Flexible hybrid electronics: Enabling integration techniques and applications

WU Hao, HUANG YongAn & YIN ZhouPing*

Flexible Electronics Research Center, State Key Laboratory of Digital Manufacturing Equipment and Technology, School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

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1 Introduction

Conventional electronic systems are composed of rigid materials and components. Due to the high modulus and hardness, they will fail to function when applied in large-deformation and dynamic conditions. Recognized as a promising technology to address these issues, flexible electronics have received increasing attention in the past few years [1–5]. Numbers of novel flexible sensors with superior stretchability and softness have been prepared and widely developed for the applications of health monitoring (such as eye therapies [6] and dysphagia [7]) and human-machine interfaces (HMI) (such as prosthetic control [8] and gesture recognition [9]). Compared with traditional rigid electronics, flexible on-skin electronics is a promising strategy for improving signal quality and wearable comfort due to their matching mechanical properties with human skin [10,11]. Besides, the stretchability [12] and durability [13] of flexible devices could be further improved by the use of advanced materials, structures, and fabrication processes.

Although a large number of sensors with high stretchability have been developed for new applications, rigid components are still highly needed for the overall electronic system to function. For instance, rigid integrated circuits (ICs) have much higher performances than their soft counterparts and are essential for data processing and transmission. Therefore, among the various approaches toward the goal of functional flexible electronic systems, flexible hybrid electronics (FHE) have been regarded as a promising alternative in recent years, which simultaneously possesses the desirable flexibility and enables the integration of rigid components for functionality [14–17]. Beyond increasing...
wearability compared with the traditional rigid system, the rigid components in FHE systems (FHES) exhibit low strain even under stretching and bending deformations, enabling sensing modalities more closely related to human physiology [18,19]. Therefore, flexible circuit interconnection with excellent stretchability and conductivity presents to be the prime issue to be solved [20,21]. Besides, with the increasing demand for multifunction and minimization of integration systems, it is particularly important to fulfill three-dimensional (3D) circuit interconnects within multilayer FHE [22]. In addition, when the rigid IC chips are mounted onto flexible substrates, it is also a critical issue to improve the bonding strength and reduce the stress concentration caused by modulus mismatch [23]. Those are the key enabling technologies to realize the flexible hybrid integration of the electronic system.

This paper presents a review on these enabling integration techniques for FHE and the wearable applications of FHE. We first introduce the flexible circuit interconnects enabled by advanced materials and structural designs. Focusing on the circuit interconnects in multilayer systems, we provide a detailed description of the strategies of interlayer 3D circuit interconnects. Then, the methods for improving the robust bonding and stability between flexible substrates and rigid IC chips, as well as the related progress of stress-isolation structures, are analyzed. Moreover, the applications of novel FHES in health monitoring and HMI are discussed. Finally, the future challenges and opportunities of this emerging field are also discussed.

2 Flexible and stretchable interconnects

The traditional method to integrate FHE was based on the polyimide (PI) substrate, and conductive metal material is directly deposited on PI for circuit interconnect [24,25]. Although such structural design possesses good stability, the high modulus of PI substrate is not sufficient to accommodate mechanical deformations of bending or stretching [26]. To further improve the flexibility and applicability of FHE, researchers have used different soft materials with lower modulus and high stretchability as the substrate, such as polydimethylsiloxane (PDMS) [27], silbione [28], ecoflex [29], and hydrogels [30,31]. These FHE generally had low thickness and bending stiffnesses, and their elastic moduli matched to the epidermis, thus could be laminated onto the skin and maintained conformal contact based on van der Waals force [32].

