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Stretchable synaptic transistors based on the field effect for flexible neuromorphic electronics

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Abstract

Using flexible neuromorphic electronics that emulate biological neuronal systems is an innovative approach for facilitating the implementation of next-generation artificial intelligence devices, including wearable computers, soft robotics devices, and neuroprosthetics. Stretchable synaptic transistors based on field-effect transistors (FETs), which have functions and structures resembling those of biological synapses, are promising technological devices in flexible neuromorphic electronics owing to their high flexibility, excellent biocompatibility, and easy processability. However, obtaining stretchable synaptic FETs with various synaptic characteristics and good stretching stabilities is challenging. Significant efforts to produce stretchable synaptic FETs have been undertaken, and remarkable advances in materials, fabrication processes, and applications have been achieved. From this perspective, we discuss the requirements for neuromorphic devices in flexible neuromorphic electronics and the advantages of stretchable synaptic FETs. Moreover, representative methods used to implement stretchable synaptic transistors, including the structural design and development of intrinsically stretchable devices, are introduced. Additionally, the application of stretchable synaptic transistors in artificial sensory systems such as light, tactile, and multisensory artificial nervous systems is also discussed. Finally, we highlight the possible challenges in implementing and using stretchable synaptic transistors, propose solutions to overcome the current limitations of these devices, and suggest future research directions.

Keywords: Flexible neuromorphic electronics, stretchable synaptic transistors, field-effect transistors, artificial sensory systems

INTRODUCTION

Neuromorphic electronics, which emulate the functions of biological nervous systems and can efficiently process large quantities of complex data, have been developed to overcome the von Neumann bottleneck[1-3]. Considerable attention has been made to incorporating neurological functions in emerging applications such as soft machines, wearable and implantable electronics, and neuroprosthetics[4,5]. These applications typically require devices with intrinsic mechanical compatibility, excellent stretchability, and deformation capacity. Flexible neuromorphic electronics satisfy these requirements and are regarded as promising candidates for next-generation artificial intelligence systems. Synapse, one of the basic structures in the biological nervous system, is soft and flexible and can perform information processing and memory functions concurrently, which can avoid the von Neumann bottleneck[6-9]. Therefore, developing flexible electrical devices with synaptic functions is expected to facilitate the development of flexible neuromorphic electronic devices.

Various types of stretchable synaptic devices, including two-terminal and three-terminal synaptic devices, have been proposed to mimic biological synapse functions and satisfy practical application requirements[10-24]. Among these, stretchable synaptic transistors based on the structure of a three-terminal field-effect transistor (FET), which is a component of flexible neuromorphic electronics, can emulate synaptic functions and provide a mechanical performance that is compatible with the human body or curved surfaces. Notably, three-terminal FET synapses can concurrently perform information processing and memory functions, simplifying the learning scheme and negating the need for complex synchronizing algorithms, owing to the presence of a gate electrode that modulates the source/drain current[25-27]. Therefore, it is important to develop stretchable synaptic transistors based on FETs, which play an important role in the implementation of flexible neuromorphic electronics.

Stretchable synaptic FETs should withstand deformations to a certain degree without undergoing fracturing and maintain their electrical performance without any significant degradations during stretching. Extensive efforts have been made to develop stretchable synaptic FETs with excellent synaptic function and mechanical performance[5,12-24]. For instance, Shim *et al.* developed a fully rubbery synaptic transistor based on elastomeric electronic materials, which emulated functions similar to those of biological synapses, including excitatory postsynaptic current (EPSC), paired-pulse facilitation (PPF), short-term memory (STM), long-term memory (LTM), and filter characteristics[5]. The transistor maintained these characteristics even when stretched at 50% strain. Meanwhile, a neurologically integrated tactile sensory skin and soft adaptive neurologically integrated robot based on a stretchable synaptic transistor were also successfully implemented. Using an ion gel as a gate insulator[19], Lee and co-workers fabricated a stretchable organic nanowire synaptic transistor (s-ONWST) that could emulate synaptic characteristics such as EPSC, PPF, spike voltage-dependent plasticity (SVDP), spike number-dependent plasticity (SNDP), and spike frequency-dependent plasticity (SFDP), even at 100% strain. An organic optoelectronic sensorimotor synapse consisting of a photodetector, s-ONWST, and a neuromuscular system, which successfully conducted optical wireless communication and activated an artificial muscle actuator, was developed. Therefore, stretchable synaptic FETs are a highly promising technology for flexible neuromorphic electronics and represent a key step toward the development of next-generation neuromorphic electronics.

From this perspective, we emphasize the advantages of stretchable synaptic transistors based on FETs, introduce the main methods for implementing stretchable synaptic transistors, and highlight their applications in artificial sensory systems. Moreover, the current challenges of stretchable synaptic transistors and possible research directions for overcoming current roadblocks are discussed. This perspective will help promote the further development of stretchable synaptic transistors and support increasingly in-depth studies toward expanding their applications in flexible neuromorphic electronics.

REQUIREMENTS OF NEUROMORPHIC DEVICES IN FLEXIBLE NEUROMORPHIC ELECTRONICS

Conventional Von-Neumann-based computation is ideal for solving structured problems[28-30]. However, this process involves many data transmissions between processors and memory units, which inevitably limits computational efficiency and increases energy consumption[6,31-33]. The human brain can quickly handle multidimensional information with a low power consumption; thus, bioinspired neuromorphic electronics have attracted attention as a novel approach to next-generation artificial intelligent systems. Many artificial neuromorphic devices have been reported, and the development of wearable computing, soft robotics, and neuroprosthetics supported by increasingly powerful neuromorphic electronics has led to the proposal of novel requirements for neuromorphic devices. Flexible neuromorphic devices have been investigated extensively as critical solutions. Compared to traditional rigid neuromorphic devices, flexible neuromorphic devices can mimic the functions of the human nervous system and are more morphologically compatible with biological organisms. Therefore, these devices provide a promising solution for developing artificial neuromorphic electronic devices that are energy-efficient, highly comfortable, and conformable to biological systems.

The biological nervous system comprises many neurons (approximately 10^{11}) and synapses (approximately 10^{15}); this system is robust and highly efficient, handling a variety of complex tasks with ultralow energy consumption (approximately 20 W) and small volume occupation (approximately 1,200 cm^3)[25,27,34-36]. Synapses, which are the most important functional units in the biological brain, can simultaneously store and process information and are responsible for various cognitive processes such as synaptic computing, learning, and memory[8,9]. Synapses are typically soft and can withstand various forms of mechanical deformation[6]. Biological bodies generally comprise arbitrarily shaped curved surfaces; thus, they require mechanical flexibility to integrate with artificial nerves and guarantee signal processing[37,38]. Impressively, artificial synapses are essential techniques to endow soft machines and many other applications with neurological functions, requiring that artificial synapses are stretchable similar to those in humans and animals[29,39-42]. To closely emulate biological synapses, it is essential to develop flexible neuromorphic devices, which have outstanding mechanical performance, low power consumption, high-density integration, and biocompatibility, that replicate the functionalities of their biological counterparts and satisfy the requirements for constructing flexible integrated systems [Figure 1].

ADVANTAGES OF STRETCHABLE SYNAPTIC TRANSISTORS BASED ON FETS

Artificial synaptic devices are promising components of neuromorphic electronic devices, and they are critical to building brain-like computers, primarily comprising two-terminal and three-terminal devices such as memristors[43-45], FETs[46-48], and hybrid memristor transistors[49]. The two-terminal structures of artificial synaptic devices have a low power consumption, simple device structure, and small cell size, and they are well-suited for large-scale integration with crossbar structures[6,50,51]; however, their variability and operational instability hinder their further application in advanced artificial intelligent systems[52,53]. Additionally, two-terminal devices integrated with artificial systems require additional circuitry components to select a target cell, and simultaneously performing signal transmission and processing may

