Stretchable hybrid electronics: combining rigid electronic devices with stretchable interconnects into high-performance on-skin electronics

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ABSTRACT
Stretchable hybrid electronics (SHE) that combine high-performance rigid electronic devices with stretchable interconnects offer a facile route for accessing and processing bio-signals and human interactions. Incorporated with sensors and wireless communications, SHE achieves novel applications such as biomedical diagnosis, skin prosthetics, and robotic skin. The implementation of reliable SHE requires the comprehensive development of stretchable electrodes, bonding techniques, and strain-engineered integration schemes. This review covers the recent development of enabling technologies for SHE in terms of materials, structures, and system engineering. We introduce various strategies for stretchable interconnects based on novel materials and structural designs. In particular, we classify SHE into three groups based on strain-relief configurations: thin-film devices on rigid islands, rigid devices with stretchable bridges, and flexible circuits with stretchable bridges. Appropriate methods for substrates, stretchable interconnects, and bonding between rigid and soft components and their pros and cons are extensively discussed. We also explore state-of-the-art SHE in advanced human-machine interfaces and discuss the challenges and prospects for future directions.

1. Introduction
On-skin electronics augment the range of accessible bio-signals and enable sensing of human interactions, accelerating the Internet of Everything (IoE) that connects every object and also exchanges the collected data for novel applications such as biomedical diagnosis [1], skin prosthetics [2], and robotic skin [3]. Micro-signals can be transferred with high fidelity when electronics form conformal interfaces with soft and complex three-dimensional (3D) geometries. Therefore, on-skin electronics should have skin-like mechanical properties. They should also be able to maintain their functions and electrical performance up to a strain of a few percentage points. In this regard, valuable efforts to render electronic systems stretchable have been actively reported.

Stretchable electronics can be classified into two systems: (1) intrinsically stretchable systems and (2) stretchable hybrid systems. Intrinsically stretchable systems comprise only soft materials as functional devices and interconnects. All components of the system are substantially strained under tensile stress. Such systems offer skin-like compliance and mechanical robustness because they contain no rigid parts. Many research groups have reported significant results about intrinsically stretchable devices [4,5], including electrodes, transistors, electroluminescent devices, and sensors. However, most of the soft devices are still in their infant stage, exhibiting limited performance, low device density, and difficulties in integrating them into complex circuits. The lack of diversity in intrinsically stretchable devices also poses limitations in the functionality of electronic systems.

An alternative is to bridge rigid electronic devices with stretchable electrodes. When the system deforms, stretchable interconnects absorb the strain energy, while rigid electronic devices become strain-free. With this approach, rigid electronic devices such as thin-film transistors (TFTs), integrated circuits (ICs), and even printed circuit boards (PCBs) can be integrated with stretchable
electrodes, creating multifunctional, customized, and high-performance stretchable circuits. These systems are called ‘stretchable hybrid electronics (SHE)’ because they contain both rigid and stretchable components. Due to its feasibility, plenty of unique applications have been demonstrated using SHE that assembles sensors, circuits, and wireless modules into stretchable displays, biosensors, and haptic interfaces for augmented reality (AR).

Enabling technologies for implementing reliable SHE include strategies for stretchable electrodes and schemes for integrating rigid and stretchable components. Various strategies for stretchable electrodes have been developed, based on novel materials such as elastomer composites and liquid metals, and stretchable structures such as serpentines and buckling. The choice of stretchable interconnects for SHE should consider system requirements such as electrical conductivity and stretchability. Deposition, patterning, and bonding techniques are highly contingent upon the types of stretchable electrodes.

For reliable operation of SHE, strain should be localized on stretchable electrodes and strain in rigid devices must be prevented. Furthermore, the system should be able to manage the concentrated strain at the interface between stretchable electrodes and rigid devices, which could result in electrical and mechanical failure. To resolve these issues and enable complex circuit configurations, supporting structures for strain engineering and robust bonding techniques have been developed. Integration schemes for SHE can be divided into three general approaches: (1) Thin-film devices on rigid islands, (2) rigid ICs directly interconnected by stretchable electrodes, (3) flexible circuits interconnected by stretchable interconnects.

In this review, we cover the materials and structures for stretchable interconnects (Chapter 2) and then describe the three strategies for integrating rigid components with stretchable interconnects into SHE from the perspective of strain engineering (Chapter 3). We also discuss various emerging applications of SHE in displays, sensors, bio-applications, and advanced human-machine interfaces, as well as the challenges and future directions in pursuit of highly reliable on-skin electronics.

2. Strategies for stretchable interconnects

Stretchable interconnects comprise the most essential building block in SHE as they efficiently absorb the strain energy between rigid electronic components, consequently enabling electronic systems to conform to complex 3D surfaces. Stretchable interconnects have been developed through two main strategies based on novel materials for intrinsic stretchability and structural designs of metallic film. Intrinsically stretchable conductors have progressed via efforts to find new materials that simultaneously have elasticity and electrical conductivity, such as nanocomposites of elastomers and conductive fillers, liquid metals, and conductive polymers. These engineered materials generally show low Young’s modulus and maintain their conductivity under large tensile strain, facilitating high mechanical conformability of electronic systems. However, they usually suffer from low electrical conductivity or a drastic increase in resistance under cyclic strain, which requires a complement such as additional additives or encapsulation. On the other hand, structural designs have been developed to enable metallic films to be reversibly stretched and released, such as wrinkles, serpentines, and origami/kirigami structures. While they have some disadvantages terms of areal efficiency and mechanical conformability, these approaches can readily achieve high electrical conductivity with stable operation under a fixed strain range. Different types of stretchable interconnects can be adopted for SHE systems considering target configurations and applications. This section introduces the recent progress of various stretchable interconnects applicable to SHE and provides detailed methodologies for each strategy.