Owing to the excellent conductivity of traditional metal materials (such as gold, silver, and copper), many efforts have been devoted to integrating metal on soft substrates. For example, Rogers and coworkers [27] invented an epidermal electronic system enabled by serpentine gold wires that were integrated on the polyester substrate in Figure 1(a). When the whole serpentine structure was stretched by 30%, the maximum principal strain of the gold material was less than 0.2%, and the whole system showed a purely elastic response. Benefiting from the excellent stretchability, the as-fabricated device could conform to the skin and accommodate to typical skin deformation (~20%). In addition, the same research team designed a second-order fractal structure with enhanced tensile capacity up to 147% in Figure 1(b) [33]. Nevertheless, the above mentioned two plane structures exhibited limited stretchability, and the rise of 3D structure has offered a promising alternative to solve this problem. As demonstrated in Figure 1(c), Rogers and coworkers [28] developed a 3D helical gold wire with outstanding elasticity. The flat serpentine gold wire was first transferred to the pre-stretched Ecoflex substrate, and only several individual points of the gold wire were bonded with the substrate. After releasing the pre-strain of the substrate, the free part of the gold wire was warped, and finally formed a 3D helical structure. The maximum elastic stretchability of the 3D gold wire could reach 350%.

Besides, the use of conductive composite material (such as polymer matrix and conductive fillers involving carbon nano tubes, graphene, metal nanowires, metal nanoparticles, and metal flakes) is another appropriate option for achieving stretchable circuit interconnects on soft substrates. These conductive fillers are in contact with each other in that matrix to form conductive pathways [34], as illustrated in Figure 1(d). Although conductive composite materials show lower conductivity compared with pure metal, its unique elasticity and stretchability are suitable for more complicated situations. For instance, Li and coworkers [34] used hydride-terminated PDMS (H-PDMS) as matrix and silver flakes as conductive fillers. At the same time, H-PDMS was used as the reducing agent to roughen the silver flakes and decrease the interparticle distance, making the conductivity of the material reach 15100 S cm⁻¹, as displayed in Figure 1(e). To further enhance the conductivity, our group used potassium iodide (KI) to treat silver flakes to form nanoparticles on their surfaces [35], as shown in Figure 1(f). Moreover, these silver flakes could be mixed with many kinds of polymer matrix (such as Ecoflex 00-30, Sylgard 184, Silbione LSR 4305, isobutylene-isoprene rubber, styrene butadiene rubber, nitrile rubber, and butadiene rubber), and all of them could achieve very low resistivity, which reflected the universality and great application potential of this material. Besides, Matsubisa et al. [36] mixed silver flakes with fluorine rubbers and surfactants to form silver nanoparticles in situ, as demonstrated in Figure 1(g). The conductivity of the obtained printable composite was 6168 S cm⁻¹ and 935 S cm⁻¹ before and after being stretched to 400%, respectively. Moreover, Choi et al. [37] deposited a gold layer on the surface of silver nanowires to enhance the bio-
compatibility, and the as-fabricated material showed high conductivity of 72,600 S cm\(^{-1}\) and stretchability of 840\%, as shown in Figure 1(h).

In addition to the above two kinds of materials, liquid metal is also a promising candidate with excellent conductivity and plasticity. Kim et al. [38] fabricated PDMS microchannel and filled it with liquid gallium-indium alloy as conductive stretchable interconnection. The bonding surface of the microchannel and liquid alloy was deposited with gold as a wetting layer, which rendered the filling of liquid...
alloy more uniform (Figure 1(i)). The interconnection microchannel showed excellent stability as the resistance change was only 0.24 Ω when stretched by 100%. Besides, Takakuwa et al. [39] have invented the water vapor plasma-assisted bonding (WVPAB) method without the requirement for the additional adhesion layer, resulting in an overall thickness of only 4 μm, as shown in Figure 1(j). Without the adhesion layer, the films bonded by WVPAB method maintained maximum flexibility, and the bending radius could be as low as 0.5 mm, which was superior to the films bonded by the anisotropic conductive film adhesive (ACF) tape, as displayed in Figure 1(j). At the same time, WVPAB could bond rough gold electrodes at room temperature and atmospheric pressure while not influencing the polymer substrate, thus having the potential to become a general-purpose integration technology.