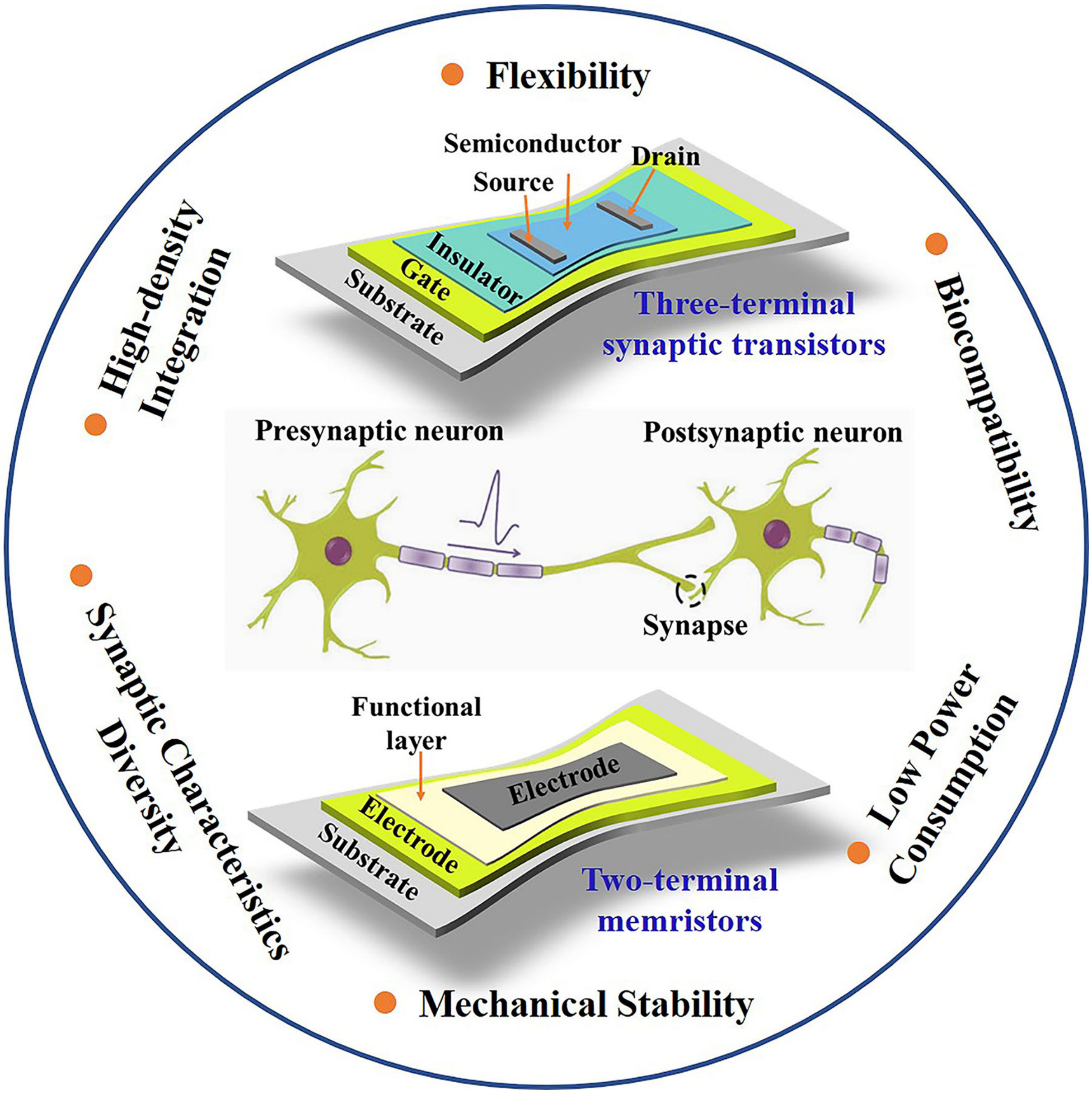

Figure 1. The main requirement of neuromorphic devices in flexible neuromorphic electronics.

be challenging for these devices[54]. Compared with two-terminal synaptic devices, three-terminal synaptic FETs have good stability, relatively controllable testing parameters, and clear operation mechanisms, and they can be constructed with more complex structures[52,53,55]. Regarding FET-based artificial synapses, they can implement synergistic control in a device by receiving signals from many sources, supporting their potential use in developing robust neural networks with fewer neural elements[56-60]. Importantly, these synapses can update the synaptic weight without interrupting the signal transmission process and thereby simplify the learning scheme without complex synchronizing algorithms, as the gate voltage of the FET can change the source/drain current[25-27,47]. Notably, in biological nervous systems, signal transmission in chemical synapses is achieved by the release of neurotransmitters from the presynaptic membrane into the synaptic cleft; then, the synapses are bound to the receptors on the postsynaptic membrane[61]. Similarly, in the working process of three-terminal synaptic devices based on FETs, the presynaptic impulse (gate voltage) is inputted from the gate electrode (presynaptic membrane) and results in a change in the channel (postsynaptic membrane) conductance between the source/drain electrodes, producing a postsynaptic drain current[62,63]. Therefore, three-terminal synaptic FETs are potentially more suitable than other neuromorphic electronic devices for emulating synaptic functions.

Artificial synaptic transistors, which mimic the functions of biological synapses, have various applications in wearable electronics, neuroprosthetics, and interactive robotics systems[64-66]. Artificial synaptic transistors need to be flexible and stretchable to satisfy the requirements of these applications. Hence, there is a need for synaptic transistors that share characteristics such as stretchability and various synaptic functions with biological synapses. Stretchable synaptic transistors are representative structures used in flexible neuromorphic electronics. Compared with traditional rigid synaptic transistors, stretchable synaptic transistors can still simulate the functions of biological synapses even after experiencing great mechanical deformation. These transistors are closely related to biological neuronal systems and enable seamless integration with the human body and curved surfaces, which is an essential requirement for flexible neuromorphic electronics. The comparison of the characteristics of stretchable synaptic transistors and traditional rigid synapses based on FETs is provided in Table 1. Recently, there has been an increasing number of reports on stretchable synaptic transistors. In the following sections, we present an overview of stretchable synaptic FETs, focusing on the implementation of stretchable synaptic transistors and their applications, the features and problems in this domain, and guidelines for future progress in flexible neuromorphic electronics.

IMPLEMENTATIONS OF STRETCHABLE SYNAPTIC FETS

Stretchable synaptic transistors have attracted extensive attention owing to characteristics resembling those of biological synapses, especially their great deformation ability and biocompatibility, supporting their excellent application prospects in wearable electronics, bio-implanted electronics, prostheses, and soft robotics. These transistors normally exhibit good mechanical strength and can withstand a certain stretching deformation, which requires each component of the transistor, including semiconductors, gate insulators, electrodes, and substrates, to exhibit excellent stretchability and mechanical stability. Currently, many efforts have been made to develop stretchable synaptic transistors; different kinds of stretchable synaptic transistors based on FETs, such as stretchable electric double-layer synaptic transistors, stretchable electrochemical synaptic transistors, and stretchable optoelectronic synaptic transistors, have been developed[5,12-24]. More detailed information on stretchable synaptic FETs is provided in Table 2. This section discusses several representative methods for implementing stretchable synaptic FETs.

Structural designs for stretchable synaptic FETs

Stretchable synaptic transistors play a core role in flexible neuromorphic electronics and usually employ both organic and inorganic materials to fabricate functional layers in devices. Recently, many materials have been used in neuromorphic electronics, of which emerging two-dimensional (2D) materials have drawn great attention owing to their unique properties; synaptic devices based on 2D materials (such as graphene, graphene oxide, hexagonal boron nitride, transition metal dichalcogenides, transition metal oxides, 2D perovskites, and black phosphorus) have been developed[67-70]. Organic materials are also considered as ideal candidates for neuromorphic electronics because of their excellent optoelectronic and mechanical properties. For instance, Chen *et al.* developed different types of synaptic devices based on organic materials, such as synaptic transistors with multi-sensing-memory-computing[71], stretchable synaptic transistors with tunable behavior[23], and artificial multisensory integration nervous systems based on synaptic transistors[72]. Notably, certain organic and inorganic functional layer materials usually have high electrical qualities; however, they cannot withstand large mechanical deformations owing to their natural

Table 1. The comparison of the characteristics of traditional rigid synaptic transistors and stretchable synaptic transistors, based on field-effect transistors

	Rigid synaptic transistors	Stretchable synaptic transistors
characteristics	Rigid substrate, brittle and fragile Terrible mechanical compliance More diverse synaptic characteristics Fabrication processes compatible with the COMS process	Stretchable substrate, soft, stretchable Biocompatibility, mechanical compliance Limited synaptic characteristics Fabrication process incompatible with the COMS process

Table 2. Summary the basic information of stretchable synaptic FETs

Gate insulator	Semiconductor	Device Structures	Working Mechanism	Fabrication Processes	Stimuli	Maximum stretching strain/cycles	Ref.
Ion gel (PVDF-HFP/EMIM-TFSI)	P3HT-NFs/PDMS	TGBC	ion migration	lamination-and-transfer	Voltage	50 %/10^3 (50 %)	[5]
queous KPF_6 electrolyte	psd-DPP-g2T	TGBC	electrochemical reaction	lamination-and-transfer	Voltage	140 %/10^4 (30 %)	[12]
Aqueous electrolyte	PEDOT:PSS	TGBC	electrochemical reaction	spin coating	Voltage	30 % 10^3 (30 %)	[13]
PUU	S-CNTs	BGBC	ion migration	photolithography and O_2 plasma etching	Voltage	50 %/400 (25 %)	[14]
PVDF-HFP	S-CNTs	TGBC	ion migration	IJ printing	Voltage	20 %	[15]
hexagonal boron nitride (h-BN) flakes	buckled MoS_2	BGTC	trapping/de-trapping	lamination-and-transfer/pre-stretched	Voltage and light	14.2 %	[16]
Ion gel (PVDF-HFP/EMIM-TFSI)	P3HT-NFs/PDMS	TGBC	ion migration	lamination-and-transfer	Voltage	30 %	[17]
PDMS	IDTBT	BGTC	photoconductivity	lamination-and-transfer	Voltage and light	100 %	[18]
Ion gel (PS-PMMA-PS/EMIM-TFSI)	FT4-DPP-based polymer NW	TGBC	ion migration	Electrospinning	Voltage	100 %/50 (100 %)	[19]
PVA/SiO_2	S-CNTs	BGBC	ion migration	photolithography and O_2 plasma etching	Voltage, temperature and strain	50 %/10^3 (30 %)	[20]
Ion gel (PVDF-HFP/EMIM-TFSI)	P3HT/PEO NWs	TGBC	ion migration	electrohydrodynamic nanowire printing	Voltage and light	50 %/10^3 (10 %)	[21]
Ion gel (PAN/LiTFSI)	P3HT-NFs	Vertical	ion migration	Spin coating	Voltage	20 %/500 (10 %)	[23]
Ion gel (PAN/LiTFSI)	P3HT-NFs	TGBC	ion migration	lamination-and-transfer	Voltage	60 %/300 (30 %)	[24]

BGBC: Bottom-gate bottom-contact; BGTC: bottom-gate top-contact; TGBC: top-gate bottom-contact.

rigidity and brittleness, limiting their application in stretchable electronics.

