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Mini Review

Manufacturing strategies for stretchable synaptic transistors

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A B S T R A C T

Neuromorphic devices mimic the function and structure of biological synapses, which can achieve simultaneous signal transmission and learning. This mini review outlines the latest progress in the fabrication and application of stretchable synaptic transistors, providing a reference for the development of future wearable neuromorphic devices. We summarize the functional layer materials used for stretchable synaptic transistors, then present advanced manufacturing methods and emerging device structures. We also explore application of such devices in artificial nervous systems. Finally, we discuss the challenges and future development directions of stretchable synaptic transistors. The application of neuromorphic devices to stretchable electronics will facilitate the development of wearable electronics, health care, and human-machine interfaces.

1. Introduction

Neuromorphic electronics, inspired by biological nervous systems, enable efficient and parallel processing of large amounts of complex information [1,2] (Fig. 1). This approach overcomes the von Neumann bottleneck caused by the separation of storage and computing, which limits energy efficiency and increases power consumption [3–5]. Synapses are specialized structures in biological nervous systems that enable neurons to transmit signals to other neurons, playing a crucial role in information processing and communication. The development of electronic devices with synaptic functions is the core of realizing neuromorphic electronics [6–10] (Fig. 1**a**). In synaptic transistors, the gate electrode and the channel are analogous to the pre-synaptic and post-synaptic terminals, respectively. The channel current or conductance represents the synaptic weight, which reflects the strength of the connection between neurons. By modulating the synaptic weight by electrical or optoelectronic stimuli, various synaptic functions can be emulated [1,2,4]. The development of neuromorphic electronics will also promote the development of smart healthcare, soft robots, and neural prostheses.

Wearable and implantable electronic technologies require stretchable devices that can conform to non-planar surfaces such as skin, fabrics, and soft robotics, but can also be applied to biological tissues and neural interfaces [11–13]. The development of stretchable synaptic devices provides new possibilities to overcome these challenges [2,5,14]. The use of stretchable materials and the modification of stretchable devices are two key strategies to optimize stretchable neuromorphic electronics (Fig. 1**b**).

Stretchable materials can be structured as either homogeneous layers or hetero-assembled bi-layers [15]. Both approaches can achieve compatibility of electrical and mechanical properties, but the inherent complexity of material synthesis and the current need to use multi-component composites to achieve stretchability limit the development of high-performance stretchable neuromorphic electronics [16,17]. Current methods that fabricate stretchable synaptic devices aim to increase stretchability by engineering the device structures to distribute the stress or by optimizing the stretchability of the assembled layers [18–20]. The quality of the manufacturing process determines mechanical and electrical properties, and scalability of the stretchable neuromorphic systems. Early strategies to improve strain tolerance often employed geometric designs, such as wavy structures, to enhance stretchability [21]. More recent approaches involve the development of stretchable neuromorphic devices using materials with honeycomb structures [22]. Advanced microtechnology has promoted the development of stretchable neuromorphic

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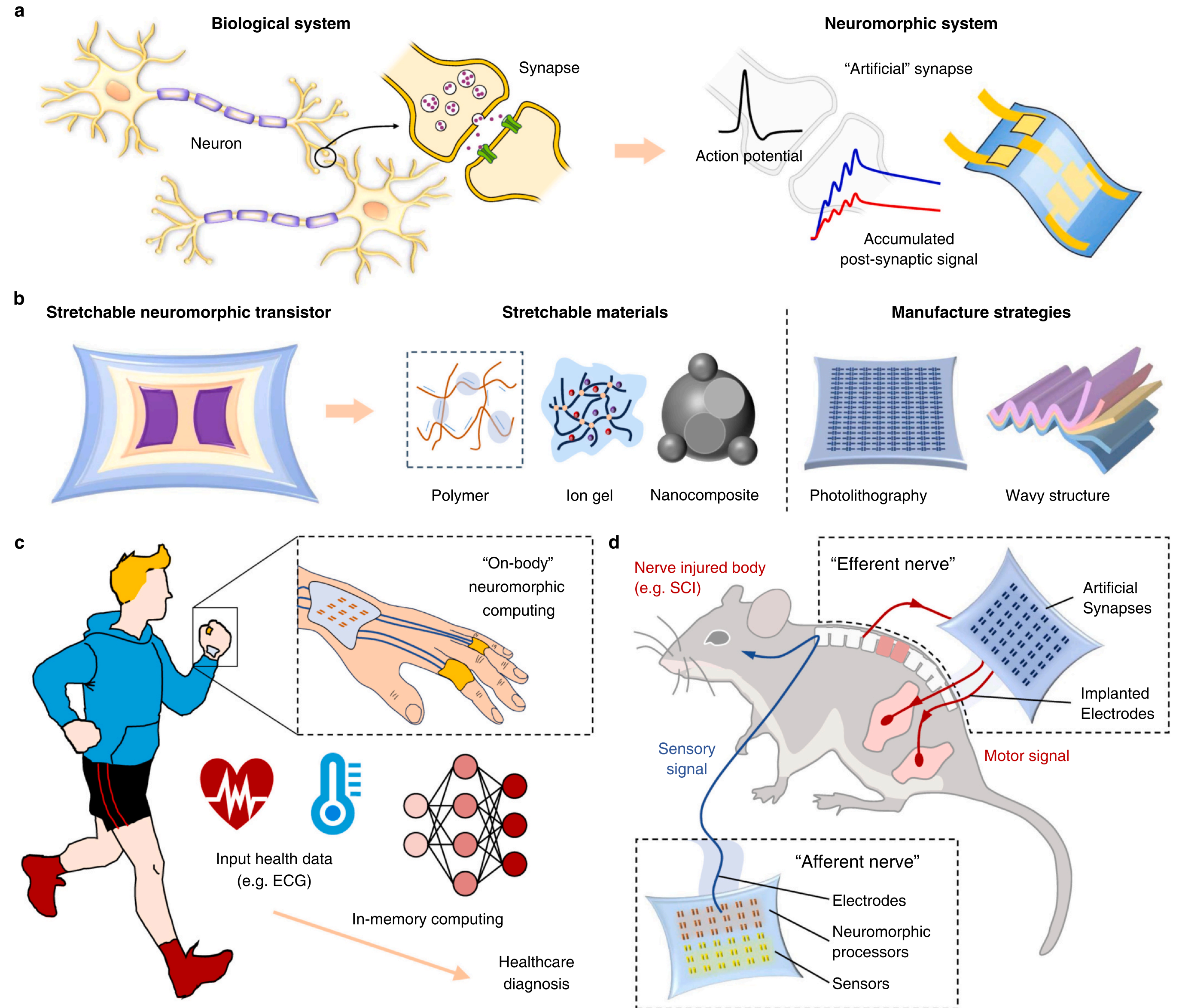