3 Flexible and stretchable 3D interconnects

More recently, flexible and stretchable electronics in 3D forms have attracted wide attention to high-density integration and advanced functionalities. This strategy offers a solution to accommodate state-of-the-art electronic components and fully functions in a stand-alone 3D stretchable system.

Huang et al. [16] reported a 3D framework for integrating a high-density multilayered stretchable system with interlayer electrical interconnections. Figure 2(a) demonstrates a stretchable four-layer structure, where each layer employed an “island-bridge” design. Each “island” hosted different electronics, such as electrodes, sensors, and active or passive components. The distributed components were interconnected in-plane by “bridges”—bilayers of copper/polyimide (Cu/PI) thin films in a serpentine pattern in response to matrix deformation. Besides, vertical interconnect accesses (VIAs) were introduced and formed by controlled laser ablation and sliding to enable reliable 3D connection of different layers (Figure 2(b)). The VIAs were enabled by conductive fillings in craters in silicone, and their size controlled by the laser could be as small as 45 μm in diameter and 100 μm in depth to minimize stress localization. As a result, the fabricated system achieved well mechanical robustness and stretchability of 50%, 35%, and 20% in the vertical, horizontal, and equal-biaxial directions, respectively. Based on the 3D framework, a four-layer stretchable HMI testbed was developed to wireless record body information (such as temperature, body motion, and electrophysiological signals) when mounted on the skin, presenting great potential in HMIs and intelligent controls.

Zhao et al. [40] fabricated an on-skin FHES with multifunctional sensing functions. As shown in Figure 2(c), the multilayer FHES consisted mainly of conductive components and a wireless flexible printed circuit board (FPCB) for sensing, processing, and transmission. Each layer had individual interconnects fabricated by stencil printing using stretchable electrically conductive composite (ECC) on the surface of PDMS substrate. The high-density electrical integration of the multilayer structures was enabled by 3D conductive via-holes, which were formed by laser-cutting

Figure 2 Flexible and stretchable 3D interconnects. (a) Exploded schematics of the 3D integrated system. (b) Cross-sectional electron dispersive spectroscopy mapping image of through VIAs created in silicon elastomers. Reproduced with permission [16]. Copyright © 2018, Nature Publishing Group. (c) Photographs showing the surface (top) and side (bottom) view of the FHES. (d) SEM images of the conductive via-holes before (top left) and after (bottom left) filled with ECC. (e) The resistance changes of the via-holes with different radii under tensile strain. Reproduced with permission [40]. Copyright © 2021, IEEE. (f) Schematic diagram of the microLED array with liquid metal-based 3D interconnects. Reproduced with permission [41]. Copyright © 2019, AAAS.
PDMS and filled with ECC materials (Figure 2(d)). The resistance changes of the conductive via-holes with different radii (60 μm, 80 μm, 100 μm) were investigated under 10% tensile strain for 100 cycles. Figure 2(e) displays that the smaller the radius, the higher the resistance. The resistance would increase under strain, and drop to the initial value after the force was released. Benefiting from the unique structural design and the selection of stretchable materials, the FHES could conform contact with human skin and simultaneously extract electrocardiogram (ECG) and acceleration signals under various conditions, transmit and display them on the mobile phone in real-time.

Besides solid materials, liquid metals have been used to construct 3D interconnects with high resolution and high stretchability by Park et al. [41]. A minimum linewidth of 1.9 μm and the 3D reconfiguration of eutectic gallium-indium alloy (EGaIn) have been realized through a direct printing method. The preprinted EGaIn line could be lifted from the substrate with the nozzle tip, and then relocated to another desired location to reconfigure into various free-standing 3D structures. This technique made it possible to electrically interconnect different contact pads or two heterogeneous electronics with different steps in height. As illustrated in Figure 2(f), a 4 × 4 flexible microLED array was realized by the transverse and longitudinal interconnects of EGaIn, and the 3D bridges of EGaIn at intersections were realized by the transverse and longitudinal interconnects of EGaIn, and the 3D bridges of EGaIn at intersections were built to avoid short-circuiting. Herein, each microLED could operate independently by biasing specific row and column interconnects. Unlike the traditional method of applying multilayer structures and processes, free-standing 3D interconnects based on reconfigurable liquid metal facilitated the in-plane construction of diverse geometries and eliminated the additional electrical interconnects between layers.