2.1. Materials for intrinsically stretchable conductors

Researchers have developed novel materials for stretchable electrodes that simultaneously have intrinsic stretchability and electrical conductivity. They can create synergy when integrated with intrinsically stretchable, functional devices such as soft sensors and transistors, constituting fully soft electronics without rigid parts. However, their low electrical conductivity (compared to metallic films), poor cyclic stability, and difficulties in integrating them with rigid components significantly limit their application in SHE for the purpose of achieving high performance and great mechanical stability. Nevertheless, with appropriate bonding strategies and improved electrical characteristics, they would achieve superior stretchability and conformability when applied to SHE. In this section, we discuss various materials for intrinsically stretchable conductors classified as composites, liquid metals, and conductive polymers. Table 1 summarizes and compares those materials in terms of performance, advantages, and limitations. State-of-the-art research is not confined to the range dealt with in this section. Innovative materials and methodologies for improving mechanoelectrical properties and processability are being actively reported.
Carbon-based nanomaterials such as carbon black (CB), carbon nanotubes (CNTs), and graphene have been widely used as conductive filler for stretchable composite interconnects. Although CB-based composites have been proposed in the early stage due to their accessibility and cost-effectiveness, they typically exhibit low electrical conductivity and low stability when stretched due to their low aspect ratio [6]. CNTs, on the other hand, are more suitable for stretchable composites, exhibiting a lower percolation threshold and higher stretchability owing to their high aspect ratio. Sekitani et al. made elastic interconnects using ultralong single-walled CNTs (SWCNTs), ionic liquid, and fluorinated copolymer (Figure 1(a)) [7]. The extremely high aspect ratio of ultralong SWCNTs played an important role in maintaining conductivity of interconnects up to 6 $\text{S cm}^{-1}$ at 134% strain. Instead of using random networks, vertically aligned CNT forests embedded in polyurethane (PU) elastomer was reported, exhibiting reversible conductivity under strain owing to accordion-like deformation of CNT forest (Figure 1(b)) [8].

Metallic nano/micro-materials are the most suitable candidates for fillers of stretchable composites, owing to their superior conductivity. Even composites with low-aspect-ratio fillers exhibit high conductivity and stretchability. For example, elastic conductors containing silver (Ag) flakes, fluorine rubbers, and surfactant showed their initial conductivity higher than 4,000 $\text{S cm}^{-1}$ and stretchability of $\sim 400\%$ (Figure 1(c)) [10]. Ag nanoparticles were formed in situ by the surfactant and heating processes, enabling composites to maintain high conductivity up to the high strain. Metal nanowires have been widely exploited as conductive fillers, providing the advantage of high aspect ratio and superior electrical conductivity. Silver nanowires (AgNWs) were embedded in the surface of the polydimethylsiloxane (PDMS), exhibiting conductivity of 5285 $\text{S cm}^{-1}$ at 50% strain (Figure 1(d)) [11]. Irreversible sliding of AgNWs during initial stretching–releasing created wrinkles, keeping conductivity stable under strain. Efforts have been made to improve the stretchability and stability of such composites by combining with axillary fillers [12,13]. Figure 1(e) shows hierarchical conductive network structures formed by AgNWs and CNTs, where CNT networks protect AgNWs and CNTs from breaking.

### 2.1.1. Composites

To secure both intrinsic stretchability and electrical conductivity, a strategy of combining elastomers and conductive fillers to form composites has been widely investigated. Conductive fillers in an elastomeric matrix could form percolating conductive pathways by direct contact or tunneling between fillers, where the conductivity of composites can be engineered by the concentration of fillers over the percolation threshold [9,27,28]. When composites are strained, fillers are relocated in an elastomer, maintaining their conductive pathway. Geometric factors of fillers, such as size, shape, aspect ratio, and orientation, directly influence the electrical conductivity and stretchability of composites [29,30]. Filler materials, mostly carbon or metal, are also an important factor determining the mechanoelectrical characteristics of composites. Composite materials are highly elastic and mostly printable, but they generally show poor cyclic reliability that must be improved for practical applications. In this section, various stretchable composite conductors classified by their filler materials are reviewed.

| Ref. | Materials | Electrical conductivity ($\text{S cm}^{-1}$) | Stretchability (%) | Cost | Advantages | Limitations |
|------|-----------|---------------------------------|-------------------|------|------------|-------------|
| [6–8] | Carbon-based composites | $-100$ | $-150$ | Low | Chemical stability | Low conductivity |
| [9–13] | Metallic nanomaterial-based composites | $-8000$ | $-400$ | Medium/High | Elastic properties | Cyclic reliability |
| [14–20] | Liquid metals | $20000$–$34000$ | $\sim 1000$ | Medium | High conductivity | Penetration into metals |
| [21–26] | Conducting polymers | $\sim 100$–$2000$ | $20$–$100$ | Low/Medium | High transparency | Leakage |

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### 2.1.2. Liquid metals

Because liquid metals, existing in a liquid state at room temperature, can flow or change their shape into various forms, they are suitable candidates for stretchable interconnects. One of the traditional liquid metals is mercury, but it is not preferred because of its toxicity [31]. On the other hand, gallium (Ga) and its alloys such as eutectic gallium-indium (EGaIn) and gallium-indium-tin (GaInSn) have been studied recently due to their non-toxicity and high conductivity. There are several advantages associated with their fluidic properties when using Ga-based liquid metals as stretchable interconnects [14,32]. Liu et al. demonstrated stretchable multilayer interconnects by introducing solid–liquid biphasic Ga-In (BGaIn) [14]. BGaIn was fabricated by thermal sintering process to create a mixture of a thin crystalline solid film on the top and a thick biphasic region composed of
solid particles embedded in liquid EGaIn (Figure 2(a)). The resulting stretchable interconnects based on BGaIn showed high conductivity and extreme stretchability over 1000%. Fluidic characteristics of liquid metals also allow its self-healing, making them suitable for use as reconfigurable circuits [32,33]. Markvicka et al. constructed self-healing stretchable interconnects using composites based on liquid metal, and EGaIn microdroplets formed new percolating networks and spontaneously re-routed without manual repair or external heat when damaged (Figure 2(b)) [32].