Fig. 1. Schematic illustration of the development of stretchable synaptic transistors: a) emulation of biological neural system principles in artificial neuromorphic systems, enabled by b) advanced manufacturing approaches to achieve stretchability and functionality in bio-inspired electronic devices. stretchable synaptic transistors for c) wearable devices and d) artificial nerve applications.

devices, such as the first intrinsically-stretchable synaptic device that are fabricated using photolithography [23] or inkjet printing [24]. Although some progress has been made in stretchable synaptic transistors, the research on high-quality stretchable synaptic transistor arrays is still in its initial stage; the advanced fabrication processes for stretchable neuromorphic devices are rarely summarized and analyzed in reviews.

This mini review summarizes the recent progress in processes to fabricate stretchable synaptic transistors. Section 2 introduces the design and optimization of functional materials for each part of stretchable synaptic devices. Section 3 introduces advanced micro-nano technologies (lithography, printing, and lamination-and-transfer) and device structures (wave structure, vertical structure, and textile-type) for realizing stretchable synaptic transistors, summarizes their characteristics, and shows representative examples. Section 4 discusses the application of stretchable synaptic transistors in wearable and implantable electronic technologies (Fig. 1**c,d**). Finally, Section 5 summarizes and discusses the main challenges and future research directions of the fabrication process of stretchable synaptic transistors. This review lays a foundation for the future research of synaptic transistors in stretchable neuromorphic electronic devices. Future development prospects of neuromorphic devices using biomaterials are envisioned, and challenges that must be overcome to achieve practical applications of sustainable stretchable electronics are discussed.

2. Materials for stretchable synaptic devices

Stretchable substrates are the basis of stretchable synaptic devices. These substrates must be designed with excellent high deformability and mechanical stability, and should also be chemically stable. Many elastomers have been developed and used in stretchable synaptic devices. Polystyrene-block-poly(ethylene-butylene)-block-polystyrene (SEBS), polyurethane (PU), poly(dimethylsiloxane) (PDMS), and thermoplastic polyurethane (TPU) are commonly used as stretchable substrates [25–29]. PDMS and SEBS are the most widely used in stretchable synaptic transistors due to excellent mechanical flexibility, good optical transparency, and low cost. The stretchability can also be increased (i.e., Young's modulus decreased) to match that of biological tissues by adding a soft interlayer such as hydrogel [13].

Stretchable electrodes require materials that can maintain electrical conductivity under considerable strain. Conventional metal electrodes are not suitable, because they are prone to cracking when stretched. Stretchable electrodes can be categorized into three main types: nanocomposites (e.g., carbon nanotubes (CNTs), silver (Ag) nanowires (NWs)), conductive polymers, and liquid metals [26,27,30–32]. Poly (3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT: PSS) is the most common type of conductive polymer. In addition, ionic gels and conductive rubbers can also serve as stretchable electrodes [32,33]. Stretchable devices constitute an emerging research topic, therefore few studies have considered stretchable electrodes.

Current strategies to achieve stretchable semiconductors can be broadly classified into three categories: creating wavy structures by pre-stretching to increase stretchability, blending elastic polymers with semiconductors, and developing intrinsically-stretchable semiconductors by inducing the formation of honeycomb porous structures [22,32,36,41]. Organic semiconductors contain conjugated main chains and side chains, which can conduct electrons and that are conducive to ion embedding, and therefore can yield effective coupling of electrons and ions [42]. Organic semiconductors also have low Young's modulus and flexible and adjustable intermolecular arrangement [43] and are therefore being evaluated for use as stretchable semiconductors. The materials used for stretchable semiconductors are mainly divided into two categories: p-type, in which carriers are mostly holes; and n-type, in which carriers are mostly electrons. In stretchable synaptic transistors, p-type semiconductors are mainly represented by poly(3-hexylthiophene) (P3HT) and PEDOT: PSS.

Stretchable insulators are also important components of stretchable synaptic transistors. Insulators can provide electric field isolation in stretchable synaptic transistors, and thereby affect the working voltage and inducing movement of carriers [5,44]. Three main types of stretchable insulators are currently used in stretchable synaptic transistors: ion gels, hydrogels, and organic polymers [31,32,35,36,45–49]. Ion gels and hydrogels can provide mobile ions, whereas organic polymers can provide trap sites. Ion gels prepared with poly(vinylidene fluoride-co-hexafluoropropylene) (PVDF-HFP) and 1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide ([EMIM][TFSI]) are the most commonly used gate insulators. Organic polymers, SEBS, PU, and PDMS, are also applied to the devices as insulators. Under an applied voltage, the corresponding carriers are induced in the semiconductor (another layer), thereby regulating current transmission and synaptic function. Representative examples of stretchable synaptic transistors are summarized in Table 1 according to their stretchable materials and the device's stretchability.

However, there are still significant challenges remaining in the field of materials for stretchable synaptic transistors. While significant advances have been made in improving mechanical stretchability, maintaining reliable electrical performance under mechanical deformation remains difficult due to structural deformation and disruption of intermolecular arrangements. Intrinsic approaches in material design have effectively maintained carrier mobility, but these methods have not fully addressed device degradation caused by repeated mechanical deformation. Additionally, for semiconductor materials, current material strategies inherently involve trade-off. Blending polymer semiconductors with insulating additives improves stretchability but typically reduces electrical conductivity, whereas intrinsically-stretchable semiconductors demand complex chemical synthesis and design. Therefore, it is becoming increasingly important to develop manufacturing methods that can maintain stable electrical characteristics regardless of mechanical deformation.

3. Manufacturing strategies for stretchable synaptic transistors

The fabrication processes and device structures of stretchable synaptic transistors also significantly influence their electrical characteristics. Under tensile strain, various components of the device experience stretching stress, resulting in corresponding deformation. The film quality of each layer directly affects interfacial interactions, playing a crucial role in achieving high-quality neuromorphic devices.

