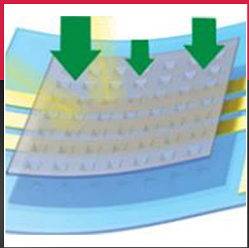

Organic synaptic transistors for flexible and stretchable artificial sensory nerves

Dae-Gyo Seo,[†] Gyeong-Tak Go,[†] Hea-Lim Park, and Tae-Woo Lee*

This article reviews artificial nerve electronics (nervetronics), an emerging field in which the goal is to develop bioinspired electronics that implement biological sensory functions. An artificial synapse is a fundamental core technology of artificial sensory nerves that can emulate functional properties of a biological synapse. Use of artificial synapses reduces the energy consumption and increases the sensitivity of low-level perception in artificial sensory nerves. Wearable and implantable devices require artificial sensory nerves that are flexible and stretchable. Therefore, development of organic artificial synapses that have these qualities is a central focus in nervetronics. Here, we review the concept and mechanism of organic artificial synapses for use as basic elements of flexible and stretchable artificial nerves. Next, we outline the research direction of the flexible and stretchable artificial sensory nerves so far, and finally, identify challenges of artificial sensory nerves that must be solved to enable actual application of this developing technology.

Introduction

"Artificial nerve electronics" (nervetronics) is a recently developed field that has the goal of developing electronic systems that emulate the processing of signals and information by biological nervous systems. The development of nervetronics is aimed to build artificial nerves that consist of central nervous system or peripheral nervous systems that possess learning and memorizing abilities, human-like stimulus sensing, and human-like motor coordination.[1,2] Therefore, nervetronics is regarded as a promising candidate that can replace von-Neumann architecture by offering low energy consumption and identical operating fundamentals as in a biological system. Most notably, the development of artificial sensory nerves that can perceive internal and external stimuli may enable construction of sensing systems that mimic the sensory detection and low-level perception of a biological peripheral nervous system.[3–5] Similar to a biological sensory nerve, the artificial sensory nerve consists of sensor, artificial neuron, and artificial synapse (**Figure 1**). Stimuli detected by the sensor unit are converted to a spike signal by an artificial neuron such as a ring oscillator,[3,6] then processed in the artificial synapse.[3] The artificial synapse consumes less energy than traditional CMOS transistors.[7–9] Also, low-level perception can be achieved without an external processing unit, because an artificial nerve can process information based on synaptic behaviors (mostly short-term plasticity).[3,10] Nervetronics can replace processing units, which consist of CMOS transistors. Therefore, an electronic system that consumes low energy can be developed.

With these advantages, artificial sensory nerves can be demonstrated for various sensing applications such as the Internet of Things (IoT), wearable electronics, neuroprosthetics, and interactive robotics.[1,11–13] Nervetronics may also have applications as edge-computing devices in sensor systems that use distributed processing. For these applications, the artificial nerves must be flexible and stretchable.

Organic materials are easily tuned at a molecular level, so they are regarded as more suitable than inorganic materials to realize flexible and stretchable properties.[14] Various kinds of electronic devices and systems that use organic materials have demonstrated flexible or stretchable properties; examples include organic artificial synapses and organic artificial

Dae-Gyo Seo,Department of Materials Science and Engineering, Seoul National University, Republic of Korea; tjeory95@snu.ac.kr
Gyeong-Tak Go, Department of Materials Science and Engineering, Seoul National University, Republic of Korea; kkt9612@snu.ac.kr
Hea-Lim Park, Department of Materials Science and Engineering, Seoul National University, Republic of Korea; haelim1017@snu.ac.kr
Tae-Woo Lee, Department of Materials Science and Engineering, School of Chemical and Biological Engineering, and Institute of Engineering Research, Research Institute of Advanced Materials, Nano Systems Institute, Seoul National University, Republic of Korea; twlees@snu.ac.kr
*Corresponding author
[†]These authors contributed equally to this article
doi:10.1557/s43577-021-00093-5

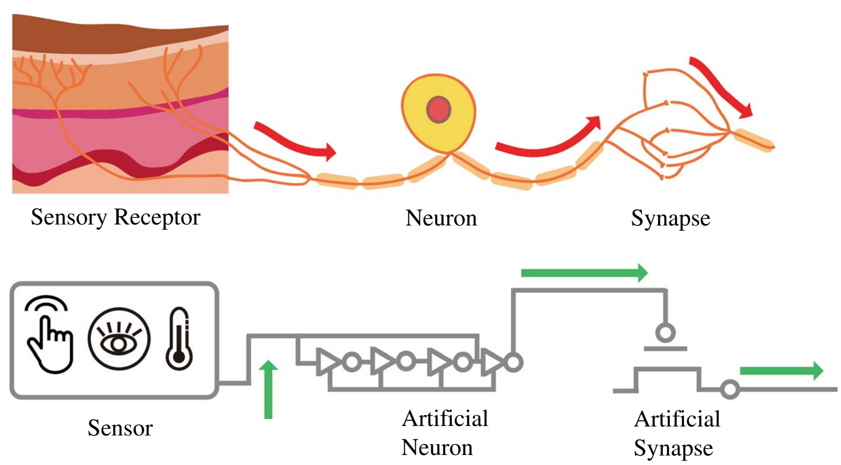

Figure 1. Schematic of biological sensory nerve (top) and artificial sensory nerve (bottom).

sensory neurons. Artificial sensory nerves that have these functionalities will have applications in future sensor-based electronics. Here, we first introduce the basics of artificial synapse that emulate biological functions. Next, we introduce the concepts of artificial sensory nerves, and recent research trends on the topic. We also discuss future challenges and possible strategies to construct reliable and functionalized stretchable artificial sensory nerves.

Basic concepts of artificial synapses

Biological synapses

Biological nervous systems in vertebrates are divided into two parts: the central nervous system (CNS) that is composed of the brain and the spinal cord, and the peripheral nervous system (PNS) that is composed of the sensory and the motor nerves.[2] In these biological nervous systems, a huge number of neural signals are transmitted through a neural network that consists of ~10^{12} intricately intertwined neurons and ~10^{15} synapses.[15,16] The system processes input information through the synaptic transmission in a massively parallel, resilient, error-tolerant, and highly energy-efficient manners, and consume only around 1 ~ 10 fJ per synaptic event.[2,3,7] Pre-neurons are connected to post-neurons by the synapses; their responses to stimuli (action potentials) can change over time;[17,18] this "synaptic plasticity" contributes to information flow, data processing, and memory.[2,19] When an action potential arrives at the axon terminal of the pre-neuron, synaptic vesicles move toward the axon terminal, where they release neurotransmitters; they diffuse across the synaptic cleft and bind to receptors on the postsynaptic membrane. As a result, ion channels open and the postsynaptic membrane potential changes. Diverse kinds of neurotransmitters are used; some increase the sensitivity (excitation) of the post-neuron, and some decrease it (inhibition).[17] Excitation depolarizes the membrane potential; the deviated potential state is called the excitatory postsynaptic potential (EPSP).[20] Inhibition negatively hyperpolarizes the membrane potential; the new state is called inhibitory postsynaptic potential (IPSP).[20] The synaptic plasticity is categorized by its duration; short-term plasticity (STP) and long-term plasticity (LTP).[21] Repeated or frequent stimulations for a long period of time may induce a transition from STP to LTP.