4 IC bonding on soft substrate

With the development of electronic packaging technology, many achievements have been made in IC bonding on hard substrates. In order to improve the flexibility and durability of the FHE and enable it to conform to interface, performing IC bonding on soft substrates has become a research hotspot in recent years.

Xu and coworkers [42] fabricated a soft, stretchable on-skin wireless electronic system for continuous physiological monitoring, as shown in Figure 3(a). The circuit chips were successfully bonded to the flexible conductive interconnect network by using low temperature solder bonding technology. The low temperature solder Sn42Bi57.6Ag0.4 was applied in the screen-printing process and could well wet the connection surface. A robust bonding interface was formed after tinning the interface between the chip pins and the interconnect network. With the stability between electrical components, interconnection network, and substrate, the system could withstand a uniaxial tensile strain of 30% and a torsion of ~75°. The excellent mechanical design in the layouts of the chips and the geometries of the serpentine shapes provided the system with an ultralow modulus, which was only slightly larger (3%–5%) than the intrinsic value of the bare elastic material substrate. Xu and coworkers [16] reported a framework for engineering 3D integrated stretchable electronics. A four-layer designed 3D stretchable system for HMI was constructed layer-by-layer as depicted in Figure 3(b). During the controlled soldering process, the solder paste Sn42Bi57.6Ag0.4 was screen-printed onto Cu pads with a shadow mask, and the robust bonding between chips and the interconnects could be formed with a reflow temperature of ~150°C. Benefiting from the strong bonding, no mechanical failure could be observed before the serpentine interconnect broke at a tensile strain of 138%.

Traditional silicon-based IC chips hold various inherent advantages in signal processing and transmission, such as high computing speed, low power consumption, and latency, which are suitable for integration with flexible materials to construct on-skin electronic systems. However, the fabrication process of the current integration scheme is complicated and cannot guarantee the high-density integration of electronic components. In order to overcome these shortcomings, Zhao et al. [40] reported a flexible hybrid integration scheme and fabricated an on-skin flexible hybrid electronic system for collecting ECG and acceleration data, as illustrated in Figure 3(c). For integrating discrete electronic components and rigid IC chips on stretchable substrates without limiting the stretchability of the system, a type of silicone-micro silver flakes based ECC was chosen for preparing stretchable interconnects and bonding chips with PDMS substrates. To enhance the bonding effect between the chip pins and ECC pads, trimethoxyallylsilane (TAS) solution was used to treat the chip pins. As a result, the subsequent die shear test proved that the shearing force of the treated chip was about twice that of the untreated chip, demonstrating the significant enhanced effect of TAS solution on the bonding strength. Hong and coworkers [43] fabricated a skin-like soft driving system for the implementation of fully soft robot. By using the mask-free and continuous fully printable surface-mountable device (SMD) assembly technology, they mounted numerous IC components on soft substrates and built complex soft networks successfully, as presented in Figure 3(d). In this soft system, Ag was used to prepare multilayer stretchable interconnects and define pad layouts by an inkjet-printing process. Besides, Ag epoxy was printed onto the Ag pads to form electrical contacts between contact pads and SMDs, ensuring stable bonding between SMDs and soft substrates.