In recent years, many efforts have been made to develop structural designs for synaptic devices that can improve their stretchability and electrical performance[13,16,19]. Providing these devices with proper structural designs can enable them to dissipate mechanical deformation and become stretchable, decreasing the mechanical damage they experience and finally improving their mechanical and electrical performances. Stretchable synaptic transistors have been fabricated using structural designs for flexible neuromorphic electronics. Nguyen *et al.* fabricated a stretchable and stable synaptic electrochemical transistor on a 3D mogul-patterned polydimethylsiloxane (PDMS) substrate [Figure 2][13]. These transistors can successfully mimic synaptic behaviors even when stretched up to 30% strain, owing to the excellent stress absorption

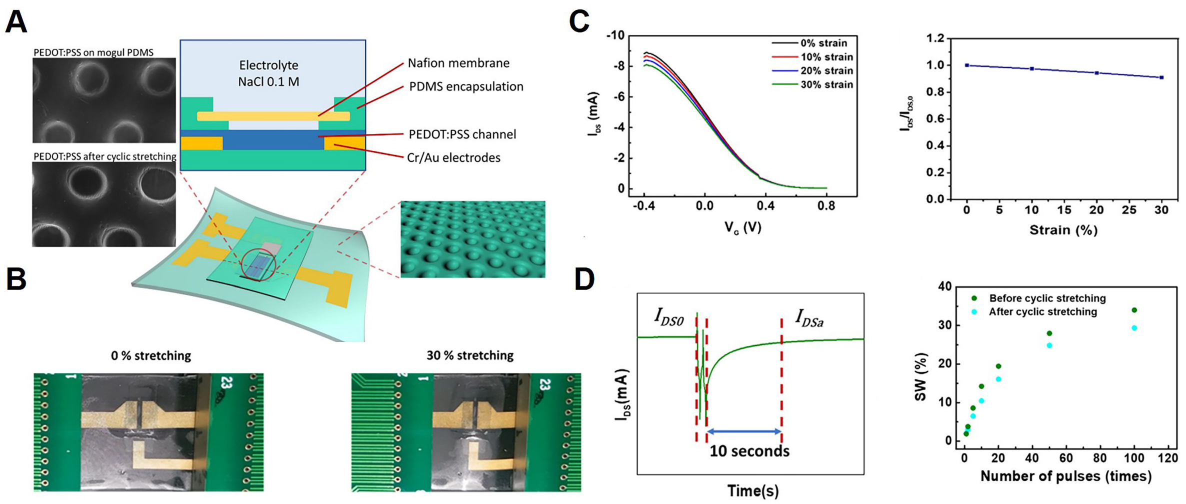

Figure 2. (A) Structure of the OECT with a membrane on a 3D mogul-patterned PDMS substrate and FESEM images of the 3D mogul-patterned substrate before (top) and after (bottom) stretching for 1,000 cycles at 30% strain, respectively; (B) Optical image of the OECT without membrane in the direction of the channel length at 0% (left) and 30% (right) strains; (C) Transfer characteristics and current change ($I_{DS}/I_{DS,0}$) of the OECT obtained under uniaxial static stretching from 0% to 30%; (D) I_{DS} value after 10 s upon removal of gate pulsing and SW values generated in the OECT with the membrane after different gate pulses number before and after cyclic stretching of 1,000 cycles at 30% strain. Reprinted with permission from Ref.[13]. Copyright 2021, John Wiley and Sons. OECT: organic electrochemical transistor; PDMS: polydimethylsiloxane.

capability of the patterned PDMS substrate. Li *et al.* fabricated buckled monolayer MoS_2 FETs on a PDMS substrate via strain engineering [Figure 3A][16]. The buckled MoS_2 devices exhibit a stable transistor performance with mobility of ~30 $cm^2 \cdot V^{-1} \cdot s^{-1}$, an on/off ratio of ~$10^8$, and a subthreshold swing (SS) of ~180 $mV \cdot dec^{-1}$, even after many stretching cycles under more than 10% strain [Figure 3B]. Moreover, the devices can mimic optoelectronic synapse functions, such as STM/LTM and long-term potentiation/depression (LTP/LTD) characteristics, and the image recognition accuracy can reach ~95% even when the strain is as high as 6.5% [Figure 3C]. Lee and co-workers fabricated an organic optoelectronic sensorimotor synapse based on the s-ONWST[19]. The s-ONWST employs a single wavy nanowire as the semiconductor layer, and the wavy nanowire retains its configuration after repeated stretching to 100% strain. During stretching tests, the s-ONWST, which is fabricated on an ion gel-gated platform, successfully emulates biological synapse functions, such as EPSC, PPF, spike voltage-dependent plasticity (SVDP), and spike number-dependent plasticity (SNDP), even after 50 cycles at 100% strain. These studies demonstrated that stretchable structural designs were promising approaches for endowing non-stretchable synaptic devices with high stretchability.

Intrinsically stretchable synaptic FETs

Stretchable synaptic transistors require that all components be stretchable and exhibit excellent electrical performance. Therefore, in addition to the development of stretchable synaptic transistors using structural designs, intrinsically stretchable synaptic transistors have been explored. Chen *et al.* developed ultra-stretchable organic electrochemical transistors (OECTs) based on a honeycomb-like porous microstructured organic semiconductor film with a biaxially pre-stretched platform [Figure 4A][12]. The resulting semiconductor film stabilized the effective electronic and ion transport pathways under deformation, enabling OECTs with stable output characteristics upon deformation and a maximum transconductance (g_m) degradation of 8% at 20% strain after 10,000 stretching cycles [Figure 4B]. Meanwhile, the stretchable OECT showed stable current output characteristics, even with strains of up to 30%-140%. The stretchable OECT also showed stable synaptic characteristics, such as PPF and EPSC, with

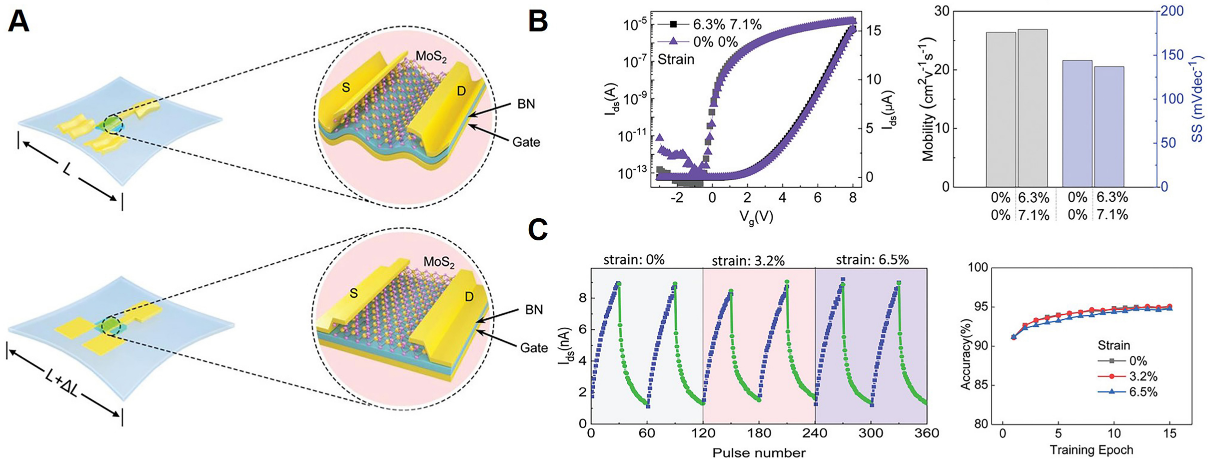

Figure 3. (A) Schematic diagram of the buckled MoS_2 FET on a stretchable PDMS substrate; (B) Transfer curves, mobility, and SS value of the device under biaxial strain with different strains, V_{ds} = 3 V; (C) Optical potentiation (1 Hz, 0.5 s) and electric depression (V_g = 12 V, 4.5 s) of the stretchable MoS_2 device under 0%, 3.2%, and 6.5% strain and the simulation results of image recognition accuracy under different strains. Reprinted with permission from Ref.[16]. Copyright 2022, John Wiley and Sons. FET: field-effect transistor; PDMS: polydimethylsiloxane.