Signals in a biological system are transmitted by depolarization of the nerve membrane; this depolarization can be represented as a voltage spike. They have the same magnitude; information is encoded as spike frequency and spike timings. The synaptic strength in biological neural networks can be changed by spike rate, either as spike-rate-dependent plasticity (SRDP) or spike-frequency-dependent plasticity (SFDP).[22]

Emulation of biological synaptic functions

Artificial synapses have emulated the STP, LTP, and other synaptic functions of biological nervous systems. By implementing these biomimetic functions, artificial sensory nerves have achieved unique properties. Artificial synapses can adjust their conductance state in response to electrical pulses, which correspond to action potentials in biological nerves; this change corresponds to synaptic weight in biological nerves.[7,23,24] Exploitation of diverse behaviors of such conductance states can yield artificial synapses that can implement natural synaptic functions.

When signals from sensors are applied to the artificial synapses, the conductance of the artificial synapses can be increased or decreased that emulates EPSP and IPSP in biological synapse. When the changed retention time of conductance state is short, the artificial synapse implements STP and when the retention time is long, the artificial synapse implements LTP. For the artificial sensory nerves, achieving STP properties in artificial synapses is important to avoid afterimage of the sensory signals in artificial sensory nerves.

Paired-pulse facilitation (PPF) and paired-pulse depression (PPD) are representative properties of STP that are induced by two consecutive spikes (**Figure 2a**). The first spike that reaches the artificial synapse stimulates an increase in synaptic weight A_1; normally this increase would then decay over time to its initial weight, but if a second spike is applied before the decay is complete, the effect A_2 of the second spike either has a greater effect on synaptic weight than the first one (PPF), or a weaker one (PPD). This strengthening or weakening effect can be expressed by the PPF or PPD index, which is calculated from A_2/A_1. PPF index and PPD index decrease as the time interval between the spikes increases.

In artificial sensory nerves, the sensory inputs can be distinguished by the spike rates applied to the artificial synapses. For example, the conductance state of an artificial synapses

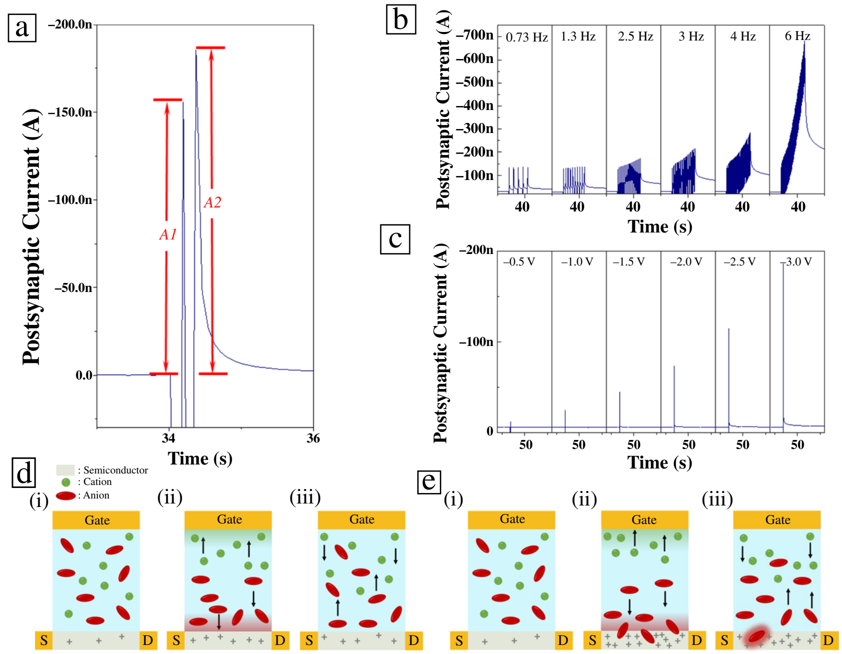

Figure 2. Synaptic plasticity (a–c) and mechanism (d, e) of ion-gel gated organic transistors. (a) Paired-pulse facilitation behavior in artificial synapses. (b) Spike-frequency-dependent plasticity. Postsynaptic changes depending on the presynaptic spike frequency. (c) Spike-voltage-dependent plasticity. Postsynaptic changes depending on the presynaptic spike voltage. Reprinted with permission from Reference 24. © 2019 Elsevier. (d) Formation of electrical double layer during ([i]) no bias, ([ii]) bias applied, ([iii]) bias removed. (e) Ion penetration to semiconductors during ([i]) no bias, ([ii]) bias applied, ([iii]) bias removed. Draw under assumption of *p*-type semiconductors.

depends on the sensory input spike frequencies, either as SRDP or SFDP (Figure 2b). By varying the frequency of a given number of spikes, the postsynaptic current of the artificial synapses can be modulated. Commonly, the gain of the postsynaptic current by various spike frequencies can be expressed as A_n/A_1, where A_n is the postsynaptic current induced by the *n*th spike voltage.

Inputs to artificial sensory nerves can also be applied in the forms of various amplitudes of spikes. As the amplitude of input spikes differs, the postsynaptic current of artificial synapses can vary (Figure 2c). This feature is called spike-voltage-dependent plasticity (SVDP). As the amplitude of the spike input from the sensors of the artificial sensory nerves increases, the postsynaptic current of the artificial synapses increases.[3] Emulating biological synaptic functions is a key to achieve bioinspired artificial sensory nerves. Among artificial synaptic transistors, organic artificial synaptic transistors can emulate biological synaptic functions with very low energy consumption, which were previously mentioned above (**Table I**).

Mechanism of artificial synapse

Organic artificial synapses are promising for artificial sensory nerves due to flexibility, stretchability, and versatility. Flexibility and stretchability are essential properties to enable application of artificial sensory nerves in nerve prosthetics and soft robotics. Such organic artificial synapses can be mainly classified into two types, according to structure: two-terminal structure and three-terminal structure.

Table I. Summary of organic synaptic transistors.

