Materials and structural designs for electronic skin

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Abstract. Skin is an essential organ of human body for sensing external changes, such as pressure, temperature, and humidity. Thus, using electronic skin (e-skin) to simulate the functions and properties of real skin has become significantly important in the realm of soft electronics. The primary obstacle in the advancement of e-skin lies in achieving stretchability and flexibility while maintaining high performance. To overcome this obstacle, researchers have developed various materials and structures with distinct properties. This paper provides a comprehensive overview of the evolution of e-skin and technological advancements in materials, including CNT-based materials, graphene-based materials, polymer-based materials, and other novel materials. The paper also delves into novel structures such as wavy structures, island-bridge structures, fractal-inspired structures, and kirigami structures that promote the development of stretchable e-skin. In addition, this paper briefly summarizes the promising properties that further advance the performance of e-skin.

Keywords: E-skin; Stretchable material; Extendable structure.

1. Introduction

Skin is the largest sensory organ of human body. It allows people to perceive changes in temperature and humidity, different shapes and textures of objects, and various degrees of tactile pressure, enabling them to feel and interact with their surroundings. It is also the main barrier to protect human body from external environment. To fulfill these functions, a diverse array of specialized receptors is integrated within the skin, serving to transduce physical stimuli into electrical signals that are subsequently transmitted to the brain for intricate processing. While human skin is highly intuitive, its complexity is often overlooked. To mimic its sensing abilities, prior arts leverage the fabrication of e-skin with structural and functional properties resembling those of natural human tissue. The potential applications of e-skin encompass a broad range of fields, such as human-machine interfaces, prosthetic devices, biomedical instruments, and soft robotics.

To replicate the multiple abilities of human skin, e-skin systems rely on a combination of diverse manufacturing techniques and electronic components, including sensors that are adept at detecting variations in temperature, humidity, and pressure. Additionally, these systems utilize advanced processors that are capable of efficiently processing the collected sensory data. In addition to the ability to interact with surroundings, the e-skin is supposed to be flexible and stretchable to ensure that it can be securely attached to the skin and be stretched as people have body motion without damaging its functions. In response to the aforementioned issue, researchers have developed a variety of specialized materials and structures to enhance the flexibility and stretchability of artificial e-skin. Whilst the primary objective of e-skin is to emulate the vast array of sensory abilities inherent to human skin, there exist several additional properties that are considered desirable in future research on e-skin. These include the abilities of self-healing, self-powering, and other properties, such as biocompatibility. All these aspects will be covered in subsequent sections.

2. Development of e-skin

2.1. 1990-2010

In 1990, flexible electronic materials have been developed by researchers to create large-area sensor sheets that can be printed. Subsequent to this development, a significant amount of research has been conducted to enhance the mechanical durability of large sensor sheets, specifically regarding

their resistance to bending. At about the same time, some works leveraged organic semiconductors for flexible arrays, outperforming amorphous Si. Significant progress in the development of e-skin has been achieved around 1990. Stretchable electrodes have been created for the first time. In 2000, A. Dodabalapur et al. developed large-scale complementary integrated circuits based on organic transistors, which significantly reduced power dissipation, as well as improved noise margins and operational stability [1]. Later, Someya et al. conducted a study aimed at producing flexible organic field-effect transistors (OFETs) with the potential for integration into pressure-sensitive sheets on a large scale [2]. In 2006, J. Rossiter et al. created an optical-based tactile sensor that combines a semi-opaque-compliant medium with LEDs [3]. In 2010, a new kind of pressure sensor based on micro-structured films was developed, which exhibits a better pressure sensitivity than unstructured elastomeric films of similar thickness. This innovation has helped e-skin accustom a great step towards future maturity. Around the same period, there were significant advancements in the field of ultra-flexible organic circuits, which resulted in a notable improvement in the reliability and stability of e-skin.