In recent years, stretchable electronics have been developed towards high-resolution ICs. For instance, Jeong and
coworkers [44] fabricated a stretchable anisotropic conductive film (S-ACF) that could form strong covalent bonds at the contact interfaces at the temperature of 80°C, as demonstrated in Figure 3(e). Au/Ni-coated polystyrene conductive microparticles (MPs) with a diameter of 20 μm were periodically and precisely embedded in the thermoplastic polystyrene-block-poly(ethylene-ran-butylene)-block-poly-styrene-graft-maleic anhydride (SEBS-g-MA) film, assuring the fine pitch capability (1200 μm² for a bump and 52.5 μm for a circuit line) and a low contact resistance (0.19 Ω per 0.25 mm²). The S-ACF showed excellent electrical stability when used in the stretchable-stretchable circuit pair, and there was no current variation under $\varepsilon = 80\%$.

5 Stress isolation structures

The inherent hard electronics (such as voltage regulating components and data transmission) may significantly affect the reliability of the overall FHES because of the modulus mismatch with soft substrate or component. To solve this challenge, stress isolation structures are essential to limit strain on rigid components during large deformation and thus enhance system reliability. Recently, researchers have made...
substantial contributions to protect the IC components through island bridge structures, fluidic cavities, and localized high hardness substrates.

Rogers and coworkers [45] also fabricated the stress-separating design with island-bridge structure. As shown in Figure 4(a-i), the rigid electronics were distributed in small localized raised regions (i.e., islands), and electrical or mechanical interconnects (i.e., bridges) were distributed by narrow deformable connections in trenches. Figure 4(a-ii) clearly shows that stretching (in this case, overall applied strain of 20%) induced dimensional changes at the top surfaces of the islands (∼0.4%) and trenches (∼123%). The rigid island could isolate regional strains under the conditions of mechanical deformation, ensuring that rigid electronics mounted on the surfaces of the islands would not experience destructive extreme stress upon mechanical deformation. In addition, the bridge structure could also enable the reliable connection and maintain the functionalities of the hybrid system under large deformations.

The high Young’s modulus may lead to the easy separation of the rigid electronics on stretchable substrates. As a further development of the island bridge structure, by designing strain separation islands for rigid structures, Zhao et al. [40] achieved the electronics island structure of low strain even under large deformations, which ensured the stability of the connection during stretching. Hong and coworkers [43] fabricated an epoxy contact pad as the localized rigid island. As shown in Figure 4(b), the contact pad layout of epoxy architectures effectively mitigated the local strain of electronics. The printed Ag epoxy and epoxy on biaxially pre-strained PDMS formed a rigid contact pad, and the electronics were placed onto the rigid island of epoxy to isolate the strain. The pre-strained PDMS released the tension and formed 2D folds to achieve desired stretchability (stretchable level ~30%). In summary, silicone with higher modulus or the contact pad layout of epoxy are often used as strain isolation structures and to protect electronic parts [46].

Compared with the island bridge structure, the preparation process of the island bridge structure is complicated, and the surface is a non-planar structure. On the contrary, the local high modulus protection structure only needs to be filled with high modulus material (e.g., silicone or epoxy) locally in the electronic components and can achieve strain isolation and ensure the component surface flatness.

Rogers and coworkers [47] developed the liquid cavity structure to reduce local strain and protect electronic com-

![Image]

Figure 4 Schematic strain separation structures for protection of flexible hybrid ICs. (a) Schematic illustrations of steps in the fabrication of stretchable island-bridge structure (i), and cross-sectional optical microscopy images (upper) and FEM (lower) of a PDMS slab of island-bridge structure in relaxed and stretched states (ii). Reproduced with permission [45]. Copyright@2011, WILEY-VCH. (b) Exploded view schematic illustrate (upper) and FEA (lower) of a unit structure of the assembled device (i), and optical image of the assembled device protected by the coplanar printed epoxy architectures (ii). Reproduced with permission [43]. Copyright@2018, AAAS. (c) Schematic illustrations of a microfluidic channel structure with a device. Liquid-filled cavity with a device mounted on the skin and its collapsed state under a stretching deformation (i). Reproduced with permission [47]. Copyright@2016, WILEY-VCH. Schematic illustrations of the wireless epidermal electronic system with the microfluidic channel structure (ii), and the image of the electronic systems stretched in the horizontal direction (iii). Reproduced with permission [48]. Copyright@2019, AAAS.
ponents, as shown in Figure 4(c-i). A liquid cavity filled with ionic liquid inside a flexible elastomer shell was used as a stress separation structure, which was set between the lower flexible object and the upper electronic component. The liquid-filled cavity could reduce stress during skin deformations and provide an excellent level of strain isolation, preventing the delamination of the device and the substrate. In addition, this novel design offered superior compatibility and ensured a perfect fit between the electronics and the natural movement of the body. As shown in Figure 4(c-ii), a microfluidic chamber filled with a nontoxic ionic liquid between the electronics and the lower encapsulation layer provided mechanical isolation between the interconnected components and the skin. When the ECG EES was stretched uniaxially to 16% (Figure 4(c-iii)), the strains of the electronics structures remained below the limits for plastic deformation. Moreover, the microfluidic chamber was used to prepare a wireless epidermal electronic system for the detection of neonatal vital signs [48].