Mechanism	Materials		Emulated Synaptic Properties	Write-Read Cycle	Energy Consumption Per Spike[a]	References
	Gate Insulator	Semiconductor				
Charge trapping	PMMA/C_3N_4	Pentacene	SNDP, SVDP, SDDP, PPF	–	18.06 fJ	12
Ion migration/electrochemical reaction	[EMIM][TFSI]/PS-PMMA-PS based ion-gel	P3HT[b]	SNDP, SVDP, SFDP, SDDP, PPF	>8	6 nJ	23
		FT4-DPP[c]	SNDP, SVDP, SFDP	>500	70 nJ	3
		PTIIG-Np[d]	SNDP, SVDP, SFDP, SDDP, PPF	>10	8.08 nJ	24
		P3HT-PEO core-sheath	SNDP, SVDP, SFDP, SDDP, PPF, STDP	–	1.23 fJ	7
		FT4-DPP nanowire	SNDP, SVDP, SFDP, SDDP, PPF	–	772 pJ	36
	[EMIM][TFSI]/P(VDF-HFP) based ion-gel	p(g2T-TT)[e]	SNDP	$>10^8$	80 fJ	31
		P3HT-NFs/PDMS	SNDP, SFDP, SDDP, PPF	–	123 μJ	37

[a](Energy consumption) = (Spike voltage) × (Peak current) × (Spike duration time).

[b]Poly(3-hexylthiophene).

[c]Fused thiophene diketopyrrolopyrrole.

[d]Poly(thienoisoindigo-naphthalene).

[e]Poly(2-(3,3′-bis(2-(2-(2- methoxyethoxy)ethoxy)ethoxy)-[2,2′-bithiophen]-5-yl)thieno [3,2- b]thiophene).

In two-terminal devices, also called memristors, the top and bottom electrodes which contain electrochemically reactive metals (e.g., Al, Cu) are separated by mostly an insulating layer. In response to stimulation, the insulating layer switch between a low-resistance state (LRS) and a high-resistance state (HRS).[2,25] Under the electric field, the metal ions are oxidized and then drive into the insulating layer. The metallic ions then are reduced to metallic atoms by electrons, which results in the formation of metallic filaments. The metallic region can be destroyed by Joule heating, spontaneous diffusion of ions/atoms, or diffusion of ions/atoms by reverse bias. Two-terminal devices have been widely used for brain-inspired computing such as artificial neural network.[26] convolutional neural network,[27] and spiking neural network.[28] But this binary response is not compatible with modulation of synaptic properties and expression of diverse synaptic functions, so two-terminal devices are seldom used in artificial sensory nerves.

Three-terminal artificial synapses have an additional electrode, called a gate. The presynaptic action potential is applied through the gate, and the conductance of the channel material changes in response. The gate at which the input is received is separated from the electrode that give output (drain), so three-terminal structure permits modulation of the channel materials by various methods.[23,24] Therefore, three-terminal devices can show STP, which is an important synaptic function for artificial sensory nerves. In three-terminal artificial synapses, which commonly use ion migration in an electrolyte gate, STP property can be achieved by modulating the interaction between ions and organic active layers.[7] Use of ion migration as an operating mechanism can match the speed of biological sensory nervous systems. Application of voltage to the gate causes ions to form an electrical double layer (EDL) between the gate/electrolyte interface and electrolyte/semiconductor interface, so the conductance of the artificial synapse changes. This EDL is very thin (nanometers), so the ions rapidly diffuse back to their initial distribution as soon as applied gate voltage is removed.

The switching between ON and OFF in artificial synapse can differ from switching between OFF and ON: formation of the EDL layer can take ~1 ms whereas the switch from ON to OFF takes 0.5 ms; which means that EDL layers can respond in <1 ms.[29,30] When the organic active layer is permeable to ions, they can penetrate the organic semiconductors when additional gate voltage is applied. Ions that penetrate to the organic semiconductors can be trapped and/or induce electrochemical doping of the organic semiconductors; the effect increases the retention time of the artificial synapses.[7,23,24] Ions that penetrate only partially may be retained for only a few seconds, but ions that have penetrated deeply may have retention time of tens of seconds to minutes, which is unsuitable for artificial sensory nerves.[23,24] Artificial sensory nerves must avoid strong penetration of the ions to the organic active layers; this requirement is different from those of artificial synapses for neuromorphic computing, which require a long retention time.

The EDL that forms between gate/ion-gel and ion-gel/semiconductor interface is very thin (Figure 2d, e). Its capacitance can be extremely large (up to μF cm^{-2}) due to its thinness and locates at gate/ion-gel and ion-gel/semiconductor interfaces.[30] The bulk electrolyte region between interfaces is neutral, so the effective capacitance that affects the functions of the artificial synapses depend not on the thickness of the ion-gel, but on ion migration under bias conditions.

The 1-ms switching time of EDL is dominated by the migration of ions in the ion gel under bias conditions.[29,30] A switching time of a few milliseconds can be suitable for biointegration, but can be too long for various sensory applications in electronic systems (e.g., IoT, robotics), so efforts have been made to decrease it. Use of a semiconducting polymer poly(2-(3,3′-bis(2-(2-(2-methoxyethoxy)ethoxy)ethoxy)-[2,2′-bithiophen]-5-yl)thieno[3,2-b]thiophene) (p(g2T-TT)) and ion gel reduced the switching time to 20 ns, and achieved write speed <1 μs. Although the mechanism of such fast switching is not yet known, the result is meaningful in that it overcame the limits of the ion-gel EDL response time. As a result, the artificial synapses can be applied to artificial nervous system that receive input signals at >1 kHz.[31]

Flexible artificial synapses have been achieved using various materials and operating mechanisms.[2,32] However, relatively few papers have reported stretchable artificial synapses. For both two-terminal and three-terminal artificial synapses, the same strategies can be applied to achieve deformability. Stretchable semiconductors will be key technologies in stretchable artificial synapse. Several approaches have reported development of stretchable semiconductors: (1) geometrical structural modulation, (2) blending semiconductor with elastomer matrix, and (3) use of intrinsically stretchable semiconducting materials. Geometrical structural modulation such as prestrained elastomer,[33] rigid island structure,[34] and wrinkles[35] have been reported for stretchable semiconductors in stretchable organic thin-film transistors (OTFTs). Especially, stretchable artificial synapses that have been prepared using a prestraining strategy have been achieved using electrospun fused thiophene diketopyrrolopyrrole (FT4-DPP)-based semiconducting polymer nanowire,[36] and poly(3-hexylthiophene nanofibrils) (P3HT-NFs) thin film has been transferred onto a prestrained elastomer.[37] A stretchable optoelectronic artificial synapse has been demonstrated using wavy electrospun nanowire and prestrained styrene ethylene butylene styrene (SEBS) (**Figure 3**a); the synapse shows identical electronic properties and synaptic characteristics under 0% and 100% strain.