3.1. Fabrication processes

3.1.1. Photolithography and photopatterning

Photolithography is the main process that is used to fabricate small, high-precision and large-area micro-nano electronic devices, and has also been used in stretchable synaptic transistors [17,44]. The photolithography process entails photoresist coating, ultraviolet (UV) exposure (photochemical reaction), development, etching, and photoresist removal [17]. Photoresists are of two types, 'Positive' and 'Negative' photoresists. 'Positive' photoresists become soluble in the photoresist developer when exposed to UV light, whereas 'Negative' photoresists harden under UV exposure [50]. A layer of oxide is deposited as a protective layer, and the photopatterned film can be protected from plasma etching and long-term ultraviolet radiation [23,51] (Fig. 2**a**). A method of depositing a silicon dioxide (SiO_2) layer as a protective layer has been proposed, and photolithography has been used to prepare neuromorphic electronic skin [51]. A layer of poly(vinyl alcohol) (PVA) was spin-coated as the gate dielectric layer, and a layer of SiO_2 was deposited on it,

Table 1
The stretchability of stretchable materials-based synaptic devices.

Electrode	Type	Fabrication method	SC	Fabrication method	IG	Sub	Struct	Stretch	Ref.
M-CNT	NP	Photolithography	S-CNT	Photolithography	PUU	PDMS	Planar	50 %	[23]
CNT	NP	Lamination-and-transfer	DPP-DTT/SEBS	Lamination-and-transfer transtransfer	SEBS	SEBS	Planar	100 %	[34]
CNT	NP	Spray coating	CONPHINE	Photopatterning	Nitrile rubber	SEBS	Planar	100 %	[35]
CNT	NP	Spray coating	FT4-DPP + PEO	Electrospinning	Ion gel	SEBS	Wavy structure	100 %	[36]
CNT	NP	Spray coating	FT4-DPP + PEO	Electrospinning	Ion gel	SEBS	Wavy structure	100 %	[26]
CNT/AgNW	NP	Spin-coating	P3HT-NF	Spin-coating	PVA	PDMS	Vertical	60 %	[37]
Au fiber	NP	-	P3HT	Die-coating	Ion gel	-	Textile-type	-	[38]
Ag fiber	NP	-	Pentacene	Thermal evaporation	P(VDF-TrFE)	-	Textile-type	-	[39]
PEDOT:PSS	CP	Printing	CNT	Printing	PVDF-HFP	SEBS	Planar	20 %	[24]
PEDOT:PSS	CP	Lamination-and-transfer	PEDOT:PSS	Lamination-and-transfer	NaCl	TPU	Planar	50 %	[28]
PEDOT:PSS	CP	Spin-coating	Pg2T-T + GO	Spin-coating	Ion gel	PU	Planar	100 %	[40]
LM	LM	Blade coating	PEDOT:PSS	Spray coating	Hydrogel	PDMS	Planar	100 %	[31]

Abbreviation: **SC**: Semiconductor; **IG**: Gate insulator; **Sub:** Substrate; **Struct:** Device structure; **Stretch**.: Stretchability; **NP**: Nanocomposites; **CP**: Conductive polymer; **LM**: Liquid metal.

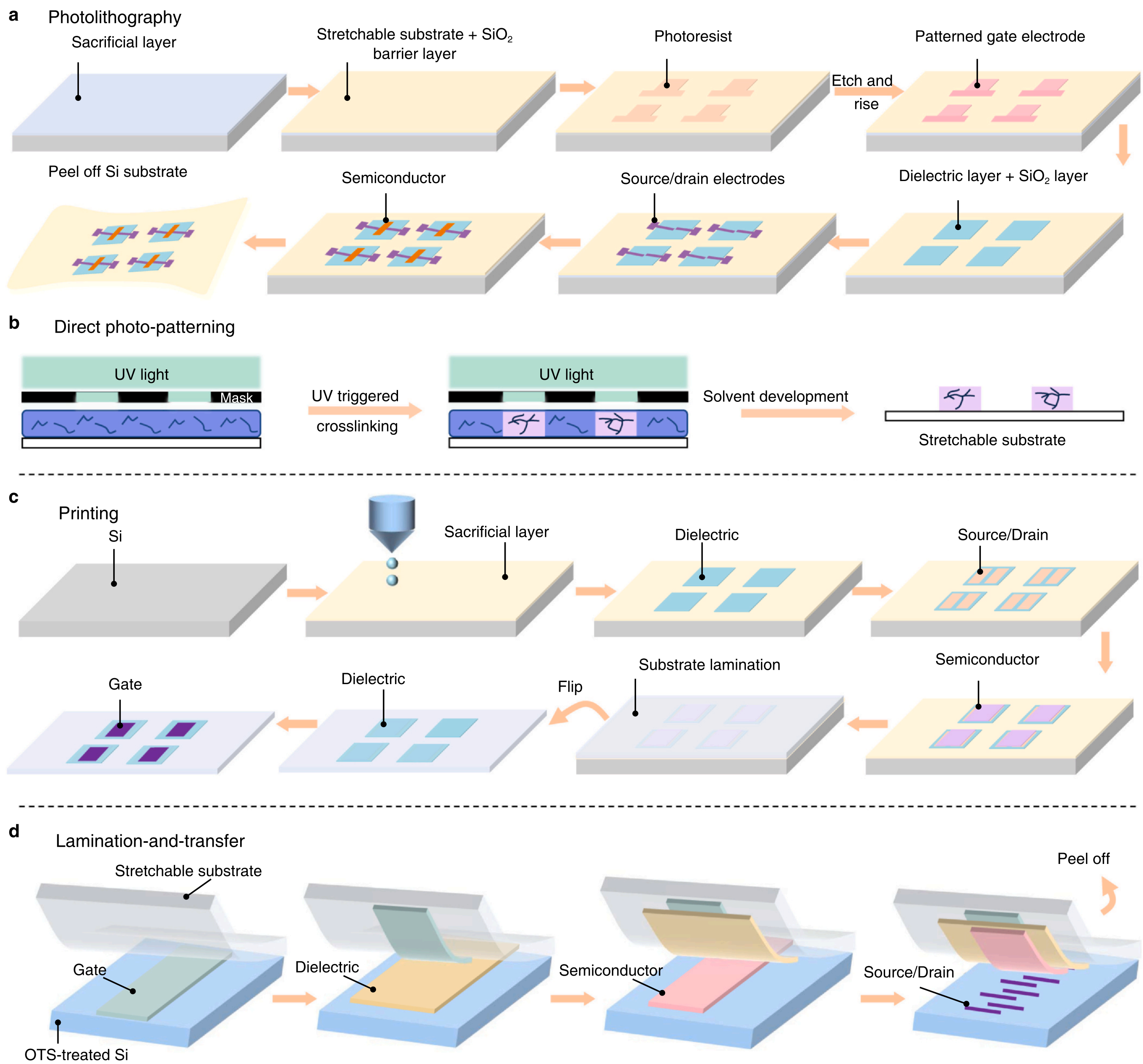

Fig. 2. Schematic diagram showing the fabrication processes of stretchable synaptic transistors. Fabrication processes of stretchable synaptic transistors: a) photolithography and b) direct photo-patterning, c) printing, and d) lamination-and-transfer.

followed by photolithography and plasma etching of metal-carbon nanotubes (M-CNTs). The presence of SiO_2 protects the PVA layer from the effects of plasma and solvents. The prepared device could maintain synaptic function under 50 % strain and exploit the temperature response characteristics of PVA to achieve temperature-adjustable synaptic activity. However, in application to organic materials, traditional photolithography technology has the problem that the organic materials may be incompatible with the photoresists or the etching solutions.