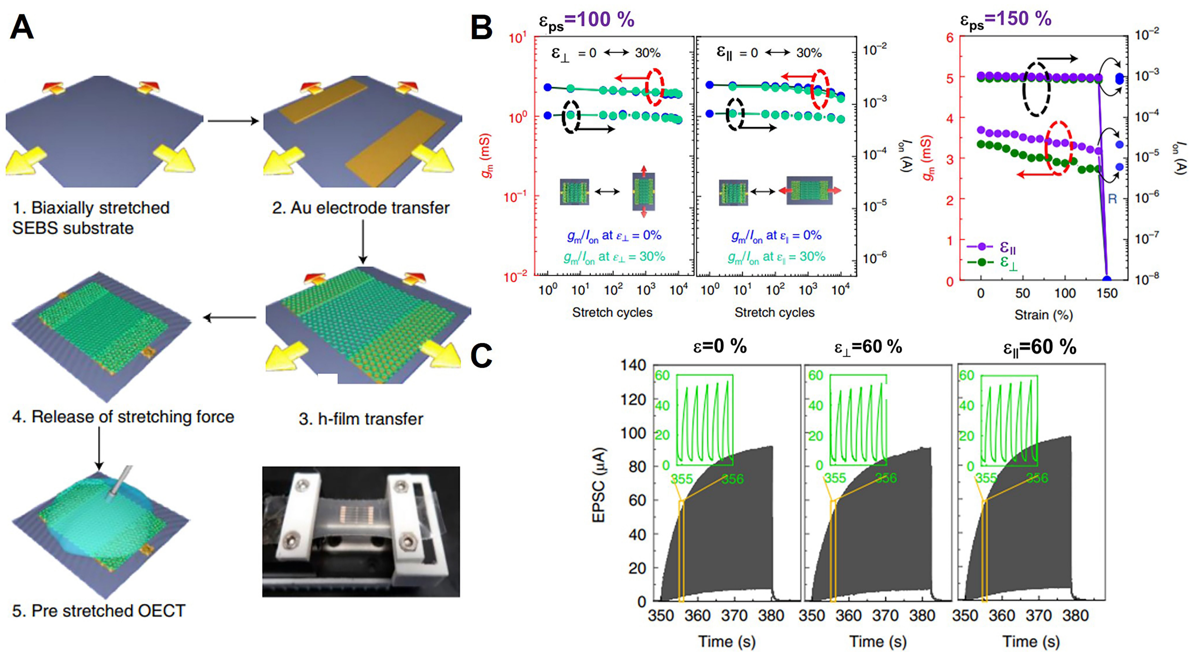

Figure 4. (A) Illustrations of the pre-stretched OECT fabrication process; (B) the g_m and I_{on} dependence on stretching cycles for psh-DPP-g2T (ε_{ps} = 100%) OECTs under 0% and 30% elongation strains and the g_m/I_{on} data for psh-DPP-g2T (ε_{ps} = 150%) OECTs under various strains (from 0% to 150%); (C) EPSCs triggered by multiple spikes (each spike, -0.7 V, 100 ms; interval, 100 ms) under 0% and 60% elongation strains in the $\varepsilon_{\perp}$ or ε direction. Reprinted with permission from Ref.[12]. Copyright 2022, The Author(s), under exclusive license to Springer Nature. EPSC: excitatory postsynaptic current; OECT: organic electrochemical transistors.

minor variations in postsynaptic currents under different strains [Figure 4C]. Molina-Lopez and co-workers fabricated stretchable transistor arrays using intrinsically stretchable active materials via the inkjet printing process[15]. Poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate) (PEDOT: PSS) was the source/drain/gate electrode; interconnect, a network of semiconducting single-walled carbon nanotubes (SCSWCNTs), was the semiconducting channel; and solid-state ionic poly(vinylidene fluoride-hexafluoropropylene) (PVDF-HFP) was the gate dielectric. The resulting devices exhibited excellent electrical performances, with an average mobility of 27 ± 5 $cm^2 \cdot V^{-1} \cdot s^{-1}$, $I_{on}/I_{off} > 10^4$, and a maximum transconductance of 47 ± 9 μS. During the stretching tests, these parameters remained stable even for independent strains of up to 20%, owing to the tube-to-tube charge transport in the SWCNT networks without strain dependence. These stretchable synaptic transistors, which emulated the characteristics representative of the synaptic behavior of double-layer capacitive dielectrics, such as EPSC, inhibitory postsynaptic currents (IPSC), and short-term plasticity (STP), exhibited outstanding mechanical stability during stretching tests. Shim *et al.* developed a fully rubbery synaptic transistor using a composite of poly(3-hexylthiophene) (P3HT) nanofibrils percolated in polydimethylsiloxane (P3HT-NFs/PDMS) as the stretching semiconductor and an ion gel as the gate insulator [Figure 5A][17]. The synaptic transistors showed unique synaptic characteristics, including EPSC, PPF, and memory [Figure 5B]. These synaptic characteristics were retained even after the transistors were stretched by 30%. Finally, a neurological electronic skin based on a fully rubbery synaptic transistor and two pressure-sensitive mechanoreceptors, which could successfully emulate the Morse Code and facilitate communication with a robotic hand, was fabricated. These studies demonstrated the feasibility and importance of developing intrinsically stretchable synaptic transistors for flexible neuromorphic electronics.

ARTIFICIAL SENSORY SYSTEMS APPLICATIONS FOR STRETCHABLE SYNAPTIC FETS

Biological sensory systems can detect external signals via sensory receptors in sensory organs and convert the sensed signals into brain-interpretable electrical impulses to process sensory information, facilitating communication and socialization. Hence, the implementation of biological sensory systems in flexible neuromorphic electronics represents a next-generation artificial sensory system paradigm. Artificial sensory systems consisting of synaptic devices and sensing elements can recognize stimuli and generate a postsynaptic response, allowing artificial sensory systems to respond to the external environment in a manner resembling that of biological sensory systems. Synapses are responsible for data processing and memory functions and play an essential role in these processes. Several studies regarding artificial sensory systems based on stretchable synaptic transistors have been published. In this section, we introduce light sensory, tactile sensory, and multisensory nervous systems based on stretchable synaptic FETs.

Light sensory systems

In the human brain, which receives more than 80% of its external environmental information from the human visual system[73,74], light can control the release of neurotransmitters and thereby adjust brain activity *in vivo*; this process is mediated by light sensory systems[75]. Some scientists have attempted to design light sensory systems composed of synaptic devices and optical sensors to mimic the processes occurring in this system[76-78]. Chen *et al.* designed an artificial flexible visual memory system by integrating memristors with ultraviolet (UV) image sensor arrays on flexible polyimide substrates[76]. The visual memory system can detect and memorize image information for at least 1 week [Figure 6A]. Wang *et al.* developed a light-triggered organic neuromorphic device (LOND) by using a ferroelectric/electrochemical artificial synapse and a light-sensitive electronic component to mimic the visual perception system[77]. This device can transduce incident light frequency, intensity, and wavelength into synaptic signals in both volatile and nonvolatile forms. The LOND can also recognize colors and shows varying degrees of synaptic signal volatility under 550 nm and 850 nm light [Figure 6B]. Additionally, a sensory synaptic device that combines synaptic and sensing capabilities into a single device has been used to emulate light sensory systems. Huang *et al.* fabricated organic/inorganic hybrid heterojunction short-wave infrared (SIR) synaptic phototransistors (OHSPTs) that successfully simulate typical synaptic behavior under SIR light irradiation[78]. The OHSPT array can successfully realize the image recognition of SIR light on dark nights under artificial white-light conditions, exhibiting good self-adaptability and strong anti-interference ability.