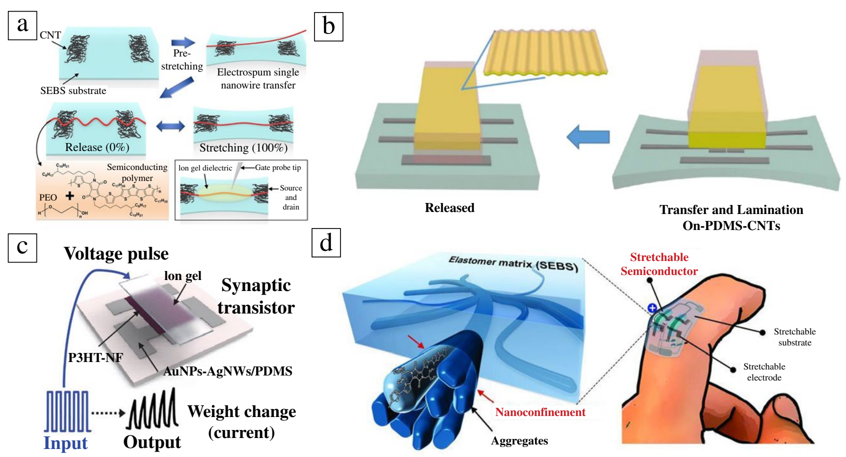

Figure 3. Stretchable artificial synapses using organic nanofibers and the network embedded in elastomers. (a) Stretchable electrospun organic nanowire artificial synapse with prestrained geometry. Reprinted with permission from Reference 36. © 2018 AAAS. (b) Stretchable artificial synapse prestrained P3HT-NFs film. Reprinted with permission from Reference 38. © 2020 Elsevier. (c) Stretchable artificial synapse with P3HT-NFs blended in PDMS elastomer. Reprinted with permission from Reference 37. © 2019 AAAS. (d) Schematic diagram of nanoscale networks of stretchable semiconducting polymer (blending of diketopyrrolopyrrole polymer and SEBS elastomer). Reprinted with permission from Reference 41. © 2017 AAAS.

Synaptic properties that can be changed by stretching of the material have been achieved using P3HT-NFs film and ion-gel film (Figure 3b);[38] when the ion gel is stretched, polymer chains open, and ion transport is facilitated. Therefore, hysteresis, PPF index, and retention time decrease as strain increases. A semiconducting polymer can be blended with an elastomer such as poly(dimethylsiloxane) (PDMS),[39,40] and SEBS[41] to yield stretchable semiconducting polymer blend.

A stretchable artificial synapse array has been fabricated using a blend of P3HT-NFs in PDMS elastomer matrix (Figure 3c).[37] P3HT-NFs percolated into the PDMS matrix, so the P3HT can be stretched up to 50% of strain and continue to emulate synaptic behaviors. Similarly, various blending combinations and ratios can be applied to obtain high stretchability and tuning of synaptic characteristic. As a result of the nanoconfinement effect, OTFTs that use blends of diketopyrrolopyrrole polymer (DPP)-based polymer and SEBS elastomer retain high charge-carrier mobility upon 100% strain (Figure 3d).[41] Although this strategy is highly effective for OTFTs, the stretching can alter the synaptic properties. Among those strategies, geometrical structural modulation shows stretching insensitive synaptic properties but blending strategy show stretching dependent synaptic properties (**Table II**). Intrinsically stretchable semiconducting materials that have been already developed for OTFTs can also be used to obtain a stretchable artificial synaptic transistors.[42] Intrinsically stretchable semiconductor can be developed with tunable electronic properties and ion-doping properties and yielded controllable synaptic properties; this possibility may be a future research direction.

Concepts of artificial sensory nerves

Mechanism of artificial sensory nerves

Artificial sensory nerves require a STP-dominant behavior, which is a different property than in neuromorphic computing. If the ions that form the EDL or penetrate the active layer lightly rather than strongly, the artificial synapses can implement synaptic functions that are suitable for artificial sensory nerves. Strategies to achieve this trait include modifying the active layer to reduce the number of ions that it traps, or using materials that tend to trap a small number of ions.[3,24,36] Also, use of ions that tend to not be trapped in the active layer may achieve STP-dominant artificial synapses for artificial sensory nerves.

Table II. Synaptic properties of stretchable organic synaptic transistors.

Strategy	Stretchable Semiconductor	PPF Ratio (A_2/A_1)		SFDP Gain (A_n/A_1)		References
		0%	Stretched	0%	Stretched	
Geometrical structural modulation	Wavy FT4-DPP nanowire	134	134% (100% strain)	1.55	1.55[a] (100% strain)	36
	Wavy P3HT-NF film	230	180% (60% strain)	2.5	2.2[b] (60% strain)	38
Blending with elastomer matrix	P3HT-NF film	146	114% (50% strain)	2.3	1.82[c] (50% strain)	37

[a]Spike number = 10 ($A_n = A_{10}$).
[b]Spike number = 10 ($A_n = A_{10}$).
[c]Spike number = 20 ($A_n = A_{20}$).

Engineering of the polymer semiconductor morphology can be a promising strategy for modulating the synaptic functions of ion-gel gated organic synaptic transistors, which are suitable for artificial sensory nerves.[24] To receive auditory signals, a triboelectric sensor was integrated with artificial synapses. When the artificial synapse showed an LTP-dominant behavior, the first auditory signal overlapped the later auditory signals; this response reduces the accuracy of artificial sensory nerves. In contrast, when the artificial synapses showed a STP-dominant behavior, they showed fast decay and rapid response to auditory signals without any overlap between first and second signals; this difference of response indicates that the interaction between the ion-gel and polymer semiconductor layers must be controlled to reduce the number of ions that the polymer semiconductors trap.

Materials that tend to trap fewer ions have also been used as artificial nervous synapses. Artificial synapses that use DPP have been used as artificial sensory nerves and stretchable organic sensorimotor synapses.[3,36] Artificial synapses that use DPP polymers tend to implement STP-dominant synaptic properties, unlike P3HT, which tends to show LTP-dominant properties,[23] or thienoisoindigo polymer (PTIIG), which can show both STP-dominant and LTP-dominant properties, depending on the microstructure.[24]

STP-dominant artificial synapses have a response time of 2 to 3 ms, which is comparable to biological response time (1.5–5 ms).[3,43,44] Artificial synapses that use DPP were integrated with pressure sensors and ring oscillators (**Figure 4**a) to implement a slow adaptive Type I (SA-I) artificial afferent nerve. An SA-I receptor is a mechanoreceptor that measures static force.[45] Measured pressure from a carbon nanotube (CNT) pyramid pressure sensor was changed to a voltage spike via ring oscillators, which is suitable for firing artificial synapses. A continuous output signal from a sensor must be converted to a voltage spike to activate the synaptic functions of artificial synapses and implement diverse synaptic behaviors. As the pressure increases, supply voltage to the ring oscillator also increases, so its output frequency increases.

The artificial synapses had a SFDP property, so the artificial afferent nerves output postsynaptic currents that varied with pressure intensity (Figure 4b). They also had spike number dependent plasticity (SNDP), so postsynaptic current also varied with the duration of pressure (Figure 4c, d).