Despite their attractive properties, a technical issue associated with the penetration of liquid metals into other metals hinders their practical applications. Liquid metals containing Ga easily penetrate other metals along the grain boundaries, causing swelling, cracking, delamination of neighboring metal films, or the dissolution of host metals [15–18]. Leakage of liquid metal can also be another critical issue in wearable applications if there is no adequate encapsulation [19]. Therefore, various methods for encapsulating liquid metal-based stretchable interconnects have been demonstrated. Injection by a needle is a simple way to fabricate liquid metal-filled channels [33,36]. Since the liquid metal can leak from inlet or outlet holes under large pressure, Zhang et al. introduced leakage-free interconnects together with a rigid alloy of bismuth, indium, and tin in the solid state to handle the leakage issues (Figure 2(c)) [19].

When exposed to ambient oxygen, Ga is rapidly oxidized at the surface and forms a thin oxide layer made of gallium (III) trioxide (Ga2O3) on its surface. A direct writing method is enabled by this oxide skin, maintaining its mechanically stable structure [20,34]. Ladd et al. utilized EGaIn to directly write liquid metals into 3D patterned shapes and embed them in a PDMS substrate to form stretchable interconnects (Figure 2(d)) [34]. Combining liquid metals with silicone elastomers was also suggested to improve printability. Zhou et al. constructed stretchable electronics with liquid metal-based printable inks composed of GaInSn microdroplets and PDMS [37]. The liquid metal-silicone ink is not initially conductive because of the oxide skin and a silicone shell around liquid metal microdroplets, but it can be activated by pressing or freezing. By this strategy, a liquid metal-rich conductive inner core and an insulating region can be divided, so the need for additional encapsulation steps is removed (Figure 2(e)) [35].

### 2.1.3. Conductive polymers

Conductive polymers such as Poly(3,4-ethylenedioxythiophene):polystyrene sulfonate (PEDOT:PSS) [21–26,38,39], polyaniline (PANI) [40], polypyrrole (PPy) [41,42], and their derivatives can be utilized as stretchable interconnects. Although they can be readily formed as robust thin-film electrodes using solution processes such as...
printing methods, they generally suffer from low conductivity that originated from their amorphous structure and low stretchability due to their film-like cracking. Among these candidates, PEDOT:PSS has been studied significantly, with a focus on enhancing its conductivity or formulating printable inks. Polar compounds such as d-sorbitol [25] and ethylene glycol (EG) [26] have been used to increase the electrical conductivity of PEDOT:PSS-based electrodes. These additives cause a rearrangement in the morphology of PEDOT:PSS films, resulting in larger PEDOT grains or increased phase separation between the conducting PEDOT and the insulating PSS. Eventually, the morphology change leads to a better-conducting network.

Surfactants such as Zonyl or Triton X-100 were utilized to enhance the stretchability of PEDOT:PSS-based electrodes [21,38,39]. Vosgueritchian et al. developed stretchable and transparent electrodes using a fluorosurfactant-treated PEDOT:PSS [38]. Surfactant-treated PEDOT:PSS films showed a 35% improvement
in sheet resistance compared to pristine films. Lipomi et al. also demonstrated PEDOT:PSS films treated with fluorosurfactant on ultraviolet (UV)/ozone (O₃)-activated PDMS substrates. These were highly stretchable and retained their conductivity under a tensile strain of up to 188% [39]. To achieve more advanced electrical and mechanical properties based on PEDOT:PSS, ionic additives-assisted stretchability and electrical conductivity (STEC) enhancers were recently applied [22]. STEC enhancers not only changed the morphology of PEDOT:PSS films to create soft domains but also acted as conductivity-enhancing dopants in PEDOT:PSS films. The resulting polymer films exhibited conductivities over 4100 S cm⁻¹ under a tensile strain of 100% (Figure 3). On the other hand, acid treatments were introduced to enhance the electrical and mechanical properties of PEDOT:PSS films [23,24]. Fan et al. reported highly conductive stretchable interconnects via mild acid treatments on a PEDOT:PSS film embedded in a PDMS elastomer [23]. The dipping-embedded transfer method enabled the PEDOT:PSS-PDMS films to have a high conductivity of 2890 S cm⁻¹ and stretchability of 20%.

### 2.2. Structural designs for stretchable electrodes

Structural designs of metal films are the most intuitive way to fabricate stretchable interconnects such as accordions and springs. From the early stage, many researchers have focused on in-plane and out-of-plane structures of thin metal films. These structures maintain their high electrical conductivity up to a designed strain range. They can also be readily integrated with rigid IC chips using standard bonding processes of PCBs due to their robust and solid architectures. For these reasons, they comprise a significant proportion of stretchable interconnects in SHE. However, their limited stretchability, inefficient areal coverage, and limited mechanical conformability should be further improved. This section covers various structural designs for stretchable electrodes classified as buckling, kirigami/origami, and serpentes.

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**Figure 3.** PEDOT:PSS-based transparent stretchable interconnects. Reproduced with permission [22]. Copyright 2017, The American Association for the Advancement of Science.
Table 2. Comparison of structural strategies for stretchable interconnects.

| Ref. | Structures       | Electrical conductivity (S cm⁻¹) | Stretchability (%) | Process                  | Advantages                        | Limitations                      |
|------|-----------------|----------------------------------|--------------------|--------------------------|-----------------------------------|-----------------------------------|
| [43–49] | Buckling structures | Depending on selection of conductive materials (e.g. metal trace, AgNP, AgNW etc.) | -200%              | Pre-stretching process    | High conductivity                  | Pre-stretching process Limited stretchability |
| [50,51] | Kirigami structures |                                      | -400%              | Cutting or laser ablation | Great stretchability               | Spatial resolution Confined deformation |
| [52–54] | Origami structures |                                      | -30%               | Folding or molding        | Simple process                     | Low stretchability Out-of-plane structure |
| [55–60] | Serpentine structure |                                      | -1600%             | Photolithography          | Great stretchability               | Spatial resolution Process complexity |

Table 2 summarizes and compares the structures in performance, advantages, and limitations. These structures are found to play a critical role in SHE incorporated with various strain-relief strategies in the next chapter.