Therefore, the photopatterning method (Fig. 2**b)** is more widely used than photolithography in organic devices [52,53]. The photochemical reaction generated by exposure to UV light changes the solubility of the original film, rather than of a resist, then high-precision patterns can be easily obtained by washing with a suitable developer. Using this method, multilayer materials can be stacked and patterned to obtain multifunctional devices [54]. Currently, the preparation of stretchable synaptic devices mainly relies on the photoinduced crosslinking method. The photo-crosslinking patterning method of organic materials uses a mixture of organic materials, photoinitiators, and photo-crosslinking monomers, then irradiates them under UV light to induce crosslinking of monomers, then forms patterns under the action of masks (Fig. 2**a**). Organic materials can be photopatterned by embedding in interpenetrating polymer networks or directly crosslinking by using crosslinkers [55]. Photopatterning method for manufacturing stretchable synaptic transistors has been proposed by photo-crosslinking with organic materials using azide chemical reactions [35]. Azide (-N_3) can undergo click chemical reactions with alkyl groups under ultraviolet irradiation to produce polymer network crosslinks [17]. The gate dielectric layer (nitrile-butadiene rubber, SEBS and octadecyltrimethoxysilane (OTS) is spin-coated with azide crosslinker, then a pattern is formed by UV crosslinking, and finally, a 2-μm high-precision pattern is obtained. At the same time, due to the high dielectric constant of the dielectric layer, a 10^6 on/off ratio can be achieved at low voltage (~3 V), and finally, a monolithic integrated soft electronic skin system can be realized.

3.1.2. Printing

Printing technology (Fig. 2**c)** avoids the damage that organic solvents and high-dose UV light in photolithography can impose on active materials. Micropatterning of these materials to prepare stretchable synaptic devices has always been a major challenge, especially for the realization of the next generation of highly integrated stretchable electronic devices. This method offers high customization, low cost, and high durability as an alternative method for depositing such materials for patterning. Printing technology can be roughly divided into two categories: non-contact patterning and contact patterning. Non-contact technology uses nozzles; some examples include aerosol jet printing, electrohydrodynamic (EHD) printing, inkjet printing, and electrospinning. Contact technology mainly includes roll-to-roll printing, gravure printing, and screen printing [56]. The basic principle of these technologies is to transfer ink to the substrate. The printing process must consider changes in the ink composition, printing-device geometry, and substrate, but the main challenges involve the composition of the ink [57]. Among printing technologies, inkjet printing and electrospinning are the most commonly used methods for producing neuromorphic devices. Inkjet printing uses a nozzle that ejects continuous droplets under mechanical pressure. Electrospinning uses the voltage between the nozzle and the translation stage to control the formation of droplets.

The ink is formed by dispersing functional materials, specific adhesives, and additives in an appropriate solvent. To optimize the printing precision, the droplets must be stable, consistently-sized, and produced in a uniform stream; the pattern design must also be reliable [58]. During the printing process, aggregation and blockage of the print head nozzle can easily occur. Therefore, the density, viscosity, particle size, and surface tension of the ink strongly influence the formation and ejection of droplets and affect the printing accuracy and resolution [56].

A stretchable organic optoelectronic sensorimotor synapse [36] has been fabricated by electrospinning, using fused-thiophene diketopyrrolopyrrole (FT4-DPP) organic semiconductor and polyethylene oxide (PEO) polymer to prepare uniform ink. The PEO can act as a molecular adhesive and improve the deformation ability so that uniform and continuous organic semiconductor NWs can be obtained. The pattern containing the wires was transferred to a SEBS elastic substrate that had been pre-strained to 100 %. After the stress was released, the electrical characteristics of the device remained stable after it was repeatedly stretched to 100 % strain.

Additionally, a sinter-free printed conductor using screen printing to prepare a stretchable sensory neuromorphic system has also been proposed [59]. A mixture of Ag flakes, polymer chains, and solvents with different boiling points was used to prepare a stretchable neuromorphic circuit [60]. Optimization of the evaporation rate of the solvent achieved a tolerance to stretching of 160 %. Self-mixing dual-phase ink has been developed to improve the stretchable properties of patterns. The ink was prepared using a dual-phase composite material of liquid metal particles and rigid metal particles mixed with graphene oxide and liquid metal and achieved a high tensile strain of 1200 % and a high conductivity of 2.3×10^6 S/m. An intrinsically-stretchable low-voltage synaptic transistor array has been achieved using only inkjet printing [24] to simultaneously deposit, pattern, and stack intrinsically-stretchable active materials. Ion migration in the gate dielectric hinders the switching speed, but this method is ideal for achieving synaptic transistor responses at operating voltages as low as 1 V.

In summary, inkjet printing offers high-resolution patterning suitable for flexible and complex structures, though issues like ink clogging may arise. Electrospinning enables the formation of stretchable nanofiber networks, enhancing device flexibility and surface area. Screen printing is low-cost and scalable, making it suitable for mass production of stretchable electrodes and circuits.

3.1.3. Lamination-and-transfer

Lamination-and-transfer (Fig. 2**d)** is a simple method that prepares stretchable synaptic transistors by directional lamination and peeling of functional layer materials. First, a soft elastomeric stamp is prepared, then pressed onto the target film (or the soft elastomeric material is deposited onto the target film), then the target film is transferred to the receiving substrate by the soft elastomeric stamp [61,62]. The success of the transfer of the target organic film to the receiving substrate is mainly controlled by the difference in work of adhesion between the interface between soft elastomeric stamp and target film, compared to the interface between the target film and the substrate. The differences are related to the surface energies E_S of the materials in each layer. Usually, E_S is much higher on the target film than on the soft elastomeric stamp and the substrate, whereas the E_S of the soft elastomeric stamp is usually very low. To assist in the release of the film to the receiving substrate, heating can also be used to reduce E_S of the soft elastomeric stamp and improve the contact between the target film and the receiving substrate [62].