With artificial synapses, processing of sensory information in artificial afferent nerves is a useful trait. When multiple pressure sensors are aligned in parallel, the direction of the pressure movement can also be detected. The pressure sensors detected the direction of movement by a rod-like object (Figure 4e–g). When an artificial synapse shows a LTP behavior, the change of the pressure by time cannot be distinguished, because they are obscured by the remaining signals after the spatiotemporally changing inputs.

The possibility of using these artificial sensory nerves as nerve prosthetics was testified by transferring the output signal to the leg of a roach (*Blaberus discoidalis*). An appropriate pressure intensity of postsynaptic oscillating signals enabled actuation and control of the tibial extensor muscle in the leg. As the time and pressure applied to CNT pressure sensor increased, the force of leg extension increased. The pressure information from the pressure sensors was successfully transmitted to the synaptic transistor, of which the output was used to induce the tibial muscle extension. This system successfully realized an artificial afferent-biological efferent hybrid reflex arc.

Artificial sensory nerves must also be able to transmute detected signals to presynaptic spikes by exploiting STP-dominant artificial

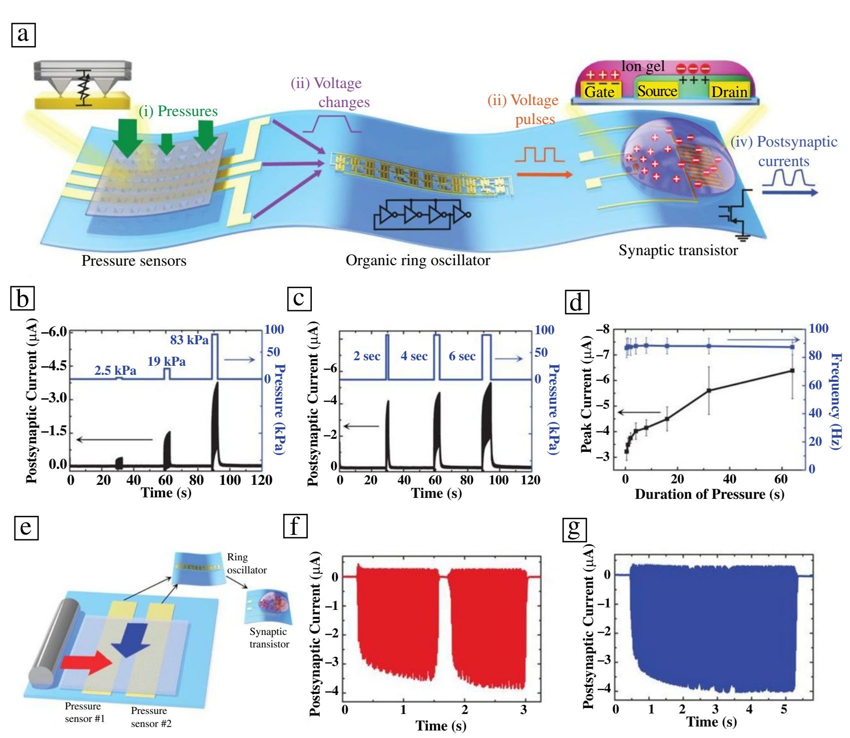

Figure 4. (a) An artificial afferent nerve composed of a pressure sensor, ring oscillator, and artificial synapses. The ring oscillator converts a signal from sensors to voltage spikes. (b–d) Postsynaptic current for three different pressure (b) intensities and (c) duration. (d) Peak current depends only on the duration of fixed pressure intensity. (e) Artificial afferent nerves with pressure sensors aligned in parallel. (f, g) Postsynaptic current when a rod-like object is moving in two different directions. The change of the rod-like object movement by time could be detected due to the short-term plasticity property of the artificial synapse. Reprinted with permission from Reference 3. © 2018 AAAS.

synapses that constitute the core part of artificial sensory nerves. Such strategies permit implementation of various artificial sensory nerves that can detect physical stimuli such as pressure, sound, strain, temperature, and vibration.

Future challenges

Microstructure engineering of polymer semiconductors is one of the important strategies to control charge transport in OTFTs. For example, edge-on orientation and compact π–π stacking leads to high charge-carrier mobility in OTFTs.[46,47] However, unlike OTFTs, how the microstructure of semiconducting polymers affects the characteristics of organic artificial synapses has not been intensively studied in depth. There are only reports that high crystallinity of polymer semiconductors leads to emulation of long-term plasticity in P3HT and PTIIG.[23,24,48] More in-depth and comprehensive microstructure engineering considering polymer chain morphology and molecular orientation have to be conducted for developing versatile organic artificial synapse and nervetronics. Also, organic/polymer material design and development to emulate STP and LTP behaviors required for specific applications of nervetronics.

Organic artificial synapses that exploit ion migration of ions have been evaluated for use as artificial sensory nerves to implement STP. Liquid-type and ion-gel-type electrolytes can emulate synaptic properties well and are not affected by strain, but they are vulnerable to environmental factors such as moisture,[49] and to solvents. To reduce environmental effects, a solid-type ionic electrolyte is more advantageous than liquids and ion gels. Especially, acquisition of environmental stability, ease of processability, and various functionalities requires development of all-solid-state stretchable artificial synapses. For this development, stretchable ion-conducting elastomer that can replace a rigid solid electrolyte or ion-gel/liquid type electrolyte can be applied.[50,51] Also, to increase environmental stability for wearable and implantable applications, reliable flexible/stretchable encapsulation materials and processes must be developed.

Processing of signals from multiple sensors requires a flexible/stretchable array of artificial synapses. Especially, a reliable patterning process is required for both a stretchable semiconducting layer and electrolyte materials. Patterning methods for a stretchable semiconducting layer have been reported for a stretchable OTFT array.[52,53] Similar to the conventional strategies on stretchable OTFT array, reliable patterning method for artificial synapse arrays have to be developed (e.g., photolithography, ink-jet printing, electrohydrodynamic nanowire printing).[54,55] Although ion-gel or solid electrolyte materials can be patterned by stencil printing,[56] cut-and-paste,[37] and aerosol printing,[57] a reliable patterning method for scaling and integration such as photolithography has not been developed.

One goal is a free-standing sensing system that can be easily constructed without wiring to an external power source. Similar approaches in a stretchable wireless biological sensing system have used radiofrequency identification (RFID) and near-field communication (NFC); these ideas may be applicable to artificial sensory nerves.[58,59] RFID and NFC application use a frequency of 13.56 MHz or such frequency levels, so wireless artificial sensory nerves must have appropriate rectifiers and other components.

Stretchable batteries composed of various materials and structures also have been studied for use in wearable and implantable electronics.[60] However, some challenges such as degradation of battery performance upon charging–discharging cycles, and under strain, must be overcome to realize reliable battery-operated artificial sensory nerves.

Self-powered devices provide another option. Photovoltaic devices and triboelectric nanogenerators have been connected as gate signals of an artificial synapse,[24,36] but not in drain and operating voltages for other components; this untested possibility provides a future research direction. Although fully free-standing artificial sensory nerves have not be developed yet, they are important components of wearable and long-term implantable applications.