2.2.1. Buckling structures

The representative structural approach for implementing stretchable interconnects is to employ strain-relieving wrinkle or buckling structures of metal films. These consist of periodic out-of-plane structures, which are reversibly deformed from wavy to planar geometry during stretching motion. In general, the formation of a wavy structure involves a pre-stretching process (Figure 4(a)) [43]. The soft elastomeric substrate is first uniaxially or biaxially extended to the desired length. The subsequent surface modification or thin-film deposition induces the modulus mismatch between the substrate and the surface. When the elastomeric substrate is relaxed to the initial size, wrinkles are spontaneously formed by minimizing the deformation energy applied to a stiff film placed on a soft elastomeric substrate [44].

The wrinkled structure consists of compliant thin metallic films on an elastomeric substrate with several μm to hundreds of μm of wavelength. Cho et al. demonstrated a drop-on-demand inkjet printing of metallic interconnects on pre-stretched PDMS substrate, enabling the freedom of designing the interconnect pattern [45]. By adjusting the inkjet printing parameters, the regularity

Figure 4. Out-of-plane wavy structure. (a) Wrinkled structure fabricated by pre-stretching process. Reproduced with permission [43]. Copyright 2008, Elsevier. (b) Wrinkled Ag interconnects fabricated via inkjet printing method. Reproduced with permission [45]. Copyright 2019, Taylor & Francis. (c) Controlled buckling with arc-shaped silicon nanoribbons (SiNRs). Reproduced with permission [47]. Copyright 2006, Springer Nature. (d) Conductive 3D helical coil structure. Reproduced with permission [48]. Copyright 2017, Springer Nature. (e) Various 3D stretchable architectures. Reproduced with permission [49]. Copyright 2015, The American Association for the Advancement of Science.
and cyclic stability of stretchable interconnects could be improved at the optimized film thickness (Figure 4(b)). Furthermore, Tang et al. deposited Ag film on a Sodium Dodecyl Sulfate (SDS)-treated PDMS after relaxation, avoiding Poisson’s effect-induced crack formation [46]. The SDS-functionalized surface and uniform periodic structures without crack improved environmental stability as well as stretchability by up to 200%.

Sun et al. also developed a controlled buckling with deterministic out-of-plane geometry (Figure 4(c)) [47]. Selective bonding of metallic ribbons on lithographically defined adhesion sites caused local delamination when force above a certain threshold level is applied. The periodic arc-shaped buckling structure was subsequently formed, achieving a high stretchability of up to 150%. In addition to the uniaxially wavy buckling, design rules for complex 3D architecture were also widely investigated. Jang et al. demonstrated a conductive 3D helical coil structure from a two-dimensional (2D) filamentary serpentine structure bonded at selective locations (Figure 4(d)) [48]. Various 3D architectures, including single and multiple helices, toroids, and conical spirals, were investigated by varying planar precursor structures and bonding sites on an elastomeric substrate (Figure 4(e)) [49].

### 2.2.2. Kirigami and origami structures

Kirigami and origami structures, inspired by papercraft, are notable methods of implementing stretchable interconnects from 2D thin films. The process for kirigami includes repetitive cutting and folding the sheets, delocalizing the stress concentration along the cutting lines. When strained, kirigami structures change their shapes into 3D structures without fracture, thereby maintaining their electrical conductivity. Shyu et al. reported a single-walled CNT-infiltrated paper sheet with a kirigami pattern [50]. The endurable strain of the CNT nanocomposite sheets increased from 5% to 290% by kirigami patterning, distributing the applied load with out-of-plane deflection. Moreover, the applicable length could be extended down to the nanoscale through top-down kirigami patterning, such as photolithography or laser-cutting (Figure 5(a)). Won et al. demonstrated transparent AgNW interconnects with the various configuration of laser-ablated kirigami patterns (Figure 5(b)) [51]. The fabricated interconnects exhibited stretchability of 400% with negligible mechanical hysteresis and high optical transparency.

Origami is the way of folding the sheets into compact 3D structures, and the Miura-ori is the most widely investigated form. The crease pattern of the Miura-ori is a periodic pattern of a unit cell consisting of four parallelograms with mountain folds and valley folds (Figure 5(c)) [52]. Due to its unique geometry, it is two-dimensionally stretchable, effectively suppressing the strain at the surface of the parallelogram [53]. Hou et al. demonstrated stretchable gold interconnects deposited on a Miura-ori-structured elastomer (Figure 5(d)) [54]. The Miura-ori structure effectively distributed the strain, while the stress is concentrated on the tip regions ensuring stable electrical characteristics. The gold interconnects with a Miura-ori structure showed small resistance change under a strain of up to 30%.

#### 2.2.3. Serpentines

In-plane design for stretchable interconnects is fabricated on a single plane, compatible with the standard silicon (Si)-based microfabrication process. System-level integration with other components is facilitated because additional processes such as pre-stretching or precut for kirigami patterning are unnecessary. One of the representative configurations is a serpentine featuring repetitive meandering shapes. The unit cell of serpentine is shown in Figure 6(a) [55]. Although ribbon-based serpentines generally are deformed in out-of-plane directions, in-plane bending of a metallic structure dominates when the ribbon thickness is larger than its width. Gray et al. demonstrated gold serpentine interconnects that endured more than 50% strain, maintaining the conductivity [56]. Furthermore, layouts of so-called ‘self-similar’ structures were integrated into serpentines for enhanced stretchability (Figure 6(b)) [57]. A single serpentine was modified into iterative multiple copies of the unit cell. The meandering structures deformed over the two stages of global and local unraveling, resulting in stretchability of 300%. The fractal design was also investigated for higher areal coverage and large stretchability [58]. Various geometries of Peano, Moore, or Greek cross architectures were further suggested (Figure 6(c) and (d)). In addition to the serpentine-derived structure, the extendible microwire that unfolds across the connected nodes (Figure 6(e)) [59], and the spiral interconnect that asymmetrically rotates around a spring structure (Figure 6(f)) [60] were reported. Both of the structures exhibited excellent stretchability up to 1600% and 1000%, respectively.