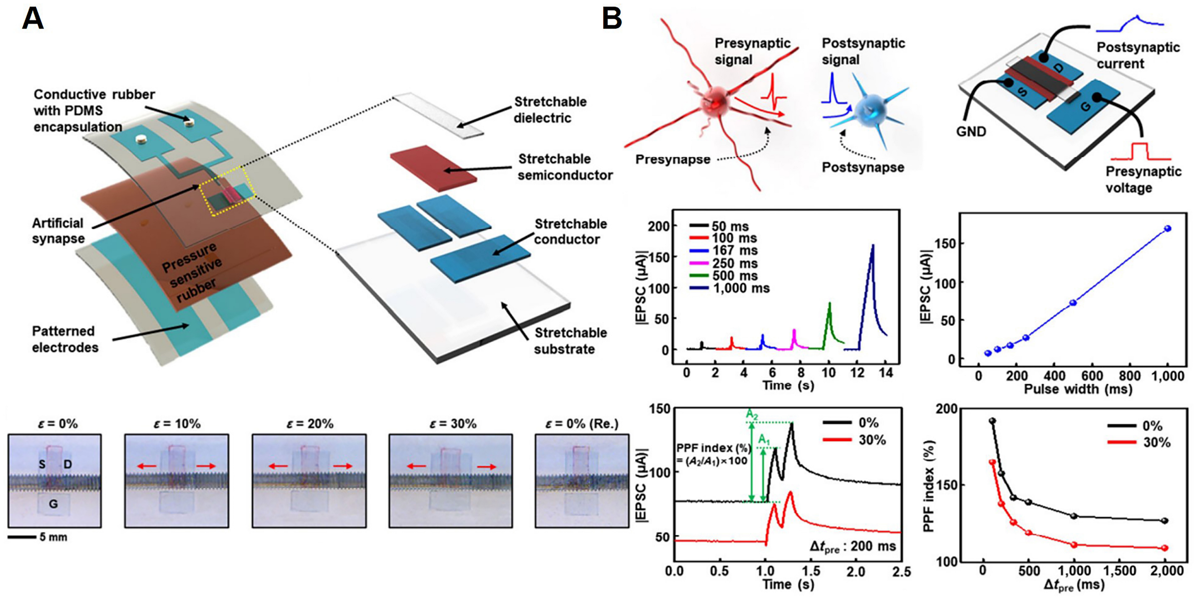

Figure 5. (A) Schematic view of an elastic neurological electronic skin and a fully rubbery, all-organic synaptic transistor, and the optical images of the fully rubbery synaptic transistor under mechanical strains of 0%, 10%, 20%, 30%, and 0% along the channel length direction; (B) Schematic illustration of the synapse and the organic synaptic transistor with an ion-gel gate dielectric, and biological synaptic functions of all-organic synaptic transistors, mainly including EPSC and PPF. Reprinted with permission from Ref.[17]. Copyright 2021, Tsinghua University Press and Springer-Verlag GmbH Germany, part of Springer Nature. EPSC: excitatory postsynaptic current; PPF: paired-pulse facilitation.

Artificial light sensory systems based on stretchable synaptic FETs have also been developed. Lee *et al.* developed a stretchable optoelectronic sensorimotor synapse system based on a stretchable organic nanowire synaptic transistor[19]. Regarding s-ONWSTs, they use a wavy organic nanowire and a high-capacitance ion-gel electrolyte as a stretchable semiconductor and gate insulator, respectively; and they show stable current-voltage characteristics and various typical postsynaptic behaviors at both 0 and 100% strains. Notably, s-ONWSTs can generate EPSCs by exploiting the output voltage of a photodetector, thereby converting light signals to postsynaptic currents. Therefore, by inducing an EPSC amplitude response, a stretchable optoelectronic sensorimotor synapse system comprising a photodetector and s-ONWSTs can achieve optical wireless communications. Every letter of the English alphabet can be expressed through the control of light signals; this expression can induce a distinct EPSC amplitude response in s-ONWSTs. Using the stretchable optoelectronic sensorimotor synapse system, the International Morse code (such as “SOS,” “HELLO” and “UNIVERSE”) has been successfully emulated; the outputted International Morse code did not show any notable changes at both 0 and 100% strains. When an s-ONWST was connected to a polymer actuator through a transimpedance circuit, forming an artificial neuromuscular junction, the polymer actuator could be activated by voltage signals converted from the EPSCs of the organic optoelectronic synapse. The biological muscle tension responses during contraction were successfully emulated using an artificial neuromuscular electronic system. This study provided a promising strategy for developing next-generation biomimetic soft electronics, soft robotics, neurorobotics, and electronic prostheses with wireless communication, and it demonstrated the role of stretchable synaptic transistors in artificial sensory systems.

Tactile sensory systems

Tactile perception enables animals to perceive and respond to external tactile stimuli, facilitating their communication with the external environment. The realization of an artificial tactile sensory system to

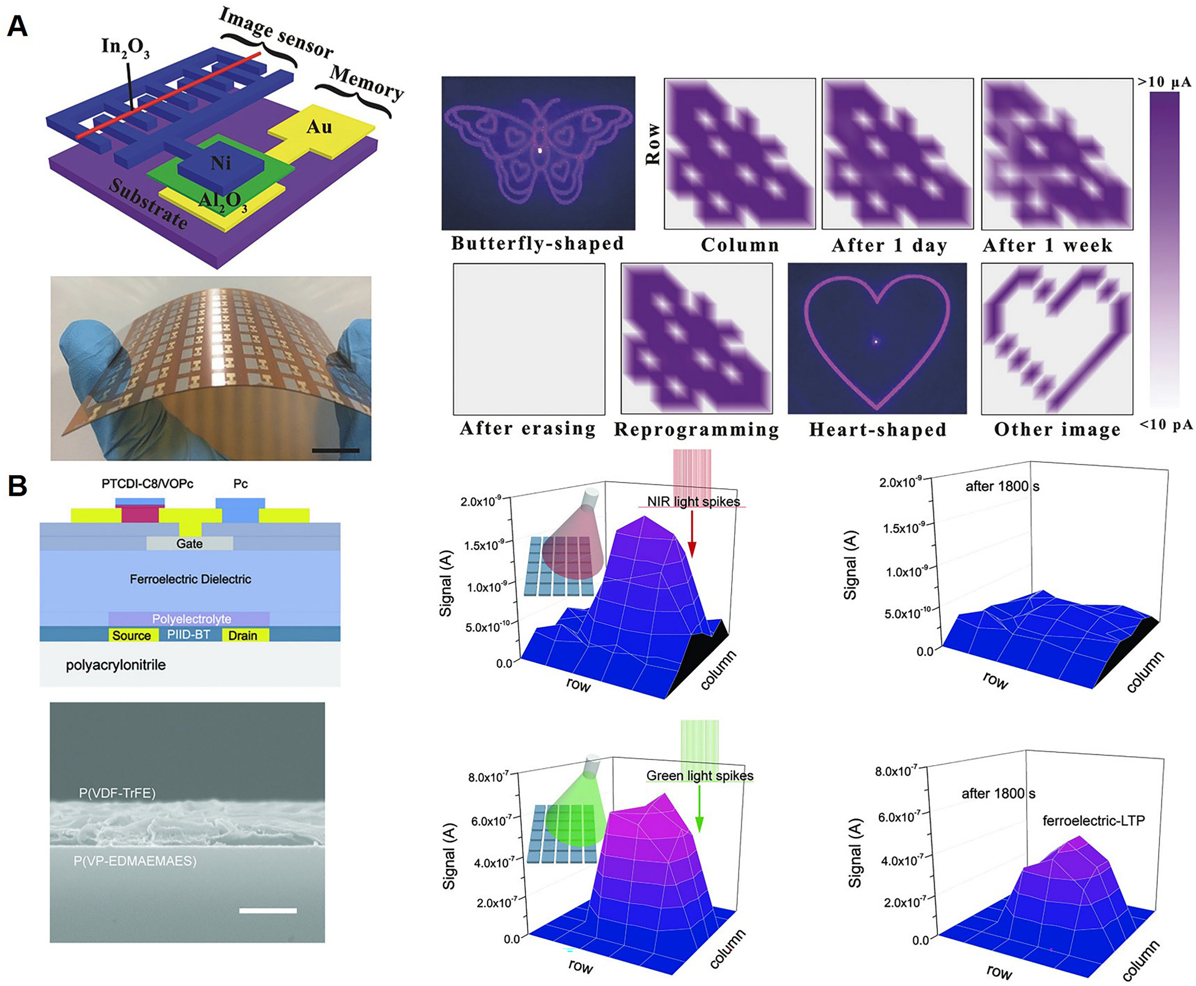

Figure 6. (A) Schematic of the artificial visual memory unit integrated by the image sensor and resistive switching memory device, photos of the integrated devices array on flexible polyimide substrates, and information storage behaviors and reusability of the flexible device arrays for the applied patterned light. Reprinted with permission from Ref.[76]. Copyright 2018, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim; (B) A LOND cross-sectional and the P(VDF-TrFE)/P(VP-EDMAEMAES) bilayer SEM image cross-sectional, and signals in the LOND array recorded after NIR and green light exposure (10.80 mW cm^{-2}, 64 Hz for 20 s). Reprinted with permission from Ref.[77]. Copyright 2018, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. LOND: light-triggered organic neuromorphic device.

achieve bionic touch perception is essential for applications in prosthetics, flexible robotics, and human-machine interfaces. Artificial tactile sensory systems based on synaptic devices and tactile sensors have been developed to emulate the biological processing of tactile signals[5,29,79-81]. Shan *et al.* proposed a novel dual-output artificial tactile sensing (DOATS) system capable of realizing the parallel outputting of photoelectric signals[80]. The DOATS system simulated human tactile perception and recognized 16 types of fabrics with an accuracy rate of 94.1%. Multitask operations that can simultaneously drive the manipulator and implement image recognition have also been successfully achieved [Figure 7]. Wan *et al.* developed a flexible neurological electronic skin with a ferroelectric nanogenerator (FENG) and an artificial synaptic transistor, which successfully processed tactile information containing the magnitude and activation history of the force stimuli [Figure 8][81].

