migration, resulting in uneven distribution of conductive channels, reduction of effective conductive area, and decreased conductivity.[5] This problem can be addressed by controlling the oxide layer thickness through adjusting alloy composition, reaction temperature, and applying mechanical stirring, ultrasonic mixing, or electrical stimulation. Damaged oxide layers can also be removed using acid-base treatment or mechanical methods to improve interface compatibility. Third, the circuit relies on the adhesive layer to bond with the substrate, but the high fluidity and surface tension of liquid metal result in weak adhesion on some flexible substrates. This limits the forming accuracy of the printed pattern and weakens the interfacial bonding with the polymer substrate. Long-term thermal cycling and repeated mechanical deformation can easily lead to interfacial fatigue and adhesion degradation, reducing circuit stability. Finally, PMA has low thermal conductivity, forming a high-resistance interface with the liquid metal oxide layer. These increases contact resistance and hinders Joule heat dissipation, leading to excessively high device temperature. Simultaneously, its high glass transition temperature results in a high thermal drive temperature, which can cause discomfort upon skin contact, requiring improvements to enhance wearability safety. Further optimization of the interface and substrate structure is needed to promote the practical application of this technology.

OUTLOOK

In summary, shape-adaptive electronics based on heat-shrinkable films and liquid metal circuits offers a novel solution for integrating electronic systems with complex 3D structures. The transformation from planar circuits to 3D structures can be achieved through a simple thermally driven process, providing important insights for the development of flexible electronics. This direction still offers significant research potential, with future research focusing on specific frontiers such as high-resolution pattern design, high-stability, oxidation-resistant liquid metal composite systems, enhanced metal-substrate interface adhesion, and the development of low-temperature controllable heat-shrinkable functional substrates. Breakthroughs in these areas will significantly improve device performance and process compatibility, potentially propelling shape-adaptive electronics from concept to practical application in wearable devices, intelligent robots, and biomedical implants.

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AUTHOR CONTRIBUTIONS

This project was jointly conceived by Z.L. and X.W. Z.L. was mainly responsible for writing, W.W. was responsible for checking and revising, S.L. was responsible for proofreading and information verification, X.W. was in charge of the presentation and direction setting, and H.A. was responsible for providing financial and technical support. All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.