### 3. Integration schemes for engineered strain distribution

The main concern of SHE is anchored on configurations where strain-free areas and stretchable interconnects are distributed since SHE comprises rigid electronic devices and stretchable interconnects. Strategies can be divided into three categories depending on the type and scale of rigid components: (1) thin-film devices on rigid islands (Figure 7(a)); (2) rigid ICs directly interconnected
Figure 5. Out-of-plane kirigami/origami structure. (a) Microscale kirigami structures through lithographic patterning. Reproduced with permission [50]. Copyright 2015, Springer Nature. (b) AgNW-based kirigami interconnects. Reproduced with permission [51]. Copyright 2019, American Chemical Society. (c) Unit cell of Miura-ori structure. Reproduced with permission [52]. Copyright 2016, Springer Nature. (d) Stretchable Au interconnects deposited on Miura-ori structure and finite element analysis (FEA) on stress distribution. Reproduced with permission [54]. Copyright 2020, Wiley-VCH.

Figure 6. In-plane stretchable interconnects. (a) Unit cell of serpentine structure and design parameters. Reproduced with permission [55]. Copyright 2014, Elsevier. (b) Self-similar serpentine structure. Reproduced with permission [57]. Copyright 2013, Springer Nature. (c) Fractal design and (d) various design of fractal type stretchable structure. Reproduced with permission [58]. Copyright 2014, Springer Nature. (e) Extendible microwire. Reproduced with permission [59]. Copyright 2010, Wiley-VCH. (f) Spiral interconnects. Reproduced with permission [60]. Copyright 2014, AIP Publishing.
Figure 7. Integration schemes for SHE. (a) Thin-film devices on rigid islands, (b) rigid ICs directly interconnected by stretchable electrodes, (c) flexible circuits interconnected by stretchable electrodes.

by stretchable electrodes (Figure 7(b)); (3) flexible circuits interconnected by stretchable electrodes (Figure 7(c)). Because thin-film devices are extremely vulnerable to tensile strain, rigid islands embedded in or attached to stretchable substrates can provide mechanical tolerance and minimize degradation in performance upon deformation. On the other hand, IC chips can act as rigid islands themselves, directly interconnected by stretchable electrodes. In this regime, robust bonding between pads on IC packages and stretchable interconnects is key to achieving highly reliable SHE. Lastly, flexible PCBs containing a cluster of ICs can be interconnected by stretchable electrodes, forming the largest strain-free area over flexible substrates. Since high-level circuit modules can be easily implemented on flexible PCBs such as wireless communication modules, more complex circuit interfaces with modularization can be achieved on SHE. This chapter describes these three strategies for the reliable integration of rigid devices and stretchable electrodes with detailed methodologies and plentiful applications for each strategy. The pros and cons of representative methodologies are summarized in Table 3.

3.1. Thin-film devices on rigid islands

For thin-film devices such as TFTs and organic light-emitting diodes (OLEDs) to be fabricated on stretchable substrates, strain-relief structures are needed to maintain their performance because they are generally brittle and vulnerable to mechanical deformation. Rigid island structures are one of the most common and conventional strain-relief structures frequently used to integrate soft and rigid components into a stretchable system.
Table 3. Comparison of integration schemes for engineering strain distribution.

| Ref.       | Integration schemes                          | Process                                           | Advantages                  | Limitations                |
|------------|---------------------------------------------|---------------------------------------------------|-----------------------------|----------------------------|
| [61–66]    | Thin-film devices on rigid islands          | Photolithography                                  | High resolution             | High cost                  |
| [67]       | Thin film devices on rigid islands          | Embedding manually cut plastic films              | Low cost                    | Low customizability        |
| [68,69]    | Thin film devices on rigid islands          | Laser cutting                                     | Low cost                    | Low resolution             |
| [70]       | Thin-film devices on high-pillar structures| Molding                                           | Simple process              | Low customizability        |
| [71–74]    | Thin-film devices on high-modulus islands   | Stencil printing UV treatment Oxidation (H₂O₂) Molding | Low cost                    | Limited resolution         |
| [75–78]    | Rigid ICs with serpentine interconnects     | Direct photolithography Integration of ICs with solder paste Molding | High integration density    | Low customizability        |
| [79–82]    | Rigid ICs with wrinkled interconnects       | Integration of ICs onto pre-strained strain-engineered substrates | High customizability        | Low integration density    |
| [83,84]    | Flexible circuit with serpentine interconnects | Polymer-based modular block Process compatibility Modularized circuits | Low integration density     | Strain concentration      |

[7,61–74]. One way to apply this structure is by directly mounting thin and rigid blocks onto elastomeric substrates (Figure 8(a)). A representative example would be the recent work presented by Lim et al., where stretchable OLEDs were realized on a rigid island-mounted platform [64]. The rigid islands, composed of an epoxy-based photoresist (SU-8), were patterned using a photolithographic process and transferred onto a PDMS pillar array. This array acted as a strain-relief structure and reduced strain on the device under deformation, resulting in OLEDs stretchable up to 35% strain (Figure 8(b)). Despite the simplicity of this method, the strain concentrated at the boundary between mounted islands and elastomeric platforms can readily lead to mechanical and electrical failures of thin-film devices.

Rigid islands can also be embedded within elastomer substrates (Figure 8(c)). Romeo et al. presented a device design based on a mechanically engineered heterogeneous stretchable substrate fabricated by embedding stiff SU-8 photoresist structures in PDMS (Figure 8(d)) [65]. Alumina disks deposited on such platforms could withstand deformations up to 20% strain, while severe fractures were found in those without the embedded structures. Due to the elastomer layer above the rigid island, the strain on the devices shows a continuous transition from rigid to elastic regions. In this aspect, this design has advantages over surface-mounted rigid islands, which can directly induce drastically concentrated strain on thin-film devices at the discontinuous boundary of rigid and elastic regions. Matsuhisa et al. also took advantage of this design and fabricated an organic TFT (OTFT) matrix on islands embedded within a platform with a modulus gradient (Figure 8(e)) [68]. The OTFT array could be stretched up to 110% strain without impairing its electrical performance. Although embedded islands provide more reliable platforms for thin-film devices, they still have discontinuous boundaries in the platform itself, which can cause delamination issues and even mechanical fracture of the entire platform.