6 Applications of FHE

With the rising prevalence of chronic diseases and the increase of the world’s aging population, it is necessary to continuously monitor the health status of the human body. FHE integrates traditional solid electronic components onto flexible substrates, which allows the electronic system for conformal contacts with irregular surfaces of the human body without discomfort and damage to functionality. Compared with the traditional rigid system, the high-level integration of FHE promotes portability and wearing comfort, which expands the application of FHE. In this section, we will introduce the application of FHE in physiological health, clinical care, physical rehabilitation, and HMIs.

Our group fabricated an on-skin flexible hybrid electronic system with a high level of integration to collect ECG and acceleration data in real-time [40]. The radio frequency (RF) antenna part and high-frequency parts of this system were integrated on FPCB, while the other parts were fabricated on PDMS substrate (Figure 5(a)). With RF front-end module, processed signals were transmitted and displayed on a mobile phone, which ensured real-time monitoring of health and motion status. The combination of the two signals could be utilized for disease diagnosis and treatment of chronic diseases (such as coronary atherosclerotic and pulmonary heart disease). Kim and coworkers [49] developed an all-in-one stretchable hybrid electronic system (SHES) that could real-time monitor the ECG signals of the human body. The system consisted of three nanomembrane gold electrodes that contact with skin to capture the ECG signals and a flexible circuit for wireless transmitting the raw physiological data via Bluetooth. The two parts were connected by a stretchable connector. By leveraging signal processing methods and deep-learning algorithm, heart rate (HR) and respiration rate (RR) were extracted and analyzed from the raw physiological data, which could reflect various cardiac diseases (such as myocardial infarction, heart failure, and ventricular ectopic beats) and human activities (including walking, climbing stairs, and running). Apart from personalized healthcare, FHE also brings disruptive progress to clinical care. Han and coworkers [50] presented a battery-free and wireless system for continuously monitoring the pressure and temperature of the human body in clinical healthcare. The system consisted of 65 flexible near field communication (NFC) devices that were mounted on skin for measuring physiological signals in real-time. Each of the NFC device included a temperature sensor, a pressure sensor, and a flexible circuit for transmitting the raw signals to a central acquisition/control system and obtaining power from the antennas. The continuous streams of data provided by NFC devices could be assembled into the spatiotemporal maps of temperature and pressure. Figure 5(b) shows that this FHES was utilized to monitor the skin status of a bedridden subject in real-time, which is of vital significance to avoiding skin sores, irritation, and cubitus ulcers in clinical care. Moreover, this FHES was also utilized to monitor circadian phase, which had potential applications in sleep studies, tumor detection, and hypothermia therapy.