2.2. 2011-present

In 2011, some epidermal electronics have been developed, which significantly promoted the advancement of e-skin. In 2012, Bao and colleagues made a noteworthy discovery in the field of e-skin by creating a flexible and electrically conducting material with the ability to self-heal both electrically and mechanically [4]. However, the recurrent and consistent demonstration of this self-healing property in e-skin has yet to be accomplished [4]. In 2013, a novel class of stretchable conductors was developed by utilizing carbon nanotube fibers through a pre-straining and subsequent buckling technique. This significant advancement has furnished a fresh avenue for enhancing the stretchability of e-skin. In 2015, Lee et al. devised a novel approach to creating ferroelectric skins by drawing inspiration from the complex properties of fingertip skin [5]. The resultant skins demonstrate exceptional abilities in discerning static and dynamic pressure stimuli as well as temperature changes [5]. This innovative work represents a significant contribution to the field of materials science and has important implications for the development of new technologies. During the same year, a pioneering technique for the transfer printing of patterned graphene was established to facilitate the production of transparent and wearable electronics. This innovative approach enables the seamless integration of e-skin, thereby streamlining the manufacturing process and facilitating the creation of e-skin prototypes. In 2018, Bao et al. proposed a novel circuit design approach for e-skin that aims to enhance the precision and resilience of a temperature sensing system relying on stretchable carbon nanotube transistors [6]. In the same year, ultra-thin Ag−In−Ga e-skin which is highly stretchable was developed. This innovative technology ensures that the resulting "Ag-In-Ga" traces exhibit exceptional conductivity and retain low electrical resistivity even when subjected to deformation and stretching to conform to non-developable three-dimensional surfaces [7]. Such properties are highly desirable for electronic devices that require high flexibility and conformability. In the year 2022, a novel Kirigami-structured liquid metal paper was developed, characterized by its exceptional properties of self-support, ultra-thinness, stretchability, and recyclability [8]. This multifunctional e-skin exhibits outstanding flexibility and conformability, allowing it to conform to curved and irregular surfaces without compromising its electronic performance.

3. Materials

One of the notable properties of human skin is its mechanical compliance, which enables it to deform and conform to the body's shape and movement, enabling it to avoid physical damage as humans change their body motion. The low mechanical young’s modulus of human skin allows it to receive information about the physical properties of the objects that people are dealing with using the receptors under the skin. Consequently, the selection of materials to fabricate synthetic skin must exhibit an equivalent degree of pliability and extensibility to authentic human skin. Furthermore, the

development of e-skin requires the incorporation of additional functionalities, such as self-healing. Below, this paper provides an overview of various materials that are frequently employed in the production of sensors and other associated electronic components in e-skin.

3.1. Substrates

Polydimethylsiloxane (PDMS) has emerged as the predominant material of choice for the fabrication of e-skin and other flexible electronic devices, owing to its commercial availability and well-documented properties. Polyurethane exhibits several notable advantages over other materials, including exceptional stability across a broad range of temperatures, optical transparency, and mechanical properties that can be tailored to specific applications. However, in some specific applications, other substrates might be advantageous, for example, polyurethane has demonstrated compatibility with stretchable printed circuit board (PCB) technologies.

3.2. CNT-based materials

Carbon nanotubes (CNTs) are renowned for their extraordinary mechanical and electronic properties. They usually have a big capacitance that can tremendously reduce the voltage overshoot, significantly improving their electrical performance. At the same time, they have chemical stability, making them one of those ideal materials to fabricate artificial skin. To take advantage of CNTs, they are always dispersed onto a flexible or stretchable substrate. The incorporation of carbon nanotubes (CNTs) within insulating elastomers has resulted in the emergence of semiconducting properties. Additionally, these materials display exceptional mechanical properties and high electrical conductivity. Due to these properties, they are often used as conductive fillers for piezoresistive sensors made of conductive polymeric composites. There are already many applications based on carbon nanotubes in soft and stretchable electronics. In 2017, the e-skin based on polymer/AFWCNT was developed, which exhibits high precision, low power consumption, and good stability. Numerous polymeric substrates, such as polydimethylsiloxane (PDMS), polyurethane (PU), epoxy, polyvinylidene fluoride (PVDF), and polymethyl methacrylate (PMMA), are widely employed in commercial applications. During 2021, a novel platform technology was developed, which integrates multiple layers of highly oriented carbon nanotube (CNT) films and polyacrylonitrile (PAN) to enable the integration of pressure and temperature sensory functionalities into an ultra-lightweight, flexible, and wearable platform with minimal thickness [9].