Instead of utilizing independent rigid and elastic platforms, strain relief can also be implemented based on gradient stiffness within a single substrate [72–74] (Figure 8(f)). This is usually done by applying surface treatments that render the substrate modulus-gradient, resulting in low-modulus and high-modulus patterned regions. Cai et al. demonstrated this concept by programming the stiffness of a soft elastomer composed of liquid benzophenone-PDMS (BP-PDMS) using a spatially selective UV exposure procedure [72]. When this mixture was exposed to UV light, BP radicals were formed and reacted with the curing agent monomers, forming low modulus exposed regions and high modulus unexposed regions. Like mounted or embedded rigid island structures, stress was concentrated in the soft, low modulus region when the substrate was deformed, generating a strain-isolated region (Figure 8(g)). The modulus-gradient structures prevent the strain from being highly concentrated on a specific location, improving the mechanical reliability of stretchable systems. Furthermore, this method has a simple fabrication process compared to other types of rigid islands that require delicate designs.

New approaches that have emerged recently include adding an additional ultra-soft strain-relief layer to enhance stretchability [63], or forming island structures
composed of the same type of materials with a higher Young’s modulus, preventing rigid island delamination issues [71]. For example, Wang et al. realized an intrinsically stretchable TFT array by utilizing a strain-engineered platform (Figure 8(h)). The platform consisted of an ‘elastiff’ layer, fabricated by varying the crosslinking density within one substrate. The demonstrated device could be stretched up to 100% strain with minimal degradation in performance, indicating high strain insensitivity. Considering their advantages and steady improvement, rigid island structures will be continuously investigated and optimized for thin-film-based SHE.

3.2. Rigid ICs directly interconnected by stretchable electrodes

Because conventional IC chips can be seen as rigid islands themselves, they can be directly interconnected by stretchable electrodes, forming a well-defined island-bridge configuration. In some cases, additional strain-isolation structures are exploited to improve the reliability of bonding between rigid ICs and stretchable interconnects. Serpentines and wrinkles of metal films are the most suitable interconnects when directly integrated with rigid ICs because they show low electrical impedance that is largely required by most
high-performance ICs. Furthermore, they are compatible with soldering technologies for conventional PCBs such as solder pastes and conductive epoxy so that robust bonding can be achieved. By applying appropriate fabrication processes, SHE with a conventional PCB circuit configuration can be readily realized, enabling high-performance skin-attachable electronics. This section introduces interesting examples of SHE and its applications, where rigid ICs are directly interconnected with stretchable conductors, especially serpentes and wrinkled electrodes. Multilayer SHE using a vertical interconnect access (VIA) and their applications are likewise discussed.

### 3.2.1 Rigid ICs with serpentes

Serpentine interconnects have been most widely used for wiring rigid ICs in SHE because of their mechanical robustness and high compatibility with well-established photolithographic processes [48,75–78,85–88]. IC chips are bonded with serpentine ribbons using solder pastes [48,85–88], or electronic devices are directly fabricated on them using additional lithographic processes [75–78]. As a representative example, Xu et al. integrated sensors, ICs, and radios using serpentes in a microfluidic structure for skin-attachable electronics [85]. Robust electrical and mechanical bonding was achieved by a low-temperature solder. A microfluidic suspension was employed to mechanically isolate rigid materials from a compliant shell, resulting in a highly conformable SHE.

Kim et al. demonstrated a prosthetic skin with serpentine single crystalline Si nanoribbons (SiNRs) that served as the interconnect [77]. The skin could function as strain, pressure, temperature, humidity sensors, and heaters when the structures and materials were changed for each purpose (Figure 9(a)). The SiNRs were patterned by thermal evaporation, photolithography, and wet-etching processes, followed by a transfer procedure of the whole system to a PDMS substrate to achieve mechanical conformability. Covering a prosthetic hand, the artificial skin integrated with numerous sensors and actuators could detect various hand motions and environmental conditions such as temperature and humidity. It could also warm the device up to a temperature similar to that of the human body through the embedded heater (Figure 9(b)).

Kim et al. introduced ribbon-shaped serpentes to develop stretchable LED (light-emitting diode) displays [78]. The GaAs-based LEDs and serpentes were fabricated using electron-beam evaporation and photolithography. The region where the LEDs were placed functioned as a rigid island itself while the serpentine interconnects served as structural bridges and electrical interconnects. After selectively evaporating Cr/SiO2 layers to achieve strong adhesion to PDMS, the LEDs and serpentine interconnects were transferred to a pre-strained PDMS substrate to form out-of-plane serpentine structures on the release of applied strain (Figure 9(c)). Due to their structural designs, the LED display showed outstanding and robust operation under various twisting conditions (Figure 9(d)).

Although serpentine-based SHE has prevailed owing to its well-established fabrication processes and facile integration processes, there are a few technical issues that need to be resolved prior to commercialization. These architectures cannot be in situ fabricated on elastomeric substrates due to their high-temperature fabrication process. They also have limitations in scalability, customizability, and cost efficiency due to their pre-defined patterns and masks. Furthermore, due to the in-plane configuration, serpentine-based SHE suffers from limited device density. Therefore, future directions would include the development of cost-effective methods or scalable, and space-efficient structures to augment the range of applications.

### 3.2.2 Rigid ICs with wrinkled electrodes

Unlike serpentes, wrinkles of thin metal films can achieve high device density owing to their out-of-plane morphologies. Thin metal films can also be in situ deposited onto a pre-stretched elastomeric substrate with high degree of freedom in design if incorporated with solution-based processes such as printing. Several attempts have been made to utilize wrinkled interconnects to wire IC chips to realize SHE [45,79–82,89]. IC chips are bonded by polymer adhesives such as epoxy before or after the pre-strain is removed. The boundary between rigid ICs and wrinkled thin films can particularly become vulnerable to the localized strain because the wrinkles are generally pre-defined by uniform pre-strain. Therefore, strain-engineered platforms are usually employed to improve the mechanical reliability of wrinkled-based SHE.