Conclusion and outlook

We have introduced the concepts of organic artificial sensory nerves and artificial synapses, which are important components of artificial sensory nerves. We also reviewed recent studies on flexible/stretchable organic artificial synapses and organic artificial sensory nerves with operating mechanisms. Artificial sensory nerves are composed of sensor, artificial neuron, and artificial synapse, and they mimic a biological sensory nerve system. Therefore, an artificial sensory nerve can process sensory information by exploiting synaptic plasticity and can enable low-level perception without external computing units. Artificial sensory nerves including STP-dominant artificial synapses enable sensing, low energy consumption, and the possibility of developing neural prosthetics with biocompatible signals. Use of organic materials means that organic artificial synapses can exhibit various functionalities (e.g., flexibility, stretchability, self-healing ability, biocompatibility) for a variety of applications such as wearable electronics, implantable diagnostic devices, soft robotics, neural prosthetics, and IoT. However, the development of artificial sensory nerves is in an early stage and many challenges (e.g., environmentally stable device, reliable pattering technology, and free-standing system) remain before they can be realized. When these challenges can be overcome, stretchable nervetronics will be widely applicable in systems that process signals from the environment.

Acknowledgments

This work was supported by the National Research Foundation of Korea (NRF) Grant funded by the Korea Government (Ministry of Science, ICT and Future Planning) (NRF-2016R1A3B1908431). This work was also supported by the Creative-Pioneering Researchers Program through Seoul National University (SNU).

Data availability

Data sharing not applicable to this article as no data sets were generated or analyzed during the current study.