The adhesion of the soft elastomeric stamp is controlled by dynamics. For example, peeling off the target film with the soft elastomeric stamp at a high enough speed will produce a strong adhesion between them, whereas releasing the target film at a low speed can increase the adhesion between the target film and the substrate. Methods to transfer the soft elastomeric stamp to the target film to the receiving substrate can be divided into 'dry' and 'wet' processes. Dry transfer entails gently lifting the soft elastomeric stamp to peel it off; wet transfer entails immersion in a solvent to peel off the soft elastomeric stamp layer.

A method to prepare stretchable synaptic transistors using PDMS as a soft elastomeric stamp has been proposed [30]. The PEDOT: PSS solution was spin-coated using a Kapton mask, then the PEDOT: PSS film was transferred using a PDMS stamp, then the channel layer and electrolyte layer were deposited. A synaptic transistor made entirely of organic materials was obtained, and the synaptic function was maintained after stretching to 30 %. The transistor was combined with a pressure-sensitive rubber sensor to prepare an elastic neurological electronic skin to achieve human-robotic interaction.

Self-assembled monolayer treatment can also be used to reduce the adhesion of the target film to the initial substrate to increase the success rate of transfer. The organic material was coated on a substrate treated with n-octadecyltrichlorosilane (OTS), and the SEBS layer was used to transfer the materials of each functional layer to prepare a stretchable synaptic visually-adaptive transistor [34]. The transistor can maintain synaptic function under 100 % tensile strain and also operate at ultra-low energy consumption (15 aJ).

In summary, each fabrication method for stretchable synaptic transistors offers distinct advantages and is suited to specific applications. Photolithography and photopatterning are suited for high-precision and large-area devices, with photopatterning better for organic materials. Printing techniques are cost-effective and ideal for customizable devices but require precise ink control. Lamination-and-transfer methods are straightforward and versatile, enabling the integration of fragile or complex functional layers onto stretchable substrates.

3.2. Emerging device structures

Device architecture also significantly influences the operation and electrical characteristics of stretchable devices. Beyond traditional planar structures, researchers are actively exploring innovative device architectures to enhance electrical characteristics and broaden applications. This section highlights several representative architectures of single-device structural innovations, mechanical design strategies for stretchability, and system-level integration approaches.

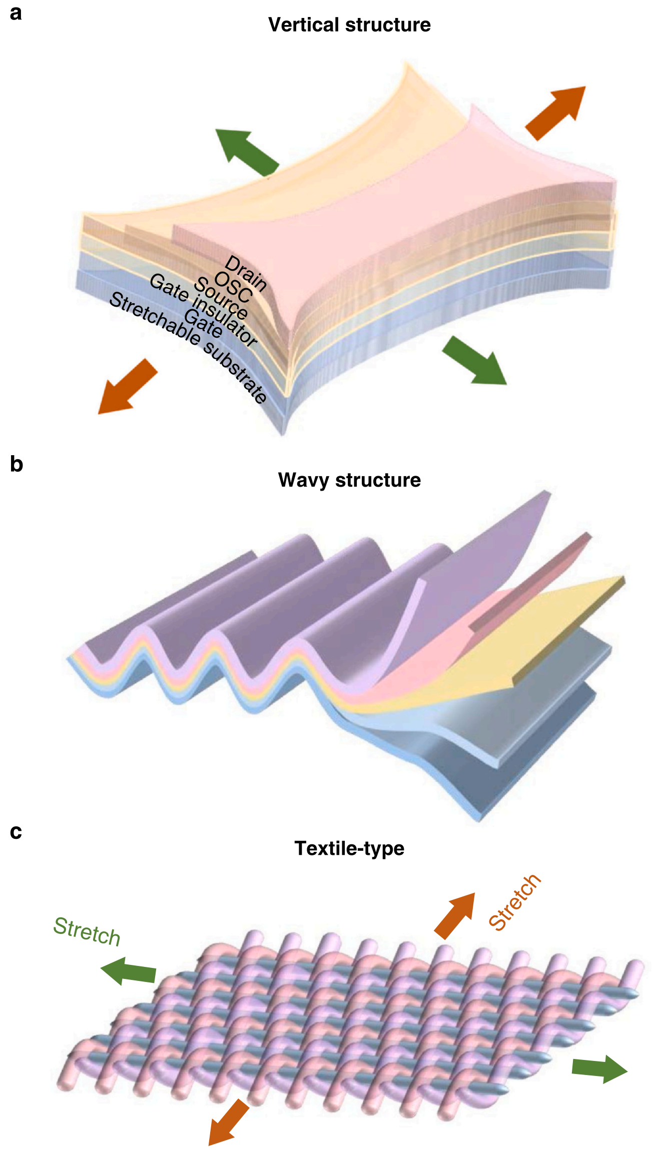

Fig. 3. Schematic diagram showing the emerging device architectures of stretchable synaptic transistors: a) Single-device structural innovations, b) Mechanical design strategies for stretchability, and c) System-level integration approaches.

3.2.1. Single-device structural innovations

Vertical structure (Fig. 3**a**) is the most-recently developed class single-device structural method to fabricate synaptic transistors. In vertically-structured organic transistors, the source and drain electrodes are not in the same plane, as they are in traditional planar organic transistors, so the channel is vertical and can be less than 10 nm long. For this reason, and because of the vertical charge-transport mechanism, vertically-stacked transistors have a higher tolerance of bias stress, lower operating voltage, and higher operating frequency than traditional planar field-effect transistors.

Moreover, in vertical transistor structures, vertical charge transfer helps mitigate the effects of semiconductor/gate dielectric interface defects on lateral charge transport, as observed in traditional planar transistors [63]. Compared to traditional planar transistors, vertically-stacked transistors exhibit superior mechanical stability [37,64]. In planar configurations, the channel with rectangular and large geometry introduces anisotropic mechanical strain under deformation. This strain can hinder efficient charge transport through the channel [65]. In contrast, in vertically-stacked transistors, the channel length is defined by the channel thickness, allowing for ultrashort charge transport paths in the vertical direction. This vertical conduction significantly reduces the influence of in-plane cracks and defects within the channel, thereby enhancing the device's tolerance to deformation-induced in-plane fractures and dislocations [66–68]. Moreover, the vertical architecture opens new opportunities for the development of stretchable synaptic transistors.