Due to the outstanding portability and comfort, FHE reduces the physical burden during long-term wearing, which endows the great potential of FHE in physical rehabilitation. Our group developed a portable headband for electroencephalogram (EEG)-based emotion classification [51]. Three on-skin electrodes were utilized to collect EEG signals, while the other parts including signal preprocessing module and Bluetooth wireless transmission module were integrated into the FPCB. Under different emotion stimuli, the emotional states of volunteers could be classified from the EEG signals with an average accuracy of 90%. Due to the high measurement performance and portability, the system had great promise in the diagnosis of neurological diseases and psychological rehabilitation. Jeong and coworkers [52] introduced a soft skin-integrated system, which could detect physiological signals without the need for complex signal processing. The core detection module of the system was a pair of time-synchronized and high-bandwidth accelerometers located at the suprasternal notch (SN) and sternal manubrium (SM), respectively. The nearby skin movements induced by cardiac and respiratory activities could be accurately captured by the accelerometers. The cardiopulmonary signal could be extracted through simple differential measurements. The optimized choices in mounting locations of the system could avoid motion artifacts during signal monitoring. The unique properties of the system ensure measurements of respiratory activities, vocal activity, and
swallowing outside hospital and rehabilitation clinics, promoting the rehabilitation of patients with aphasia or chronic obstructive pulmonary disease. Furthermore, this system was able to monitor the key symptoms of patients with COVID-19, which was significant to the formulation of rehabilitation protocols.

Meanwhile, FHE also has great prospects in HMIs. Our group reported a stretchable electronic system which could capture electromyography (EMG) signals [35]. The low thickness and high stretchability of the electrodes array enhanced conformal contact with skin, which reduced impedance and improved signal quality. As shown in Figure 5(c), the electrode array was attached to the forearm of a volunteer to collect EMG signals during hand gestures. After the analysis of raw signals and the classification of hand gestures, the EMG signals were utilized to control the

Figure 5 Applications of FHE. (a) SHES monitored ECG and acceleration. Reproduced with permission [40]. Copyright@2021, IEEE. (b) Real-time monitoring of skin pressure and temperature in specific areas of bedridden patients. Reproduced with permission [50]. Copyright@2018, American Association for the Advancement of Science. (c) The electrodes array on the forearm (left), characteristics of EMG signals during four types of hand gestures (middle), motions of wheeled mobile robot controlled by EMG signals (right). Reproduced with permission [35]. Copyright@2019, American Chemical Society. (d) EMG signals of forearm were utilized to precisely control a flying drone and a RC car. Reproduced with permission [54]. Copyright@2020, Spring Nature.
motions of a wheeled mobile robot. Four gestures, including wrist flexion, ulnar flexion, wrist extension, and fist, could control the robot to turn clockwise, move forward, turn counterclockwise, and stop. Furthermore, we proposed customized electrode arrays, which were in accordance with the position and orientation of the target muscles [53]. The customized arrays could cover more muscles and record higher-quality signals than orthogonal arrays under the same condition. With the SVM algorithm, six gestures were classified with an accuracy of 98%, which demonstrated that the customized arrays had great promise for HMI systems.

Kwon and coworkers [54] exhibited an all-printed nanomembrane hybrid electronics system for recording high-fidelity muscle activities. Electrodes with high-resolution patterns prepared by printing functionalized conductive graphene were utilized to wireless monitor EMG signals. Three FHEs were mounted on the specific muscle groups of the human forearm to acquire motions of five fingers and wrist flexion. This lightweight and the compact system exhibited remarkable accuracy and outstanding stability among multiple HMI scenarios such as flying drone and RC car. Four gestures (open hand, closed hand, flexion of index finger, and wrist flexion) were utilized to control two target machines to achieve different movements (stop, forward, rotate right, backward, take off, and land). As shown in Figure 5(d), the closed hand controlled the flying drone forward, and the flexion of index finger controlled the RC car backward.