References

1. Y. Lee, T.-W. Lee, Organic Synapses for neuromorphic electronics: From brain-inspired computing to sensorimotor nervetronics. *Acc. Chem. Res.* **52**, 964 (2019)
2. H.-L. Park, Y. Lee, N. Kim, D.-G. Seo, G.-T. Go, T.-W. Lee, Flexible neuromorphic electronics for computing, soft robotics, and neuroprosthetics. *Adv. Mater.* **32**, 1903558 (2019)
3. Y. Kim, A. Chortos, W. Xu, Y. Liu, J.Y. Oh, D. Son, J. Kang, A.M. Foudeh, C. Zhu, Y. Lee, S. Niu, J. Liu, R. Pfattner, Z. Bao, T.-W. Lee, A bioinspired flexible organic artificial afferent nerve. *Science* **360**, 998 (2018)
4. C. Wan, G. Chen, Y. Fu, M. Wang, N. Matsuhisa, S. Pan, L. Pan, H. Yang, Q. Wan, L. Zhu, X. Chen, An artificial sensory neuron with tactile perceptual learning. *Adv. Mater.* **30**, 1801291 (2018)
5. K. Xiao, C. Wan, L. Jiang, X. Chen, M. Antonietti, Bioinspired ionic sensory systems: The successor of electronics. *Adv. Mater.* **32**, 2000218 (2020)
6. B.C.K. Tee, A. Chortos, A. Berndt, A.K. Nguyen, A. Tom, A. McGuire, Z.C. Lin, K. Tien, W.G. Bae, H. Wang, P. Mei, H.H. Chou, B. Cui, K. Deisseroth, T.N. Ng, Z. Bao, A skin-inspired organic digital mechanoreceptor. *Science* **350**, 313 (2015)
7. W. Xu, S.-Y. Min, H. Hwang, T.-W. Lee, Organic core-sheath nanowire artificial synapses with femtojoule energy consumption. *Sci. Adv.* **2**, e1501326 (2016)
8. W. Xu, H. Cho, Y.-H. Kim, Y.-T. Kim, C. Wolf, C.-G. Park, T.-W. Lee, Organometal halide perovskite artificial synapses. *Adv. Mater.* **28**, 5916 (2016)
9. S.-I. Kim, Y. Lee, M.-H. Park, G.-T. Go, Y.-H. Kim, W. Xu, H.-D. Lee, H. Kim, D.-G. Seo, W. Lee. T.-W. Lee, Dimensionality dependent plasticity in halide perovskite artificial synapses for neuromorphic computing. *Adv. Electron. Mater.* **5**, 1900008 (2019)
10. D.W. Kim, J.C. Yang, S. Lee, S. Park, Neuromorphic processing of pressure signal using integrated sensor-synaptic device capable of selective and reversible short- and long-term plasticity operation. *ACS Appl. Mater. Interfaces* **12**, 23207 (2020)
11. J.C. Yang, J. Mun, S.Y. Kwon, S. Park, Z. Bao, S. Park, Electronic skin: Recent progress and future prospects for skin-attachable devices for health monitoring, robotics, and prosthetics. *Adv. Mater.* **31**, 1904765 (2019)
12. H.-L. Park, H. Kim, D. Lim, H. Zhou, Y.-H. Kim, Y. Lee, S. Park, T.-W. Lee, Retina-inspired carbon nitride-based photonic synapses for selective detection of UV light. *Adv. Mater.* **32**, 1906899 (2020)
13. X. Bu, H. Xu, D. Shang, Y. Li, H. Lv, Q. Liu, Ion-gated transistor: An enabler for sensing and computing integration. *Adv. Intell. Syst.* **2**, 2000156 (2020)
14. D.J. Lipomi, Z. Bao, Stretchable and ultraflexible organic electronics. *MRS Bull.* **42**(2), 93 (2017)
15. A.L. Hodgkin, A.F. Huxley, A quantitative description of membrane current and its application to conduction and excitation in nerve. *J. Physiol.* **117**, 500 (1952)
16. J.F. Otto, Y. Yang, W.N. Frankel, H.S. White, K.S. Wilcox, A spontaneous mutation involving Kcnq2 (Kv7.2) reduces M-current density and spike frequency adaptation in mouse CA1 neurons. *J. Neurosci.* **26**, 2053 (2006)
17. A.E. Pereda, Electrical synapses and their functional interactions with chemical synapses. *Nat. Rev. Neurosci.* **15**, 250 (2014)
18. M. Tsodyks, K. Pawelzik, H. Markram, Neural networks with dynamic synapses. *Neural Comput.* **10**, 821 (1998)
19. M. Inagawa, H. Yoshikawa, T. Yokoyama, K. Awaga, Electrochemical structural transformation and reversible doping/dedoping of lithium phthalocyanine thin films. *Chem. Commun.* **23**, 3389 (2009)
20. D. Ferster, B. Jagadeesh, EPSP-IPSP interactions in cat visual cortex studied with *in vivo* whole-cell patch recording. *J. Neurosci.* **12**, 1262 (1992)
21. L.F. Abbott, W.G. Regehr, Synaptic computation. *Nature* **431**, 796 (2004)
22. H. Markram, J. Lübke, M. Frotscher, B. Sakmann, Regulation of synaptic efficacy by coincidence of postsynaptic APs and EPSPs. *Science* **275**, 213 (1997)
23. G.-T. Go, Y. Lee, D.-G. Seo, M. Pei, W. Lee, H. Yang, T.-W. Lee, Achieving microstructure-controlled synaptic plasticity and long-term retention in ion-gel-gated organic synaptic transistors. *Adv. Intell. Syst.* **2**, 2000012 (2020)
24. D.-G. Seo, Y. Lee, G.-T. Go, M. Pei, S. Jung, Y.H. Jeong, W. Lee, H.-L. Park, S.-W. Kim, H. Yang, C. Yang, T.-W. Lee, Versatile neuromorphic electronics by modulating synaptic decay of single organic synaptic transistor: From artificial neural networks to neuro-prosthetics. *Nano Energy* **65**, 104035 (2019)
25. Y. Sun, C. Song, J. Yin, X. Chen, Q. Wan, F. Zeng, F. Pan, Guiding the growth of a conductive filament by nanoindentation to improve resistive switching. *ACS Appl. Mater. Interfaces* **9**, 34064 (2017)
26. M. Hu, C.E. Graves, C. Li, Y. Li, N. Ge, E. Montgomery, N. Davila, H. Jiang, R.S. Williams, J.J. Yang, Q. Xia, J.P. Strachan, Memristor-based analog computation and neural network classification with a dot product engine. *Adv. Mater.* **30**, 1705914 (2018)
27. P. Yao, H. Wu, B. Gao, J. Tang, Q. Zhang, W. Zhang, Fully hardware-implemented memristor convolutional neural network. *Nature* **577**, 641 (2020)
28. Y. Li, J. Lu, D. Shang, Q. Liu, S. Wu, Z. Wu, X. Zhang, J. Yang, Z. Wang, H. Lv, M. Liu, Oxide-based electrolyte-gated transistors for spatiotemporal information processing. *Adv. Mater.* **32**(47), 2003018 (2020)
29. J. Lee, L.G. Kaake, J.H. Cho, X.-Y. Zhu, T.P. Lodge, C.D. Frisbie, Ion gel-gated polymer thin-film transistors: Operating mechanism and characterization of gate dielectric capacitance, switching speed, and stability. *J. Phys. Chem. C* **113**, 8972 (2009
30. M.J. Panzer, C.D. Frisbie, Exploiting ionic coupling in electronic devices: Electrolyte-Gated organic field-effect transistors. *Adv. Mater.* **20**, 3177 (2008)
31. A. Melianas, T.J. Quill, G. LeCroy, Y. Tuchman, H.V. Loo, S.T. Keene, A. Giovannitti, H.R. Lee, I.P. Maria, I. McCulloch, A. Salleo, Temperature-resilient solid-state organic artificial synapses for neuromorphic computing. *Sci. Adv.* **6,** eabb2958 (2020).
32. Y. Van De Burgt, E. Lubberman, E.J. Fuller, S.T. Keene, G.C. Faria, S. Agarwal, M.J. Marinella, A.A. Talin, A. Salleo, A non-volatile organic electrochemical device as a low-voltage artificial synapse for neuromorphic computing. *Nat. Mater.* **16**, 14 (2017)
33. I. You, M. Kong, U. Jeong, Block copolymer elastomers for stretchable electronics. *ACC Chem. Res.* **52**, 63 (2019)
34. S.-W. Jung, J-.S. Choi, J.B. Koo, C.W. Park, B.S. Na, J.-Y. Oh, S.S. Lee, H.Y. Chu, Stretchable organic thin-film transistors fabricated on elastomer substrates using polyimide stiff-island structures. *ECS Solid State Lett.* **4**(1), 1 (2015)
35. D.-H. Kim, J.-H. Ahn, W.M. Choi, H.-S. Kim, T.-H. Kim, J. Song, Y.Y. Huang, Z. Liu, C. Lu, J.A. Rogers, Stretchable and foldable silicon integrated circuits. *Science* **320**, 507 (2008)
36. Y. Lee, J.Y. Oh, W. Xu, O. Kim, T.R. Kim, J. Kang, Y. Kim, D. Son, J.B.-H. Tok, M.J. Park, Z. Bao, T.-W. Lee, Stretchable organic optoelectronic sensorimotor synapse. *Sci. Adv.* **4**, 7387 (2018)
37. H. Shim, K. Sim, F. Ershad, P. Yang, A. Thukral, Z. Rao, H.-J. Kim, Y. Liu, X. Wang, G. Gu, L. Gao, X. Wang, Y. Chai, C. Yu, Stretchable elastic synaptic transistors for neurologically integrated soft engineering systems. *Sci. Adv.* **5**, 4961 (2019)
38. X. Wang, Y. Yan, E. Li, Y. Liu, D. Lai, Z. Lin, Y. Liu, H. Chen, T. Guo, Stretchable synaptic transistors with tunable synaptic behavior. *Nano Energy* **75**, 104952 (2020)
39. E. Song, B. Kang, H.H. Choi, D.H. Sin, H. Lee, W.H. Lee, K. Cho, Stretchable and transparent organic semiconducting thin film with conjugated polymer nanowires embedded in an elastomeric matrix. *Adv. Electron. Mater.* **2**, 1500250 (2016)
40. D. Choi, H. Kim, N. Persson, P.-H. Chu, M. Chang, J.-H. Kang, S. Graham, E. Reichmanis, Elastomer-polymer semiconductor blends for high-performance stretchable charge transport networks. *Chem. Mater.* **28**, 1196 (2016)
41. J. Xu, S. Wang, G.-J.N. Wang, C. Zhu, S. Luo, L. Jin, X. Gu, S. Chen, V.R. Feig, J.W.F. To, S. Rondeau-Gagné, J. Park, B.C. Schroeder, C. Lu, J.Y. Oh, Y. Wang, Y.-H. Kim H. Yan, R. Sinclair, D. Zhou, G. Xue, B. Murmann, C. Linder, W. Cai, J.B.-H. Tok, J.W. Chung, Z. Bao, Highly stretchable polymer semiconductor films through the nanoconfinement effect. *Science* **355**, 59 (2017)
42. J. Mun, G.-J.N. Wang, J.Y. Oh, T. Katsumata, F.L. Lee, J. Kang, H.-C. Wu, F. Lissel, S. Rondeau-Gagné, J.B.-H. Tok, Z. Bao, Effect of nonconjugated spacers on mechanical properties of semiconducting polymers for stretchable transistors. *Adv. Funct. Mater.* **28**, 1804222 (2018)
43. Y. Takeuchi, M. Yamasaki, Y. Nagumo, K. Imoto, M. Watanabe, M. Miyata, Rewiring of afferent fibers in the somatosensory thalamus of mice caused by peripheral sensory nerve transection. *J. Neurosci.* **32**, 6917 (2012)
44. F. Bengtsson, R. Brasselet, R.S. Johansson, A. Arleo, H. Jörntell, Integration of sensory quanta in cuneate nucleus neurons *in vivo. PLoS ONE* **8**, e56630 (2013)
45. J.A. Pruszynski, R.S. Johansson, Edge-orientation processing in first-order tactile neurons. *Nat. Neurosci.* **17**, 1404 (2014)
46. A. Salleo, Charge transport in polymeric transistors. *Mater. Today* **10**, 38 (2007)
47. H. Sirringhaus, P.J. Brown, R.H. Friend, M.M. Nielsen, K. Bechgaard, B.M.W. Langeveld-Voss, A.J.H. Spiering, R.A.J. Janssen, E.W. Meijer, P. Herwig, D.M. de Leeuw, Two-dimensional charge transport in self-organized, high-mobility conjugated polymers. *Nature* **401**, 685 (1999)
48. H. Han, Z. Xu, K. Guo, Y. Ni, M. Ma, H. Yu, H. Wei, J. Gong, S. Zhang, W. Xu, Tunable synaptic plasticity in crystallized conjugated polymer nanowire artificial synapses. *Adv. Intell. Syst.* **2**, 1900176 (2020)
49. S. Thiemann, S. Sachnov, S. Porscha, P. Wasserscheid, J. Zaumseil, Ionic liquids for electrolyte-gating of ZnO field-effect transistors. *J. Phys. Chem. C* **116**, 13536 (2012)
50. Y. Cao, T.G. Morrissey, E. Acome, S.I. Allec, B.M. Wong, C. Keplinger, C. Wang, A transparent, self-healing, highly stretchable ionic conductor. *Adv. Mater.* **29**, 160599 (2017)
51. L. Shi, T. Zhu, G. Gao, X. Zhang, W. Wei, W. Liu, S. Ding, Highly stretchable and transparent ionic conducting elastomers. *Nat. Commun.* **9**, 2630 (2018)
52. K. Sim, Z. Rao, H.-J. Kim, A. Thukral, H. Shim, C. Yu, Fully rubbery integrated electronics from high effective mobility intrinsically stretchable semiconductors. *Sci. Adv.* **5**, eaav5749 (2019)
53. S. Wang, J. Xu, W. Wang, G.-J.N. Wang, R. Rastak, F. Molina-Lopez, J.W. Chung, S. Niu, V.R. Feig, J. Lopez, T. Lei, S.-K. Kwon, Y. Kim, A.M. Foudeh, A. Ehrlich, A. Gasperini, Y. Yun, B. Murmann, J.B.-H. Tok, Z. Bao, Skin electronics from scalable fabrication of an intrinsically stretchable transistor array. *Nature* **555**, 83 (2018)