Byun et al. demonstrated SHE based on wrinkled Ag interconnects on a strain-engineered PDMS substrate fabricated by embedding printed rigid islands (PRIs) as the strain-relief structure (Figure 10(a)) [79,80]. Both the PRIs and wrinkled interconnects were fabricated using printing-based methods, providing high customizability and scalability. The PRI-embedded PDMS substrate was fabricated and treated with UV/O3 to enhance the adhesion between the printed metal film and substrate. After releasing the pre-strain, well-defined wrinkles formed on the printed film. Due to the strain-engineering islands,
Figure 9. SHE with serpentine interconnect. (a) Various sensors and actuators with serpentine SiNRs structure. (b) A prosthetic limb integrated with numerous serpentine-shaped sensors, actuators, and interconnects caring a baby doll. Reproduced with permission [77]. Copyright 2014, Springer Nature. (c) Transferred light emitting diodes (LED) on PDMS substrate connected by serpentine-shaped ribbons serving as structural bridges and electrical interconnects. (d) Operation of LED array under twisting from 0° to 720°. Reproduced with permission [78]. Copyright 2010, Springer Nature.

gradual wrinkles that relieve interfacial strain were generated at the interface of the interconnects and PRIs (Figure 10(b)). By integrating rigid IC chips with wrinkled electrodes using conductive epoxy on the PRIs, they demonstrated highly reliable SHE with various circuit layouts such as stretchable displays and an analog watch that operated stably on human skin (Figure 10(c)).

Design rules including bonding techniques and areal configurations for improving mechanical reliability of wrinkled-electrode-based SHE have been further investigated [81,82]. Non-conductive epoxy was used not only for robust bonding between IC chips and elastomeric substrate but also for forming strain-free regions around the electrical bonding. Because of the high adhesive force between the epoxy and hydroxyl groups on a UV/O3-treated substrate, the printed epoxy effectively protected the rigid IC chips from mechanical deformations (Figure 11(a)). Based on this approach, two skin-like soft driving systems, each operating as the controlling and activating e-skin, were fabricated by integrating IC chips, passive components, antennas, and actuators with wrinkled electrodes. Each e-skin operated reliably in wireless inter-skin communications even under multidimensional deformations such as bending and stretching (Figure 11(b)). A further advanced design of printed epoxy structures was proposed depending on shapes of various IC chips, to achieve a more conformable, compact e-skin without using bulky components that degrade the stretchability of the whole system [45] (Figure 11(c)).

Based on the aforementioned achievements, wrinkled-electrode-based SHE has emerged as a low-cost, high-density, and mechanically reliable alternative for skin-attachable electronics and robotic skin. Further improvement in process automation and mechanical reliability would bolster the development of commercialized multifunctional on-skin electronics.

3.2.3. Multilayer circuits using vertical interconnect access

Stretchable platforms with advanced functionalities were conventionally achieved by integrating numerous electrical components such as IC chips, sensors, and interconnects into a single layer [45,48,75–78,80–82,85,86,89]. In this case, however, the spatial constraint was one
of the most critical issues, since highly dense arrangements of rigid components in a single platform directly affected stretchability. Several attempts were made to overcome this spatial limitation by integrating electrical components into multiple layers through VIA technologies [14,79,87,88]. With these new approaches, multilayered circuits have recently attracted considerable attention due to their great potential in the implementation of highly integrated stretchable circuits. Adjacent circuit boards in multilayered systems can be electrically connected with each other through a VIA, generally implemented by penetrating a substrate and filling the hole with conductive materials. However, this hole cannot be physically drilled into a stretchable substrate because it significantly affects mechanical stability and the damaged substrate can be easily torn. Considering these issues, we discuss several strategies to implement multilayered SHE focusing on developing robust interlayer VIAs in stretchable electronic systems. Since there are commonly used combinations of interconnects and VIAs, the strategies were classified into three groups depending on the type of stretchable interconnects used: serpentine [87,88], wrinkled [79], and liquid metal interconnects [14].

Xu et al. introduced a 3D integrated stretchable circuit by using VIAs and serpentine interconnects [88]. Because elastomer substrates were difficult to be etched, a laser ablation method was proposed in order to directly pattern VIAs on the soft substrate. The solder paste was screen-printed into the VIAs and reflow-soldered to contact pads, with increasing diameter from the first to fourth layer to ensure sufficient contact with the serpentine interconnects in each layer (Figure 12(a)). The VIA implemented in multilayered SHE showed a robust connection between adjacent layers and could be deformed up to 35% strain without any noticeable delamination. By integrating additional electrical components into the multiple layers, a highly integrated SHE whose size is comparable to a US dollar coin was implemented (Figure
Figure 11. SHE with strain-relief structures based on wrinkled interconnects: (a) Electronic skin (e-skin) composed of various rigid IC chips with printed epoxy structures and wrinkled interconnects. (b) Two skin-like soft driving systems operating in wireless communications under multidimensional deformations. Reproduced with permission [82]. Copyright 2018, The American Association for the Advancement of Science. (c) Operation of conformable e-skins under various mechanical deformations with a further advanced design of printed epoxy structures depending on the shape of each IC chip. Reproduced with permission [45]. Copyright 2019, Taylor & Francis.

12(b)). This SHE could detect various bio-signals such as respiration, skin temperature, EMG, EOG, ECG, and EEG signals as well as wirelessly operate robotic arms based on the detected bio-signals.

Byun et al. established functionally graded core–shell structures for stretchable VIAs with wrinkled electrodes [79]. A mixture of metal particles, silicone resin, and elastomer was printed on a carrier substrate and embodied as the core–shell structure using an applied magnetic field (Figure 12(c)). The metal particles converged and formed the core with vertical chains by the magnetic field, while the remaining silicone resin formed the shell. Since the shell formed a modulus-gradient structure with a higher Young’s modulus compared with the soft substrate, the concentrated strain at the interface was effectively mitigated by this core–shell structure with a securely protected electrically conductive core. Based on this approach, double-sided SHE was developed by integrating IC chips and passive components with the VIA, enabling high-level integration (Figure 12(d)).