A stretchable neuromorphic system that uses vertically structured organic transistors has also been proposed [37]. It uses P3HT nanofibers to improve the stretchability of semiconductors, CNTs to realize the source and drain electrodes, and Ag NWs to strengthen the source contacts. The π–π stacking orientation in P3HT-NF films was improved under tensile stress and thereby promoted charge transport along vertical channels. Notably, few reports have presented stretchable synaptic transistors that use vertical structures.

Compared to conventional planar transistors, the fabrication of vertically structured transistors still faces critical challenges in constructing the organic semiconductor layer and contact electrodes. Current solution-based fabrication processes are relatively complex and mostly limited to single devices or small-scale arrays [69]. In particular, the isolation between the active layer and electrodes remains a significant bottleneck, highlighting the urgent need for scalable integration strategies [70]. On the other hand, the thermal evaporation of top electrodes tends to generate heat, which can induce unintended annealing of the channel layer and severely degrade device performance [71].

3.2.2. Mechanical design strategies for stretchability

Among various mechanical design strategies for stretchability, the wavy structure (Fig. 3**b**) stands out as one of the most representative and widely adopted approaches. Pre-stretching the device, then relaxing it to produce wrinkles, can impart bending and stretching capabilities to the device. When tensile stress is applied, the original wrinkles in the device will be stretched and flattened. When the tensile stress is released, the device returns to its original wrinkled shape. During these processes, the electrical properties of the device remain stable without mechanical deformation. This structure enables the fabrication of stretchable electronic devices that are composed of non-stretchable elements [72,73]. Rigid-island designs deposited on wavy or bent structures usually require a large spacing between units to effectively dissipate the strain energy that accumulates in the serpentine interconnection structure during stretching [59,74]. Although the wavy structure can fabricate stretchable electronic devices using non - stretchable elements, considering the overall performance and application requirements, it still has limitations. When achieving high stretchability, due to the non - stretchability of functional materials, the electrical performance stability of the device under large strain conditions also is limited. Moreover, during multiple stretching processes, stress concentration is likely to occur at the interface between non - stretchable elements and the stretchable structure, leading to device failure.

The method to realize a stretchable device based on a corrugated structure can also be combined with an intrinsically-stretchable semiconductor. The combination of biaxial pre-stretching and a porous honeycomb polymer film achieved stable charge transfer capability under a tensile strain > 140 % and stable synaptic behavior under a tensile strain of 60 % [22].

3.2.3. System-level integration approaches

As a recently proposed system-level integration strategy, the textile-type structure offers free-form design and inherent scalability, positioning it as a promising platform for next-generation wearable optoelectronic systems. With the rapid development of wearable technologies, textile optoelectronics have evolved from single-function modules to complex logic systems. Textile devices with multifunctional fibers and programmable structures are free-shaped and scalable and can fit closely to various parts of the human body, on which they can withstand stretching and twisting deformation while maintaining good breathability and wearing comfort. Textile-type devices are also suitable for large-scale manufacturing and integration and have a wide range of potential applications.

Textile electronic products are usually prepared by assembling one-dimensional functional fibers (Fig. 3**c**). The ideal one-dimensional fiber artificial synapse should operate at low power, have excellent linearity of electrical response, possess programmable multi-state storage capability, efficient execution of parallel vector matrix operations, and high pattern recognition accuracy under tensile stress [75,76]. A neuromorphic system that uses textile arrays prepared on Ag fiber has been proposed [39]. Organic transistors were prepared by coating ferroelectric materials on the Ag fibers and depositing organic semiconductor layers and electrodes. The resulting one-dimensional fiber synaptic devices were cross-connected to prepare a textile array; it achieved a 90 % recognition rate on the MNIST dataset of handwritten digits. Another dendritic neuromorphic network was prepared by using OFETs that were composed of P3HT or P3CT fibers. This network achieved speech recognition accuracy as high as 88.9 % on of the TI-46 speech corpus [38]. The stretchability of the artificial synaptic devices that use textiles has rarely been discussed.

4. Applications of stretchable synaptic transistors

Stretchable synaptic transistors are being applied in bioelectronics, to integrate the functionality of biological synapses with the mechanical adaptability required for wearable and implantable technologies. These innovations exploit advanced materials, scalable fabrication techniques, and sophisticated structural designs. Such advances enable real-time neuromorphic processing and redefine the functions of neuromorphic devices in healthcare, robotics, and human-machine interfaces. The operational stability of stretchable neuromorphic devices under strain makes them ideal for applications ranging from wearable electronics to implantable systems. Practical applications of stretchable synaptic transistors require stability of electrical characteristics such as on/off current ratio under different strain conditions and different repeated stretching cycles.

4.1. Wearable devices application

The development of synaptic transistors devices propels the emergence of intelligent wearable electronics. These devices offer advanced sensing, signal processing, and computing capabilities that can withstand complex movements on the body's surface, which are essential for real-time health monitoring, IoT integration, and adaptive human-machine interaction.

Intrinsically-stretchable synaptic transistors represent a key development in on-body health data processing systems [77] **(**Fig. 4**a)**. This device is designed to analyze biosignals such as electrocardiograms (ECGs), and is fabricated using lithography and transfer techniques to integrate electrochemical transistors made from redox-active polymers and hybrid organo-hydrogel electrolytes. This fabrication approach enables efficient ionic migration within the electrolyte layer, so the weight updates at synapses are highly linear and symmetric; this response is essential in neuromorphic computing. The system achieves 100 % stretchability, so it can conform naturally to body movements without degradation of electrical responses. It could maintain over 800 memory states, perform symmetric weight updates, and execute vector-matrix multiplication under strain, and would therefore be a reliable tool for wearable health diagnostics.

Textile neuromorphic systems offer a scalable and flexible approach to embedding neural networks into wearable electronics [39]. The system is fabricated using dip-coating and thermal evaporation techniques. Ag wires coated with ferroelectric P(VDF-TrFE) films provide precise control of synaptic functions, modulated by the degree of polarization in their ferroelectric domains. Subsequent deposition of pentacene semiconductors by thermal evaporation ensures uniformity and reduces defects. The fabricated devices had excellent multi-state programmability and high linearity of response. They achieved stretchability and retained their functionality after 100 bending cycles to a radius of 2.5 mm. In validation tests, the systems achieved 90 % accuracy in recognition tasks of the MNIST database of handwritten digits. This result shows their potential for use as wearable neural networks.