7 Discussion and conclusions

In this review, we summarize the latest research progress in FHES, particularly the enabling techniques for FHE integration. Highly conductive and stretchable interconnects (i.e., serpentine wires, 3D wires, gold nanowires, and silver nanosheets) have been developed to further enhance the tensile stability of FHES. To achieve multifunctional and minimization of FHES, interlayer interconnection schemes (i.e., multilayer via interconnect, isolation between elastomer layers) are regarded as effective approaches to achieving high-integration electronic systems. The stability of interlayer interconnects under shear force has yet been investigated. In addition, due to modulus mismatch between flexible substrates and rigid IC chips, it is also crucial to strengthen the bonding toughness of the interface. At present, typical strategies of stable integration between soft substrates and IC chips have been proposed, including chemical bonding, ACF, soldering, and stress isolation structure. Nonetheless, further explorations are still needed to ensure robust bonding and low impedance of interfaces simultaneously. In the subsequent content, we will discuss the remaining challenges and promising opportunities of FHES in detail.

Although significant progress has been achieved in improving the stretchability and conductivity of circuit interconnects, several challenges remain to be addressed in the development of high-performance stretchable interconnects. Among them, the scheme using traditional metallic materials has superior performance. However, the bonding strength between metals and soft polymer substrates is relatively low. This is due to the fact that the metal layer cannot be directly deposited on the soft substrate. Even though the researchers realized the bonding of these two materials through the processes of plasma treatment and transfer printing, the bonding was still not firm, and it was difficult to be adopted for large-scale fabrication due to the difficulty in processing and high costs. As for the liquid metals, the fabricating process of microchannels is complicated, and the relatively large thickness could limit the flexibility and stretchability of the whole system. At the same time, some oxidable non-toxic liquid metals, such as gallium-indium-stannum alloy and eutectic gallium-indium alloy, can also lead to the failure of the circuit interconnections. In contrast, the conductive composite material has sufficient performance. It can be rapidly patterned by simple fabricating processes such as screen printing and stencil printing. However, its resistivity is always relatively large, resulting in a large line width, which limits the density of electronic components. The conductivity of this material needs to be further optimized. In addition, the technical difficulty of the multilayer structure is far beyond that of the single layer circuit. On the one hand, its interlayer joints are subjected to shearing force, which makes them easy to fail; on the other hand, its larger thickness increases bending stiffness and reduces wearing comfort. Therefore, stronger interlayer joints and thinner thickness are the future development trends of multilayer flexible circuits.

In addition, further development is required to strengthen the bonding between flexible substrates and IC chips. Currently reported materials for chip bonding mainly include low-temperature solders, conductive composites, and S-ACFs. Among them, the low-temperature solder bonding process usually requires a much higher temperature than the ambient environment to realize the fluidity of the solder, which may lead to thermal failure of electronic components. For preparing conductive composite materials, expensive metal particles or flakes, such as gold particles and silver flakes, are essential to forming the conductive network inside the materials, which may increase the overall cost. Besides, various printing processes such as stencil printing and inkjet printing often need to ensure the precise layout of conductive composite materials in the bonding process, which apparently increase the complexity and difficulty in processing. As for S-ACFs, the complex fabrication process remains a notable issue, hindering the efficient fabrication and wider
application of S-ACFs. Therefore, to achieve stable chip bonding in FHE, the challenges still lie in the selection of bonding and conductive materials and the optimization of bonding processes.

Simplifying the fabrication process of stress-separation structures is another challenging issue. Several methods have been reported for stress-separation structures in hybrid electronics, but these methods still have significant limitations in daily use due to the manufacturing process and the fragility of the electronics. To be specific, the relatively low integration density of island-bridge structures and localized rigid-island structures contradicts the trend of the high integration and the miniaturization of electronic systems. Liquid cavity structures are prepared based on traditional semiconductor processing (e.g., photolithography, etching), and these complex operational processes and corrosive etching solvents impose limitations on the development of FHE integration. In summary, current stretchable flexible hybrid electronic systems cannot adapt to large-scale applications, suffering from low integration density and complex preparation processes. In this way, to promote the development of flexible hybrid integrated electronic systems, new manufacturing processes and equipment are worth to be explored. The complex processing of the structure designs and the cost of the electronic systems should be optimized while maintaining the functionalities and performances to achieve widespread applications of FHEs.

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