3.3. Graphene-based materials

Graphene, a carbon allotrope, is composed of a single layer of carbon atoms with an atomic thickness and exhibits extraordinary carrier mobility. Its function varies due to how it was produced, it can demonstrate similar performance as either a semiconductor or conductor.

Graphene can be produced through a variety of techniques that are suitable for the fabrication of artificial skins, and then the graphene films must be transferred to plastic substrates. The commonly used techniques are similar to those of CNT-based materials, including vacuum filtration, spin-coating, and inkjet printing, which guarantee the direct deposition of graphene on large-scale, flexible, and stretchable substrates that can be used in e-skin-related applications. In 2022, a novel and sophisticated e-skin was developed, incorporating laser-scribed graphene and polyurethane (PU) nanomesh. This intelligent e-skin demonstrated exceptional versatility and functionality while maintaining optimal levels of comfort for the user.

3.4. Organic and polymer-based materials

Conducting small molecules and polymers, which are carbon-based materials, have emerged as promising candidates for e-skin due to their inherent adaptability and unique properties. Common semiconducting and conducting polymers include polyaniline (PANI), polypyrrole (PPY), and their derivatives. They demonstrate various properties related to the production of e-skin.

As a result of their superior processibility to CNTs, graphene, and NWs, this category of materials has garnered considerable attention owing to its ability to facilitate the fabrication of cost-effective, high-density device arrays on a large scale. Polymer composites have emerged as a preferred material choice for the development of flexible electronic devices due to their superior mechanical flexibility, excellent stretchability, and ability to be functionally engineered to meet specific application requirements. As a result, polymer composites represent the most auspicious materials to enable the realization of the forthcoming generation of flexible and wearable electronic devices. An advantageous property of organic and conducting polymer-based materials is their remarkable mechanical compatibility with natural human skin, in contrast to their inorganic counterparts, making them ideal for implementation in the e-skin. Many other materials have a mechanical mismatch with human skin due to different Young's modulus, causing uncomfortable sensations or physical damage when people apply e-skin on their bodies. For example, many small molecule semiconductors show very little tolerance for strain, while in contrast, most of the polymers have demonstrated a strong ability to go through severe deformation, yet maintain their great electrical performance. Moreover, polymer-based materials are also crucial to the development of self-healing e-skin. There has long been much progress in stretchable and self-healing conductors, semiconductors, and substrates.

3.5. Other materials

There are other types of materials aim to improve the performance of e-skin. In 2018, Lopes et al. devised an ultra-thin, highly conductive, and stretchable e-skin made of Ag–In–Ga. This innovative e-skin demonstrated exceptional electrical performance, maintaining low electrical resistivity even when subjected to significant stretching to conform to non-developable three-dimensional (3D) surfaces [7]. Furthermore, it has been widely acknowledged that liquid metal (LM) represents an optimal material choice for electrodes in the development of e-skin. However, the inadequate performance of monitoring can be attributed to the incapacity of conventional sealed liquid metal (LM) electrodes to expose the LM layer for direct interaction with the skin [8]. Traditional printed LM electrodes are difficult to transfer or recycle, and fractures easily occur under the stretching of the substrate. To address these challenges, Li et al. successfully devised a novel type of liquid metal (LM) electrode known as kirigami-structured LM paper in 2022, which is self-supporting, exposes the conductor, demonstrates exceptional stretchability and ultrathin properties, and is recyclable, thereby enabling the realization of multifunctional e-skin [8].

4. Structures

A crucial attribute of the human skin is its remarkable ability to stretch and bend without incurring any physical harm when people have body motion. Although large-scale arrays of soft and flexible electronics have already been achieved, the development of stretchable devices has proved to be substantially more challenging. Despite new materials, researchers have also made much progress in structural designs for stretchable electronics such as e-skin. Below, this paper will briefly discuss some of these structural design strategies.