In-sensor computing platforms that integrate sensing and processing capabilities constitute another wearable system [78]. The system consists of OECT arrays fabricated using multi-channel inkjet printing. Devices are printed with a supramolecular buffer layer, which minimizes interface defects under the strain. This approach improves transconductance and ensures stable current modulation under mechanical deformation. The devices achieved 50 % stretchability and consistently processed biosignals with high reliability under repeated stretching cycles and are therefore highly suitable for use as wearable edge-computing systems.

Additionally, neuromorphic devices designed to mimic nociceptive functions replicate human pain perception and are particularly suited for prosthetics and tactile feedback systems [79] **(**Fig. 4**b)**. These devices were fabricated using electrospinning techniques to produce PQT-12/PEO nanofibers, which are embedded in a polydimethylsiloxane (PDMS) matrix by using pre-stretching techniques. This fabrication method creates a fiber network with improved charge transport pathways, which provide stable synaptic responses such as excitatory postsynaptic currents (EPSC) and paired-pulse facilitation (PPF). These devices achieved stretchability of 50 % and maintained EPSC and PPF under dynamic bending conditions such as finger joint movements.

Temperature-responsive neuromorphic skin provides an advanced solution for multimodal sensing that combines sensory detection and memory capabilities [51]. These devices are designed to detect and store thermal patterns and are therefore ideal for adaptive sensory applications. Fabrication involves photolithography to pattern single-walled carbon nanotubes (S-CNTs) and a PVA/SiO_2 dielectric layer. The system had 50 % stretchability and stable synaptic behaviors under 30 % strain. Tests using spatial thermal mapping and recovery assessments confirmed their reliability for use as wearable adaptive sensory skin.

4.2. Artificial nerve application

Stretchable synaptic transistors are also useful in bioelectronics by emulating biological neural pathways and providing innovative solutions for neural rehabilitation, prosthetics, and bioelectronic interfaces. These devices are designed to adapt properly to the motions of soft biological tissues while maintaining reliable electrical performance.

An artificial afferent nerve system utilizing neuromorphic electronics has been demonstrated to emulate tactile sensing and reflex-arc pathways **(**Fig. 4**c)**. The system integrates pressure-sensitive ion gel dielectric, ring oscillators, and artificial synapses, and emulates generation, processing, and transmission of sensory signals in afferent nerves [80]. The device successfully replicates tactile sensing by generating electrical spikes in response to mechanical stimuli, and induced motion of a cockroach leg. Also, a monolithic soft electronic skin that can mimic biological sensorimotor loops was developed. It integrates tactile and thermal sensing with neuromorphic signal processing [35]. The system is composed of low-voltage organic semiconductors and ion-gel dielectrics that are fabricated using photolithography and transfer printing methods and achieve 100 % stretchability. Nano-confined morphology of semiconducting polymers and stretchable electrodes imparts stretchability to the neuromorphic system. They ensure conformance to soft tissues mechanically and deliver stable multimodal sensory inputs and outputs. Their use in neuroprosthetics has enabled