Studies have explored ways to improve the compatibility of stretchable artificial tactile sensory systems, which are based on stretchable synaptic transistors and tactile sensors, with animals. Shim and co-workers

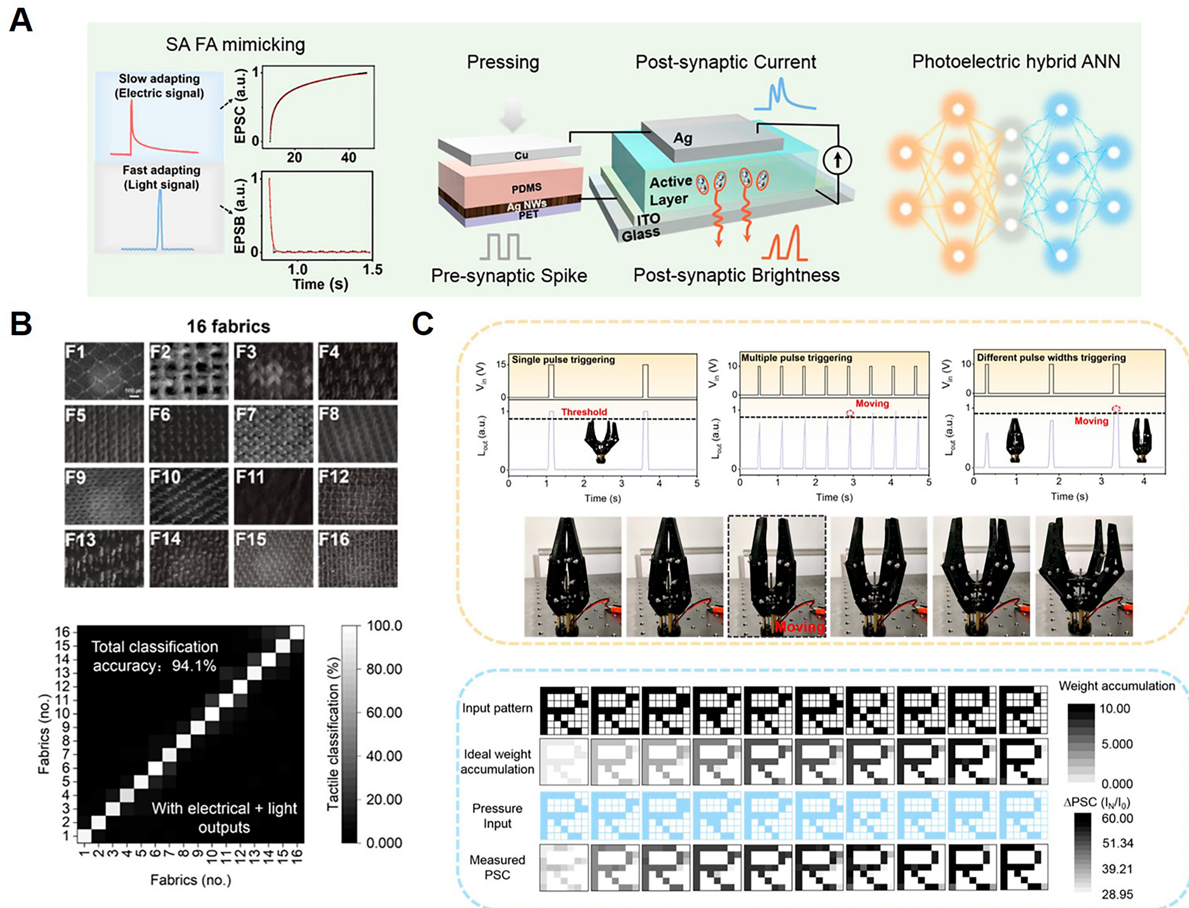

Figure 7. (A) Parallel output signals simulate slow adaptative/fast adaptative, and the schematic of photoelectric signal DOATS system and the photoelectric hybrid artificial neural network; (B) Optical images of 16 different fabric textures and texture total classification accuracy; (C) Photographs of the manipulator from resting state to moving state, and the DOATS system realizes the image learning process through electrical signals. Reprinted with permission from Ref.[80]. Copyright 2022, American Chemical Society. DOATS: dual-output artificial tactile sensing.

developed a fully rubbery, neurologically integrated, tactile sensory skin consisting of an array of rubber pressure-sensitive mechanoreceptors and fully rubbery synaptic transistors[5]. Mechanoreceptors respond to physical touches and generate presynaptic pulses, which are transmitted to synaptic transistors and excite postsynaptic potentials. Noticeably, the excitatory postsynaptic potential (EPSP) mapping from the sensory skin was achieved; for instance, the "U" and "H" patterns have been successfully marked by tapping the sensory skin with objects and recording the EPSP mapping. The EPSPs remained stable even after a mechanical strain of 50% was applied. Moreover, a soft adaptive neurologically integrated robot, namely a soft pneumatic robot covered with fully elastic skins of triboelectric nanogenerators (TENGs) and synaptic transistors, was fabricated. This robot could adaptively sense physical stimuli such as taps, touches, and locomotion, which were attributed to synaptic memory-encoded signals. When the TENG was physically tapped, presynaptic pulses were generated and transmitted to the synaptic transistors. Subsequently, the EPSC and short-term weight change w_n/w_1 values were obtained, using which the locomotion of the programmable robot could be controlled. Notably, the skin on the left and right sides guided the robot to turn right and left, respectively; and the top skin controlled the time at which the robot turned on or off. Controlling the tapping numbers from one to four times on the side skin could guide the robot to turn 10, 20, 30, and 40°. For instance, tapping the right skin of the soft robot four times could turn it 40° to the right.