4.1. Wavy designs

In wavy design, wavy structures are created and combined with elastomeric and flexible substrates. There are two strategies to produce such wavy structures, as illustrated in Fig. 1a. The ribbon-shaped thin films are applied to a PDMS substrate that has already been pre-stretched. The surface chemical treatment allows for powerful bonding at either specific locations or along the entire length of the ribbons, and then the thin films are pressed into wavy shapes after removing the prestrain [10]. There are many applications based on wavy structure. For example, in the year 2021, researchers developed an advanced methodology for designing ultrahigh molecular weight polyethylene (UHMWPE) fibers with a wavy configuration to function as a reinforcement filler [11].

4.2. Island-bridge

To achieve high levels of stretchability, beyond wavy designs, researchers have come up with the island-bridge design. The proposed island-bridge architecture entails the integration of discrete islands, comprising inflexible electronic components, onto malleable substrates with interconnecting stretchable bridges. This novel approach ensures that the islands maintain a robust bond with the substrate, while the bridges exhibit a relatively weaker connection to the substrate. Thus, the rigid, unbendable electronic components could be mechanically isolated. The vast majority of the strains applied to the system are accommodated using stretchable and dissociative interconnects. Since they are more tolerant of deformation, this strategy could help protect the functional components. The focal point of island-bridge designs centers on the composition of the interconnects, which may take various forms, including but not limited to arc-shaped, serpentine, 2D spiral, and 3D helical configurations [10].

The first type is arc-shaped interconnects, which undergo a compressive buckling process to transition from a two-dimensional planar configuration to its final three-dimensional shape, as shown in Fig. 1b. Upon the application of external strain to this particular configuration, the arc-shaped interconnects exhibit a notable capacity to deform effectively out of their original plane [10]. The interconnects have lower stiffness compared to the islands of rigid components, providing perfect mechanical isolation of the islands.

The second type is serpentine interconnect. To fully investigate the buckling physics in serpentine structures, researchers have created analytical models for the suspended serpentine interconnects. They then provided a design strategy for the serpentine interconnects to achieve the desired stretchability. Subsequently, in 2014, Zhang et al. introduced a prestrain methodology wherein serpentine interconnects, firmly adhered to a pre-stretched substrate, exhibited a markedly enhanced mechanical performance. Specifically, this approach resulted in an increase in stretchability by over twofold when compared to the corresponding scenario without prestrain [12].

The third type is 2D spiral interconnects, which are curves formed by winding a circle from a fixed point [10]. This kind of geometry structure is easy to find in the natural environment. Upon the application of lateral strain to the 2D spiral-shaped configuration, the spiral undergoes an unwinding process through out-of-plane deformations. After the force is removed, the strain energy is released, and the spiral returns to its initial location and shape subsequently. In comparison to the conventional serpentine interconnects with identical area coverage and contour length, the adoption of a 2D spiral-inspired bridge/interconnect design can generate interconnected islands that experience minimal stress and exhibit superior stretchability properties. The researchers have found that in this structure, the incorporation of uniform and minute curvatures in the interconnects typically yields an enhanced stretchability that allows for the effective linkage of the islands [12].

The alternate form of interconnects discussed is the 3D helical configuration, which presents a structural arrangement with an exceptionally low effective modulus and a high degree of elastic stretchability, making it an ideal structure for inorganic electronics.

Many of the commercially available applications related to e-skin have already applied the island-bridge design strategy. For example, in 2019, the recent developments and potential applications of e-skin in closed-loop systems were reviewed, utilizing island-bridge architectures [13]. In 2022, Zhang et al. employed the island-bridge framework to construct a versatile, temperature-responsive e-skin that can accommodate a broad range of temperatures while remaining flexible [14]. The implementation of island-bridge structures has notably enhanced the pliability and wearability of e-skin systems.

4.3. Fractal-inspired designs

Fractal-inspired designs are a highly effective approach towards achieving exceptional stretchability and extensive areal coverage in inorganic stretchable electronics, such as e-skin, as illustrated in Fig. 1c. Such designs leverage the unique properties of fractals to create patterns that exhibit a high degree of structural self-similarity across multiple length scales. This property enables