Finally, strategies for forming multilayered SHE with liquid metal will be explained. Liu et al. employed solid–liquid BGaIn interconnects and VIAs to maintain connections with rigid electrical components under extreme strain [14]. The BGaIn interconnects were produced by thermally sintering printed EGaIn interconnects and transferring them onto a stretchable substrate.
The VIAs were fabricated by filling BGaIn into laser-cut cavities of the substrate and bridging them with top and bottom interconnects (Figure 12(e)). By using BGaIn as the material for intrinsically stretchable interconnects and VIAs, robust interfacial connections of soft and rigid electrical components were achieved. The fabricated device could maintain its mechanoelectrical properties under deformation, showing a reliable connection with both the top and bottom circuits even under diagonal stretching conditions (Figure 12(f)).

As described in the examples above, multilayered SHE enables a higher level of integration in one platform, allowing devices to have wider functionalities. Despite this advantage, the tradeoff between the density of rigid components and stretchability remains a chronic problem. It is necessary to conduct careful optimizations in
circuit designs and material development in parallel for advanced, future applications of stretchable electronics.

3.3. Flexible circuits interconnected by stretchable electrodes

A flexible substrate containing various electronic components (e.g. IC chips, sensors, and electrodes) can act as a strain-relief island interconnected with stretchable electrodes. More complex circuit modules such as wireless modules can be integrated into SHE using this approach. Because ICs are bonded to rigid interconnects on flexible substrates (not directly to stretchable electrodes), reliable and robust operation of high-performance circuits can be achieved. The number of rigid/soft interfaces that can result in system instability can also be minimized. Despite these advantages, concerns exist from the perspective of strain engineering. For instance, a large dimension of the strain-free area induces high strain concentrated at the interface between the flexible substrates and stretchable materials. Therefore, dimensions and areal coverage of flexible circuits and stretchable electrodes should be deliberately optimized.

As a representative example, Brand et al. developed SHE based on flexible circuits on thin PI (polyimide)-based islands interconnected by serpentes using photolithography [83]. They demonstrated a prototype for a phototherapy device that consisted of islands with dozens of LEDs and meandered stretchable interconnects (Figure 13(a) and (b)). Patch-type wearable devices with various IC chips (e.g. Bluetooth modules, accelerometers, and sensors) were also presented (Figure 13(c)). Similarly, Kim et al. demonstrated all-in-one, wireless wearable health-monitoring systems, which gave functionalities to both sides of the devices to take full advantage of flexible circuits on a thin PI film with stretchable electrodes (Figure 13(d)) [90]. Demonstration of an in-vivo animal study showed that even with various patterns of a rat’s activity, the hybrid-type of stretchable device was conformably contacted and could monitor multiple vital signals (Figure 13(e)).

Because each flexible circuit can become a functional module, modular type SHE can be configured by bridging the flexible circuits. Yoon et al. developed the modular type SHE for customizable health monitoring applications [84]. Since human bodies from different groups vary significantly in terms of size and proportion, it is necessary for body-attachable devices to overcome these variations. The assembly of soft modular electronic blocks could resolve this issue. Island modular blocks containing circuits for various functionalities (e.g. data processing, sensing, or displaying modules) were prepared and bridged via AgNW-based stretchable interconnects in order to complete a single health-monitoring device. Each block with siloxane bonding on its surface is treated with O2 plasma, and subsequently, sandwich activated surfaces of blocks in order to form a robust bond (Figure 14(a)). Figure 14(b) shows the plausibility of the tailored soft wearable devices by completing body-attachable wearable devices onto hands of different sizes using the identical composition of modular blocks.

![Figure 13. SHE based on flexible circuits interconnected by stretchable electrodes.](image-url)
4. Conclusion

In summary, SHE not only plays to the strengths of rigid electronic devices such as high performance, diverse functionalities, and electrical stability but also secures the stretchability of stretchable interconnects, which allows a conformal interface with human skin. Based on these unique characteristics, conventional multifunctional, high-performance PCBs can be reproduced into SHE on human skin, paving the way for unprecedented applications. The comprehensive development of stretchable interconnects, bonding techniques, and schemes for strain engineering enable the reliable implementation of SHE. In the case of stretchable interconnects, novel materials for intrinsically stretchable conductors and stretchable structures of thin metal films have also been developed. Although intrinsically stretchable electrodes provide superior softness and stretchability, technical issues including low electrical conductivity, poor cyclic reliability, and difficulties in bonding with rigid devices must be further addressed. On the other hand, stretchable structures of metal films show high electrical conductivity, great stability, and compatibility with conventional soldering techniques, that is why serpentes and wrinkled metal films have been most widely exploited in SHE. The scheme for strain engineering determines the configuration of SHE: introducing additional rigid islands for protecting thin-film devices, directly bridging rigid ICs with stretchable electrodes, or bridging flexible circuits containing a cluster of ICs with stretchable electrodes. Fabrication methods, bonding technologies, and pros and cons for each scheme are being actively investigated.

With the rapid growth of IoE, SHE has become a central technology for futuristic applications such as health monitoring, diagnosis, and optogenetics on human skin. However, SHE applications are not only limited to on-skin electronics. The strategies for SHE that assemble conventional ICs on soft platforms offer the most compatible frameworks for sensory, control, and communication circuits to achieve multiplexed sensing, processing, and communications in soft robots. Another area where SHE can play a key role is new-form-factor displays. Because most materials for lighting such as OLEDs and micro-LEDs are rigid and brittle, the strategies for SHE can become an alternative, protecting existing rigid and brittle devices and assembling them with stretchable interconnects into stretchable displays.

Future directions are not just limited to the improvement of SHE reliability and performance but are oriented towards practical and comprehensive applications where various future technologies are integrated. One direction is the incorporation with machine-learning technologies where the high-fidelity detection of spatial interactions is of primary importance. Consequently, SHE for tactile ability needs to achieve high spatial/temporal fidelity, which requires high sensor density, bulky electrical wirings, and complex circuit configurations. Reliable interfaces between high-density sensor arrays and processing circuits would be the next challenges in this area. Another direction is the realization of energy-autonomous systems where energy harvesting devices replace external power sources and batteries. For reliable operation of SHE powered by energy harvesting devices, circuit designs considering power efficiency and the integration with apposite power management systems are highly recommended. These directions would extend the functionalities and applications of SHE, spurring the growth of the IoE and robotics sectors.

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