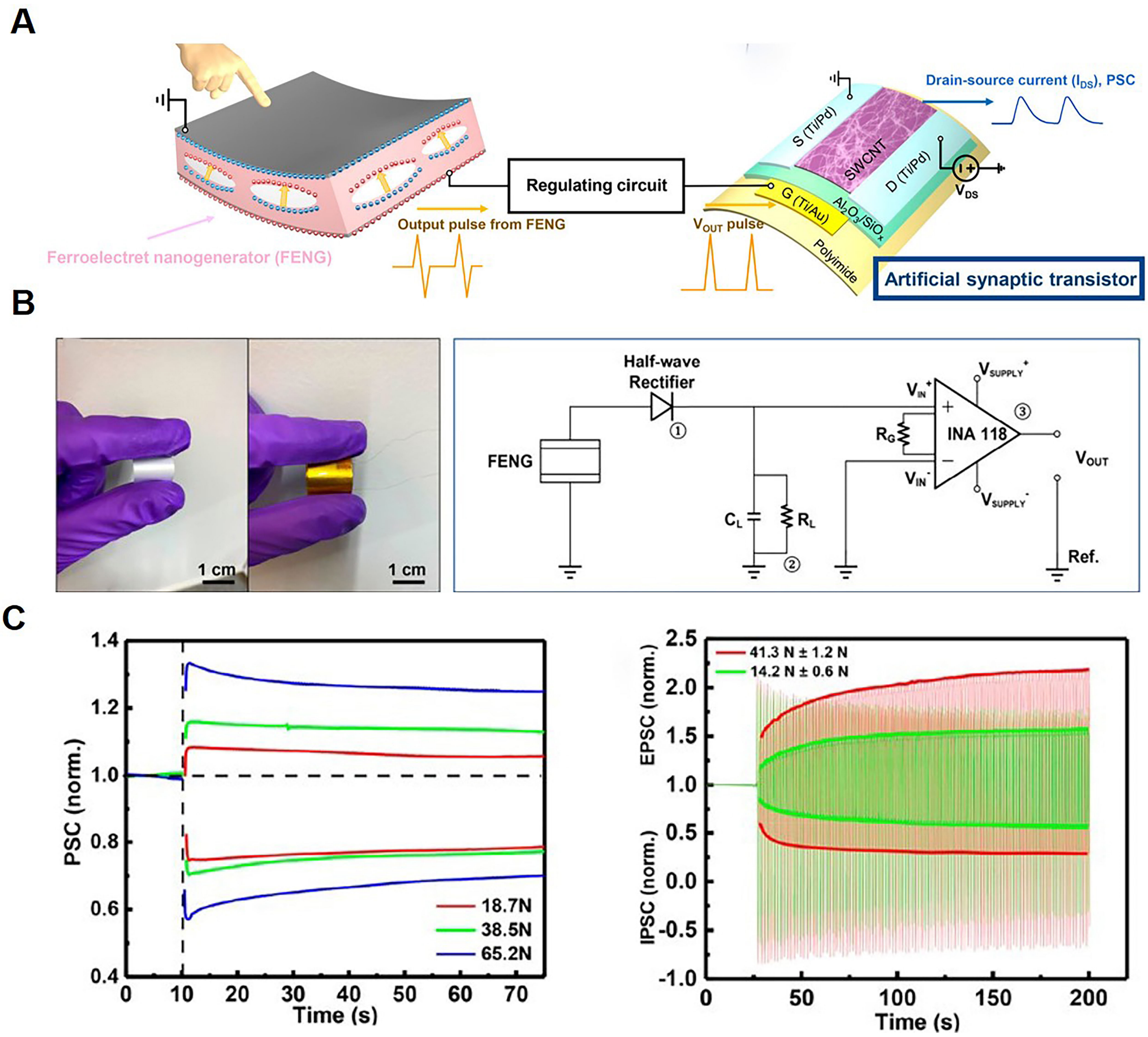

Figure 8. (A) Schematic illustration of artificial electronic sensory skin; (B) Photograph of a 1.2 × 1.2 cm^2 pristine PPFE film and complete ferroelectric nanogenerator device, respectively, and schematic of the regulating circuit based on ferroelectric nanogenerator; (C) Normalized PSC change of a synaptic transistor under different loading forces, and synaptic weight curves (peak and raw values of EPSC and IPSC) measured with periodical loading forces of 41.3 or 14.2 N at a frequency of 0.67 Hz. All synaptic behavior is measured at $|V_{DS}|$ = 1.0 V. Reprinted with permission from Ref.[81]. Copyright 2020, American Chemical Society. EPSC: excitatory postsynaptic current; ferroelectric nanogenerator ; IPSC: inhibitory postsynaptic currents; SWCNT: single-walled carbon nanotubes.

The soft neurorobot could perform adaptive locomotion along a complex path, turning right by 30° and then continuing to locomote straight for 10 s. Stretchable rubbery synaptic transistors based on elastomeric electronic materials such as rubbery conductors, semiconductors, and ion gels play an important role in the processing of tactile signals. Stretchable synaptic transistors have exhibited a set of synaptic characteristics including SM, STM, LTM, and filter characteristics, retaining them even after stretching to 50% strain. This study demonstrated the possibility of enabling neurological functions in soft machines and other applications.

Multisensory artificial nervous systems

Biological sensory systems can receive external stimuli and transfer different forms of physical stimuli into information coding for brain processing, enabling precise perception and appropriate reactions to complex real-world scenarios[82,83]. In biological systems, external stimuli are often processed synchronously and integrated into a comprehensive awareness; thus, humans are more sensitive to complex stimuli than they are to single stimuli[84]. Therefore, the incorporation of multisensory learning capabilities into electronic devices for the development of artificial sensory systems is increasing. Previous studies have attempted to emulate biological multisensory functionalities by integrating various types of sensors with artificial neuromorphic devices[27,72,85,86]. Wu *et al.* proposed an artificial multisensory integrated nervous system that integrates a flexible triboelectric nanogenerator (TENG) with an organic photosynaptic transistor and can emulate both haptic and iconic perception behaviors[72]. The multisensory integration nervous system successfully emulated typical multisensory integration behaviors, including the inverse effectiveness effect and temporal congruency, and the pattern recognition accuracy of the multisensory integration system was higher than that of a single-sense system. Liu *et al.* fabricated a multisensory artificial nervous system with a multisensory-memory-computing function and multitask emotion recognition in a self-powered vertical tribotransistor (VTT), which integrated a triboelectric nanogenerator (TENG) and transistor[71]. The multisensory artificial nervous system could simulate tactile, auditory, and visual perceptions, and a multi-model emotion recognition system based on the VTT was achieved with an emotion recognition accuracy reaching 94.05%.

Multisensory nervous systems based on stretchable synaptic FETs have been introduced into flexible neuromorphic electronics. Liu and co-workers developed a nanowire-channel intrinsically stretchable neuromorphic transistor (NISNT) that integrated the functions of a synapse and tactile sensor and could perceive both tactile and visual information[21]. This transistor employed P3HT/PEO nanowires and ion gel as the stretchable semiconductor and gate insulator, respectively, and it successfully mimicked synaptic characteristics, including EPSC, PPF, SFDP, SNDP, LTP, and LTD. These characteristics did not degrade even after 1,000 stretching cycles, demonstrating the high tolerance of the NISNT to stretching. When the stretchable NISNT was used as a tactile afferent nerve, it adhered to the five figures of the hand and achieved gesture recognition. For example, the 270 samples for the hand gestures “Good,” “Yeah,” and “OK” could be distinguished even under stretching deformation, and the accuracy was approximately 92.6%. Notably, NISNT could also process visual information owing to the light-sensitive feature of the P3HT/PEO channel, and through the introduction of light information, the accuracy of gesture recognition could be further improved, reaching 96.3%. Wang and co-workers developed a stretchable temperature-responsive multimodal neuromorphic electronic skin (STRM-NES) based on an array of intrinsically stretchable carbon nanotube synaptic transistors with mechanoreceptors and thermoreceptors [Figure 9][20]. Temperature sensing and modulation, deformation sensing and modulation, perception and memory, and healing from burning could be simultaneously realized in STRM-NES. Integrated synaptic carbon nanotube transistors (IS-CNT-STs) can emulate essential synaptic characteristics such as EPSC, IPSC, PPF, LTP, LTD, and the Pavlovian conditional reflex. The synaptic characteristics of these devices showed no obvious changes, even after 1,000 stretching cycles at 30% strain. These synaptic characteristics could be modulated by different stretching and deforming states; for instance, the PPF index declined by 120% when the strain was up to 50%. Temperature variations can also modulate the synaptic characteristics of a device, and the postsynaptic current can increase or decrease with the accumulation of thermal temperature. The synaptic characteristics of the STRM-NES could be tuned by both temperature and stretch deformation; the postsynaptic currents of the skin were weaker after a 30% strain with an increasing temperature than when it was unstretched. Additionally, the STRM-NES successfully emulated the self-healing abilities and temperature-location resolution of the skin. These studies demonstrated that stretchable synaptic transistors had great potential for the development of multisensory artificial nervous systems.

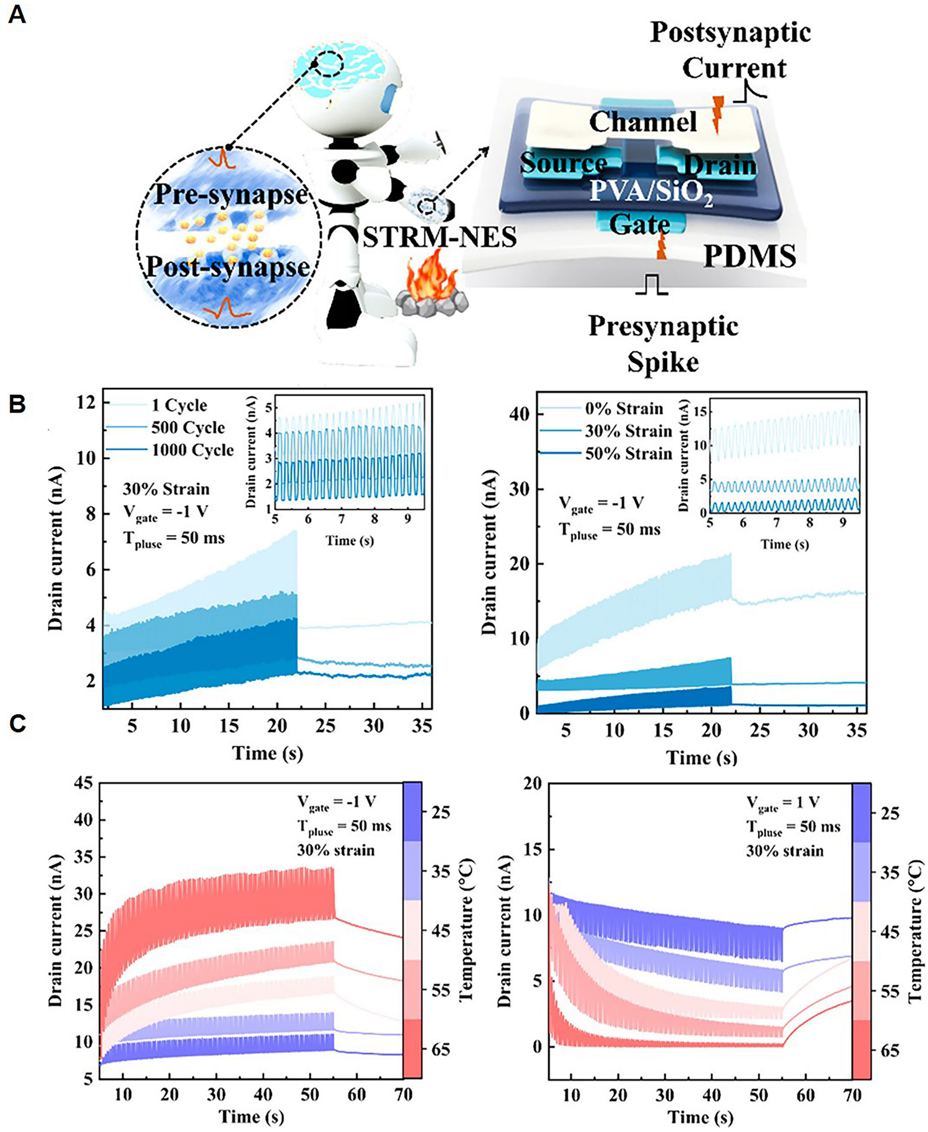

Figure 9. (A) Structure diagram of the neuromorphic device and its application; (B) Multiple negative presynaptic pulse induced postsynaptic currents at different stretch cycles and under different levels of mechanical strain, respectively; (C) Temperature-responsive LTP/LTD after 30% strain. Reprinted with permission from Ref.[20]. Copyright 2022, American Chemical Society. LTP/LTD: long-term potentiation/depression.