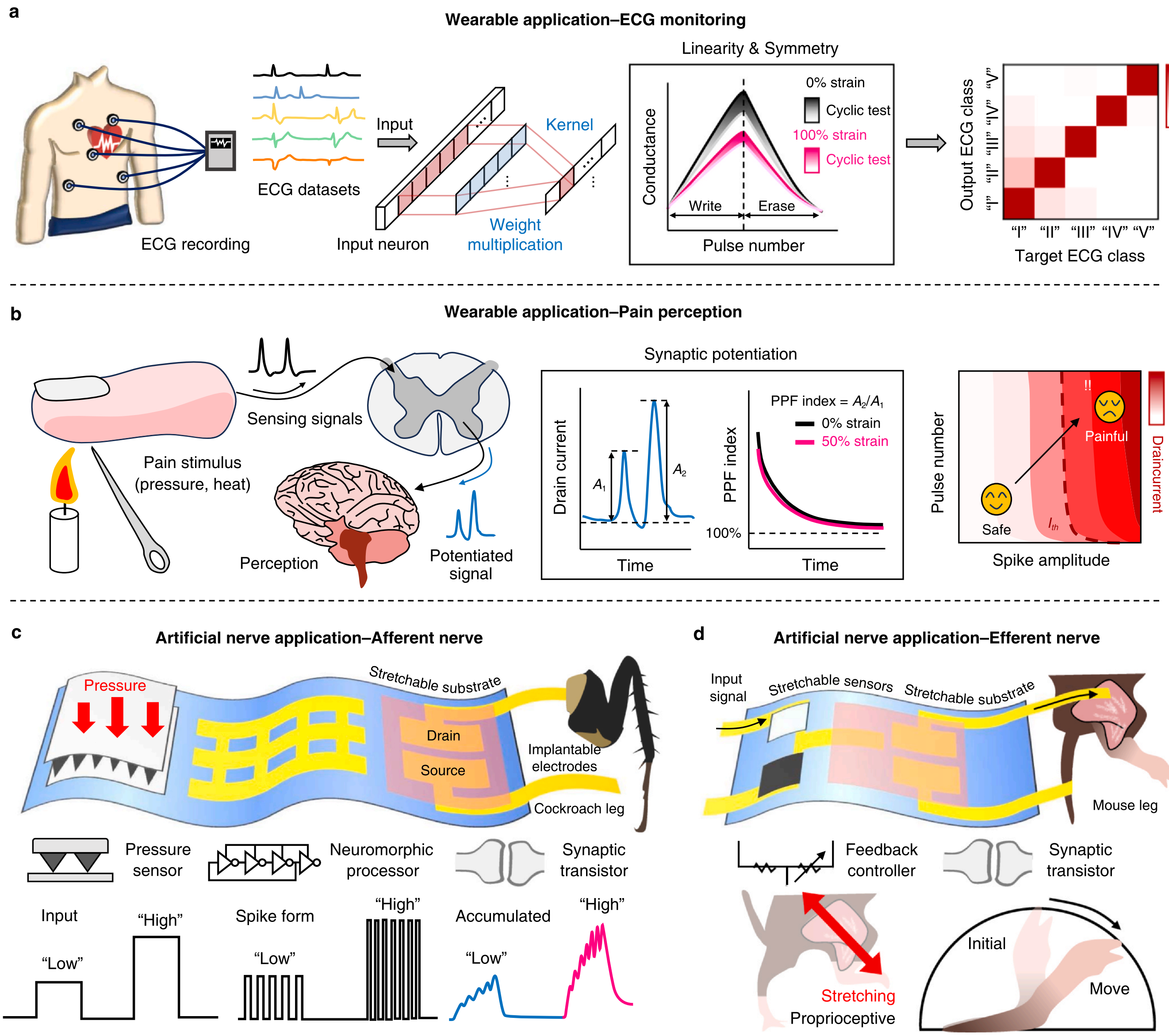

Fig. 4. Applications of stretchable synaptic transistors. a) Healthcare application using neuromorphic computing in array. Memory stability (Linearity, Symmetry of conductance states) under the stain. It ensures the correctness of computing result. b) Stimulus-responsive application that exploits synaptic plasticity for pain perception. Synaptic property PPF (Paired Pulse Facilitation) stability under the strain from time-dependent current measurement. The system showed nociceptive behaviors. c) Artificial afferent nerve application uses a sensor/neuromorphic processor to convert sensory information to neuromorphic spike signals and achieve signal accumulation. d) Artificial efferent nerve application uses an artificial synapse. Neural spike signals accumulated in artificial synapse occur muscle contraction of the body.

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the restoration of sensory-motor feedback, so they have potential clinical applications.

Stretchable neuromorphic artificial efferent nerves that can bypass damaged neural pathways to restore motor function provide a significant breakthrough in neurorehabilitation [26] (Fig. 4d). These systems use organic nanowire synaptic transistors and carbon nanotube strain sensors that had been fabricated using electrospinning and lamination methods. Printing of the fibers ensures high alignment as an active layer and efficient ion-electron coupling. Therefore, they tolerated 100 % strain and consumed ultra-low power (~ 1/150th of traditional systems), so they are energy-efficient neuroprosthetics. These systems also provide proprioceptive feedback, which is essential for smooth, coordinated movements in restored motor function in animal models with nerve injuries.

5. Conclusions and outlook

In this mini review, we introduced the stretchable materials used in each functional layer (e.g., substrate, electrode, semiconductor, insulator) of stretchable synaptic transistors, and focused on the main manufacturing methods and emerging device structures of stretchable synaptic transistors. Finally, we introduced applications of stretchable synaptic transistors in artificial nervous systems. Although stretchable synaptic transistors have achieved impressive results, great challenges remain before these systems can be applied as smart wearable bioelectronics:

(1) Materials: At present, the research on stretchable synaptic transistors is mainly focused on p-type organic semiconductor materials;

little research has considered n-type organic semiconductors or bipolar organic semiconductors. However, the synthesis of stretchable semiconductors with both high electrical performance and mechanical resilience remains a major challenge. Organic materials are easily damaged by solvents and by processing and manufacturing technologies, so appropriate organic materials with high stability must be developed. Currently, only a few functional materials used in stretchable neuromorphic devices for implantable applications are biocompatible. In the future, it will be necessary to develop fully biocompatible stretchable materials with scalable synthesis routes for devices to expand their practical applications.

(2) Devices: At present, work on stretchable synaptic transistors mainly focuses on emulating synaptic operating characteristics. While there have been some advances, including our contributions, research on emulating the functions of biological neurons is still limited. Achieving this is crucial for realizing the integration of wearable neuromorphic devices with biological systems. Additionally, the impact of mechanical deformation on the device's electrical characteristics is also of great significance. However, research on how mechanical properties affect functional materials and thus control synaptic performance has not been studied in depth. This is particularly important in complex architectures such as vertical transistors, where mechanical strain and charge transport pathways are highly coupled, further increasing process complexity.

(3) Manufacturing process: Printing has limited patterning accuracy during the manufacturing process, and the lamination transfer method is prone to surface defects. Photolithography and soft lithography methods have problems with the compatibility of photoresists with functional materials. The mechanisms and materials that can be used for photocrosslinking patterning are relatively limited and focus mainly on polymer semiconductors. Little research has addressed development of photocrosslinking mechanisms and materials for small-molecule semiconductors and electrolyte materials. Vertical organic transistors are primarily fabricated using photolithography or photo-crosslinking techniques [81–83]. However, for organic materials, traditional photolithography often faces compatibility issues with photoresists and etching chemicals, primarily due to their chemical sensitivity by the polar solvents used in photoresist development and subsequent plasma etching or chemical etchants. Photo-crosslinking methods, on the other hand, require specially designed photoactive materials to enable effective patterning. The interface isolation between the active layer and electrodes remains a major challenge, underscoring the need for scalable integration strategies [70]. Additionally, excessive heat during top electrode evaporation may cause undesired channel annealing and degrade device performance [71]. In addition, the size and functional materials of devices manufactured by the current preparation method are incompatible with the current standard CMOS process. Therefore, progress in this field requires the development of new methods that are compatible with the standard CMOS process to enable the preparation of large-scale, high-quality stretchable synaptic transistor arrays. Meanwhile, manufacturing strategies must also consider cost-effectiveness and compatibility with industrial-scale processes. Although advanced techniques such as microfluidic patterning, microcontact printing, and nanoscale self-assembly are being explored, they remain limited by scalability and integration with existing fabrication ecosystems.

(4) Integration: The current stretchable synaptic transistors are mainly combined with single sensors and synaptic transistors, but only limited research has explored integrating self-healing functions [84,85], self-powered multifunctional e-skin, or comprehensive neuromorphic systems. Realizing such complex systems requires not only materials and device innovation but also careful consideration of synthesis complexity, process cost, and system-level compatibility. Such integrations hold the potential to open new avenues for wearable electronic systems, promote commercial development, transform human-computer interaction, and provide new possibilities for the next generation of smart electronics.

Looking ahead, future development of stretchable synaptic transistors will likely focus on: 1) synthesizing high-performance stretchable semiconductors, including n-type and ambipolar materials; 2) improving CMOS-compatible fabrication for scalable integration; 3) incorporating additional functionalities such as self-healing and self-powering; and 4) developing biocompatible materials for long-term use in implantable systems. These directions will pave the way for practical deployment of multifunctional wearable neuromorphic electronics.

CRediT authorship contribution statement

Tingyu Long: Writing – original draft, Visualization. **Chunghee Kim:** Writing – original draft, Visualization. **Yanfei Zhao:** Writing – review & editing. **Tae-Woo Lee:** Writing – review & editing, Project administration, Supervision.

Declaration of Competing Interest

SN Display is a venture startup founded by Professor Tae-Woo Lee and has been approved as a faculty-led startup by Seoul National University.

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