54. F. Molina-Lopez, T.Z. Gao, U. Kraft, C. Zhu, T. Öhlund, R. Pfattner, V.R. Feig, Y. Kim, S. Wang, Y. Yun, Z. Bao, Inkjet-printed stretchable and low voltage synaptic transistor array. *Nat. Commun.* **10**, 2676 (2019)
55. S.-Y. Min, T.S. Kim, B.J. Kim, H. Cho, Y.Y. Noh, H. Yang, J.H. Cho, T.-W. Lee, Large-scale organic nanowire lithography and electronics. *Nat. Commun.* **4**, 1773 (2013)
56. F. Zare Bidoky, B. Tang, R. Ma, K.S. Jochem, W.J. Hyun, D. Song, S.J. Koester, T.P. Lodge, C.D. Frisbie, Sub-3 V ZnO electrolyte-gated transistors and circuits with screen-printed and photo-crosslinked ion gel gate dielectrics: New routes to improved performance. *Adv. Funct. Mater.* **30**, 1902028 (2020)
57. S.H. Kim, K. Hong, K.H. Lee, C.D. Frisbie, Performance and stability of aerosol-jet-printed electrolyte-gated transistors based on poly(3-hexylthiophene). *ACS Appl. Mater. Interfaces* **5**, 6580 (2013)
58. S. Niu, N. Matsuhisa, L. Beker, J. Li, S. Wang, J. Wang, Y. Jiang, X. Yan, Y. Yun, W. Burnett, A.S.Y. Poon, J.B.-H. Tok, X. Chen, Z. Bao, A wireless body area sensor network based on stretchable passive tags. *Nat. Electron.* **2**, 361 (2019)
59. S. Han, J. Kim, S.M. Won, Y. Ma, D. Kang, Z. Xie, K.-T. Lee, H.U. Chung, A. Banks, S. Min, S.Y. Heo, C.R. Davies, J.W. Lee, C.-H. Lee, B.H. Kim, K. Li, Y. Zhou, C. Wei, X. Feng, Y. Huang, J.A. Rogers, Battery-free, wireless sensors for full-body pressure and temperature mapping. *Sci. Transl. Med.* **10**, eaan4950 (2018)
60. W.-J. Song, S. Yoo, G. Song, S. Lee, M. Kong, J. Rim, U. Jeong, S. Park, Recent progress in stretchable batteries for wearable electronics. *Batter. Supercaps* **2**, 181 (2019) □

Dae-Gyo Seo is a doctoral candidate in the Department of Materials Science and Engineering at Seoul National University, Republic of Korea. He received his BS degree in 2018 from the Department of Materials Science and Engineering from Korea University, Republic of Korea. His research interests include organic transistors, neuromorphic electronics, artificial nerve systems, and biointegration systems. Seo can be reached by email at tjeory95@snu.ac.kr.

Gyeong-Tak Go is a doctoral candidate in the Department of Materials Science and Engineering at Seoul National University, Republic of Korea. He received his BS degree in 2018 from the Department of Materials Science and Engineering at Seoul National University. His research interests include organic neuromorphic electronics based on artificial synapse devices, and stretchable electronics. Go can be reached by email at kkt9612@snu.ac.kr.

Hea-Lim Park has been a postdoctoral researcher at Seoul National University, Republic of Korea, since 2018. She received her PhD degree from the School of Electrical Engineering at Seoul National University in 2018. She received her BS degree in electrical and electronic engineering from Yonsei University, Republic of Korea, in 2012. Her current research interests include organic transistors, sensors, and bioinspired neuromorphic devices. Park can be reached by email at haelim1017@snu.ac.kr.

Tae-Woo Lee is a professor in materials science and engineering at Seoul National University, Republic of Korea. He received his PhD degree in chemical engineering from the Korea Advanced Institute of Science and Technology, Republic of Korea, in 2002. He joined Bell Laboratories as a postdoctoral researcher and worked at the Samsung Advanced Institute of Technology as a member of the research staff (2003–2008). He is a Fellow of the Materials Research Society. His research focuses on printed flexible electronics based on organic and organic–inorganic hybrid materials for flexible displays, nerve-inspired artificial electronic devices, solid-state lightings, and solar-energy-conversion devices. Lee can be reached by email at twlees@snu.ac.kr.