Different sensory systems based on stretchable synaptic FETs with a wide range of application prospects in bioinspired soft robots and neural prostheses have been developed[5,17,20,87]. For instance, Shim *et al.* proposed an artificial neuromorphic cognitive skin based on an array of biaxially stretchable elastomeric synaptic transistors[87]. Each biaxially stretchable synaptic transistor could emulate a full set of synaptic behaviors, such as the EPSC, PPF index, and memory characteristics, under various mechanical strains. The stretchy neuromorphic imaging sensory skin device based on stretchable elastomeric synaptic transistors exhibited a stable pattern reinforcement function under non-uniform deformation [Figure 10]. These studies demonstrated that stretchable synaptic transistors had the potential for application in next-generation wearable electronics, soft robotics, and neuroprosthetics, which are potential future development directions for flexible neuromorphic electronics.

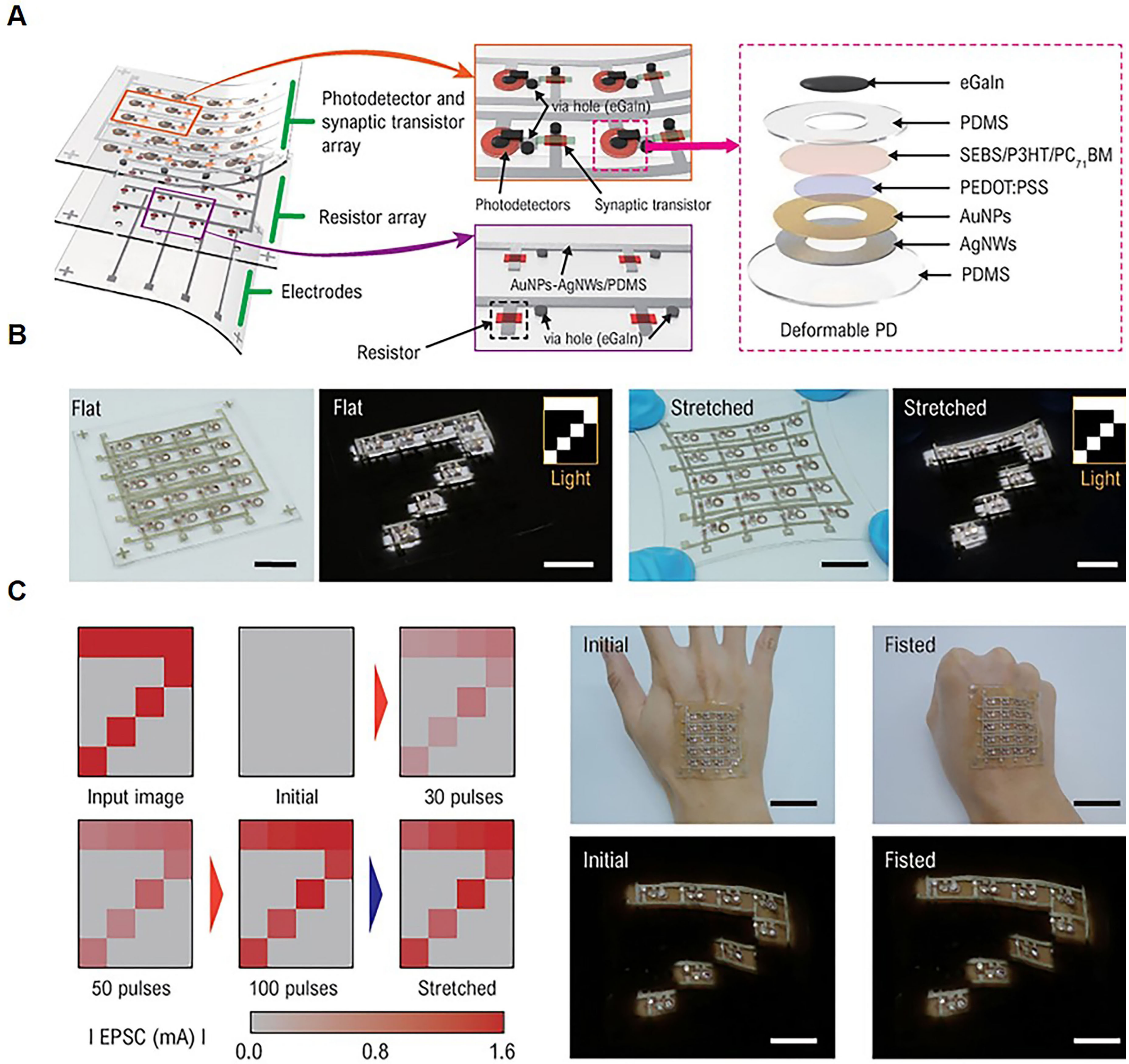

Figure 10. (A) Schematic of the stretchy neuromorphic imaging sensory skin device; (B) Optical photographs of the neuromorphic imaging sensory skin device at initial and biaxially stretched states before and after light illumination ("7"-shaped); (C) Mapped photoresponsive EPSC of the stretchy neuromorphic imaging sensory skin device with a different number of light pulses, and optical photographs of the stretchy neuromorphic imaging sensory skin device adhered on human skin at initial and fisted state before (Top) and after (Bottom) the light illumination. Reprinted with permission from Ref.[87]. Copyright 2022, the Author(s). Distributed under Creative Commons Attribution-NonCommercial-NoDerivatives License 4.0 (CC BY-NC-ND). EPSC: excitatory postsynaptic current.

CONCLUSION AND OUTLOOK

Stretchable synaptic transistors have gained significant attention owing to their mechanical softness and biocompatibility, seamless integration with the human body, and ability to perceive and react to real-world scenarios. Therefore, these transistors have great potential for use in health monitoring, electronic skins, human brain interfaces, and wearable consumer electronics. Currently, progress has been made in the development of stretchable synaptic transistors based on FETs. Stretchable synaptic transistors have been fabricated through the structural design and development of intrinsically stretchable devices. Regarding this, designing strain-absorbing structures, such as wavy structures using pre-stretching and releasing processes, can support the development of stretchable synaptic transistors with decreased mechanical damage and improved stretchability and electrical performance. Additionally, stretchable synaptic transistors can be fabricated using intrinsically stretchable functional layer materials, including substrates, electrodes, gate insulators, and semiconductors. Moreover, the applications of stretchable synaptic transistors in flexible neuromorphic electronics, including light sensory, tactile sensory, and multisensory artificial nervous systems, have been explored.

Although stretchable synaptic transistors have been implemented and their related applications have been explored, they need to overcome substantial challenges before being realized in real-world applications. First, mechanical compliance is important for flexible neuromorphic electronics; thus, the stretchability and stretchy stability of stretchable synaptic transistors should be further optimized based on device structures, fabrication processes, and functional materials. Second, mechanical deformation is significant for flexible synaptic device performance, and the systematic investigation of mechanical deformation on the performance of stretchable synaptic transistors is still limited and should be further extended. Third, a simple fabrication process that is compatible with the current standard processing of CMOS and does not increase the complexity of the current fabrication process or sacrifice device performance should be developed for the implementation of stretchable synaptic transistors. Fourth, the applications of stretchable synaptic transistors in artificial sensory systems are currently in their early stages, and fully functional and sophisticated artificial sensory systems based on stretchable synaptic transistors, such as those for audio, motion, and smell, should be developed. Fifth, the self-healing ability, biocompatibility, and synaptic characteristics of stretchable synaptic transistors should be considered because these transistors have a wide potential for application in wearable electronics, soft robotics, and neuroprosthetics. Stretchable synaptic transistors based on FETs will facilitate the development of transformative technologies in fields ranging from healthcare to artificial intelligence; thus, the role of these transistors in flexible neuromorphic electronics is of great interest.

DECLARATIONS

Authors' contributions

Wrote the original draft and revised the manuscript: Wang X
Review the manuscript: Yang H, Qi L, Rao Y
Supervised and reviewed the manuscript: Chen H

Availability of data and materials

Not applicable.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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