the resultant materials to maintain their structural integrity and electrical conductivity even under significant mechanical deformation. Therefore, the incorporation of fractal-inspired designs in the development of stretchable inorganic electronics holds great promise for a wide range of applications. Fractal layouts for stretchable functional components enable conformal matching to soft materials and curvilinear surfaces, which is crucial for applications in bioelectronics and other fields involving bio-interfaces and bio-inspired designs. The implementation of fractal layouts has been demonstrated to significantly augment the stretchability of materials, while simultaneously enhancing the space-filling ratio. The utilization of fractal-based patterns facilitates the creation of structures with a high degree of geometrical self-similarity, enabling the resultant materials to maintain their structural integrity and electrical conductivity even under considerable mechanical strain. This property makes fractal layouts an attractive approach for the design of advanced materials that require exceptional flexibility and conformability [15]. Some of the prior research has shown how Peano, Greek cross, Vicsek, and other fractal forms can be used to produce space-filling electronic structures. The findings imply that fractal-based patterns are significant fabrication techniques for e-skin.

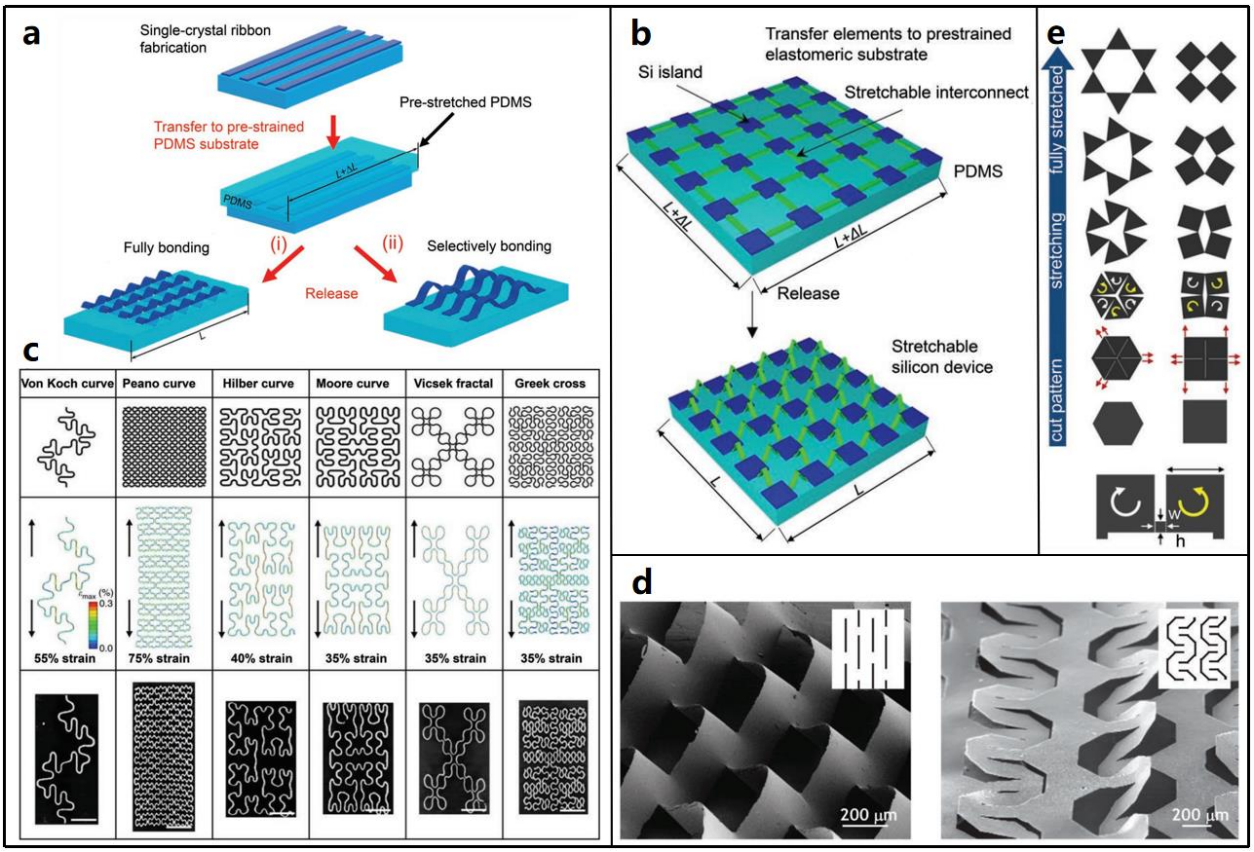


Fig 1. Illustrations of some structures. a) Schematic illustration of two different bonding strategies on the elastomeric PDMS substrate for wavy structures that are fully and selectively bonded onto the substrate. Adapted with permission [16]. b) Schematic illustration of the fabrication and mechanics model of the device island mesh with arc-shaped design. Reproduced with permission [17]. c) Representative fractal layouts and their FEA, MicroXCT images under elastic tensile strains. Scale bars are 2 mm. Reproduced with permission [10]. d) SEM images of two examples of kirigami patterns in graphene oxide/poly (vinyl alcohol) nanocomposites. The insets are the corresponding kirigami unit cells. Reproduced with permission [18]. e) Schematic of an in-plane rotation kirigami design. The planar materials are cut and separated, enabling in-plane rotations with stretching. Reproduced with permission [10].

4.4. Kirigami strategy

The kirigami strategy means dividing a thin film (2D sheet) into many periodic parallels and repeated units by fine wire cutting, using the deformation between those units to accommodate the large in-plane stretching, instead of making the units themselves deform, as illustrated in Fig. 1d. Simultaneously, investigations indicate that a uniform distribution of applied force can be achieved across a majority of the domains on the kirigami substrate, thus preserving electrical resistance [10]. So this strategy significantly improves the material's tolerance towards damages that are caused by the stretching and rotating to which they are attached. The kirigami methodology can facilitate in-plane component rotation in response to in-plane extrusion. This is accomplished by segmenting the planar structure into rotatable units utilizing a precise cutting scheme, which confers rigidity between the interstices of the rotatable units [10]. Its mechanical properties can be adjusted according to the cutting mode [10], as illustrated in Fig. 1e.

5. More desirable properties for e-skin

E-skin has the potential to replicate the sensing abilities of the human skin. E-skin has can detect and interpret properties such as the pressure and texture of objects with a high degree of accuracy. Additionally, researchers have imbued this artificial skin with flexibility and stretchability, rendering it less susceptible to physical damage and more comfortable to wear. These properties also contribute to the durability of the e-skin, allowing it to maintain its functionality over an extended period of time without requiring repair or replacement.

In addition to the aforementioned abilities, e-skin requires a multitude of desirable properties, such as self-healing, self-powering, and low power consumption. Self-healing ability, an inherent property of human skin, is considered one of the most coveted properties of e-skin. Furthermore, the development of e-skin devices with low power consumption or self-powering ability warrants further investigation, given the persistent energy crisis that remains one of the most pressing challenges in modern society.

In light of the requirement for direct contact with biological entities, it is imperative that the fabrication of e-skin involves the utilization of materials that demonstrate biocompatibility. It has been discovered that some of the biocompatible materials, such as CNTs, which were initially considered for this purpose, do not demonstrate biocompatible properties. This is attributed to their minute size and needle-like morphology, which has been found to mimic the pathogenic behavior of asbestos [19]. High concentrations of CNTs have been verified to be detrimental to human cells, indicating their toxicity [19].

6. Conclusion

This paper offers in-depth research into the development process of e-skin, as well as a comprehensive review of two important factors taken into account during the fabrication of the highly-integrated e-skin. First, this paper lists many types of materials that are suitable to fabricate e-skin, such as CNT-based, graphene-based, polymer-based, and other novel materials. Second, this paper shows some of the existing structures that can improve the stretchability of e-skin, such as the famous island-bridge structure and the fractal-inspired structure. Consequently, the discussion briefly touches upon some of the desirable properties of e-skin.

Despite the demonstrated feasibility of e-skin systems in recent research, there exist several challenges that must be addressed to enable their widespread adoption in everyday activities. The demand for diverse categories of sophisticated smart e-skin has become increasingly pressing, particularly in the emerging fields of healthcare, encompassing health monitoring, prosthetic methodologies, and clinical medicine. Analogous to the extraordinary adaptability of natural human skin, which can promptly respond and provide feedback to various external stimuli via the peripheral nervous system, the forthcoming artificial e-skin has the potential to intelligently react to alterations

in its surroundings through advanced information transmission technology. This holds great promise for future advancements in e-skin technology.

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