Organic Artificial Synapse for Human-friendly Wearable Neuromorphic Electronics

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ABSTRACT

Inspired by the biological neural network and cognitive functions, neuromorphic computing architecture has been envisioned as an alternative computing system. Especially, this brain-inspired computing architecture might be suitable for an e-textile/wearable computing platform because of the potential to efficiently process the large amount of unstructured sensing data, including diverse and complex signals from the human body or the surrounding environment. This study presents organic artificial multi-synapses for wearable neuromorphic electronic applications. In particular, various synaptic functions and mechanical characteristics of the organic ferroelectric-based artificial synapse are introduced. In addition to the fundamental characteristics of the artificial synapse, several demonstrations are discussed for moving forward to building an e-textile neuromorphic platform. In this conference, I am going to present overall works on the ferroelectric organic artificial synapses for wearable neuromorphic applications mainly including following results.

1 Introduction

As a unit for the wearable device, one-dimensional (1D) fiber-shaped device form based on organic materials, is becoming as a promising strategy for smart electronic-textiles or e-textiles owing to their unique characteristics such as soft, light, flexible, and simple fabrication.[1]
However, the conventional computing platform consisting of these 1D fiber-based device constituents (e.x, transistor-based logic circuits) may not suitable to immediately process and classify the numerous unstructured sensing data continuously received from the human body or surroundings.
In this study, we report the 1D organic artificial multi-synapses whose has the potential to efficiently process the unstructured large number of sensing data including diverse and complex signals from the human or the surrounding environment [2].
Our device was fabricated multiple ferroelectric organic transistors on a 1D Ag wire using poly(vinylidene fluoride-trifluoroethylene) (P(VDF-TrFE)) and utilized them as a 1D fiber-shaped multi-synaptic device platform for the e-textile neural network. The 1D fiber-shaped device form can be easily coiled or bended on various forms of tubes and operated well under the bending conditions without severe switching degradation. They can exhibit the well-defined essential synaptic functions by meticulously modulating in the degree of polarization of its ferroelectric domain according to the electrical stimulus. In addition, their synaptic characteristics can have excellent reliability under repeated pulse cycles and mechanical bending stress. Notably, a NOR-type synaptic array is simply fabricated based on the weaving of 1D multi-synapses and Ag wires, where the postsynaptic responses received by individually addressing the synaptic cells can be integrated. From the conventional back-propagation learning algorithm in the single-layer neural network, ~90 and ~70 % recognition accuracy for each MINST and ECG patterns are achieved regardless of the mechanical bending stress.

2 Results and Discussion

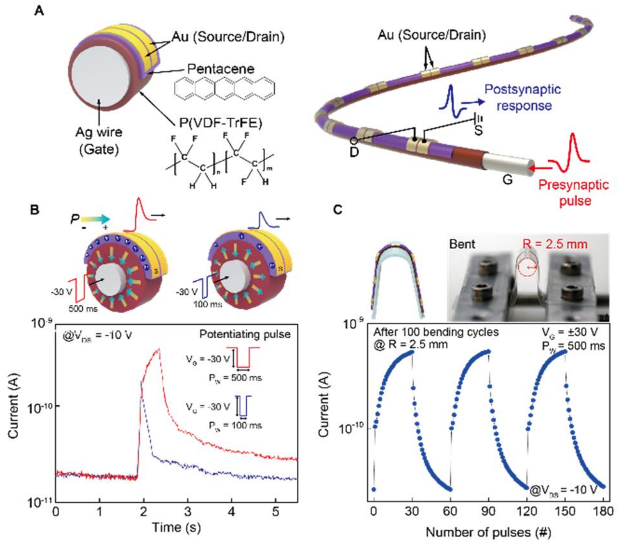

Fig.1. (A) Fabrication process and schematics of the 1D artificial multi-synapses. (B) The current responses triggered by different potentiating pulses. The top schematic represents the postsynaptic

responses generated by different degrees of downward P in the P(VDF-TrFE) layer according to the different widths of V_G. (C) Repetitive transitions of LTP/LTD of current at fixed bending radiuses (*R* = 2.5 mm) after 100 bending cycles. Reproduced with permission.[2] Copyright 2020 AAAS

Figure 1A shows the fabrication process for 1D artificial multi-synapses implemented by substrate-free ferroelectric organic transistors on a thin Ag wire (100 µm diameter). Organic ferroelectric P(VDF-TrFE) film, which functions as a common gating dielectric layer, was uniformly and directly coated onto the whole surface of Ag wire through the dip-coating method using a capillary tube. Then, Au metals were patterned on the top of pentacene channel through a shadow mask with the interval of 15 µm, which are utilized as source and drain electrodes. When the relative shorter P_W (V_G = –30 V for 100 ms) was applied to the pre-neuron, the I_{PSC} (postsynaptic current) was temporally changed, namely, its value returns to the original one. This I_{PSC} behavior analogs to STP of biological synapse is excited for only a short period of time. In contrast, when the longer pulse P_W (V_G = –30 V for 500 ms) was applied to the pre-neuron, the I_{PSC} slightly increased, then retained its changed value for longer period of time. This I_{PSC} behavior analogs to the one aspect of long-term potentiation (LTP) that represents the memory consolidation in the brain. (Fig. 1B)

As the switching principle, these synaptic characteristics are originated from the change of the polarization (P) of the ferroelectric domains in the P(VDF-TrFE) layer according to the magnitude of applied V_G (top inset in Fig. 1B)

We also performed the mechanical stability test for the LTP and LTD functions, as shown in Fig. 1C. We confirmed that the 1D device form can exhibit mechanical stable synaptic functions.

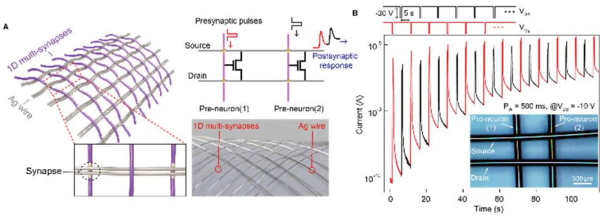

Fig.2. (A) Schematic (left) and photograph image (right below) of the NOR-type textile 10 × 12 array structure consisting of 10 1D multi-synapses and 12 Ag wire. Schematic of the circuit diagram of inner 2 × 2 array, representing the integrated postsynaptic response generated by two presynaptic pulses with different timing (right top). Plot of the integrated current in the inner 2 × 2 array when alternately applying potentiating V_{G1} and V_{G2} pulses (–30 V for 500 ms) with Δt = 5 s at each pre-neuron. Reproduced with permission.[2] Copyright 2020 AAAS

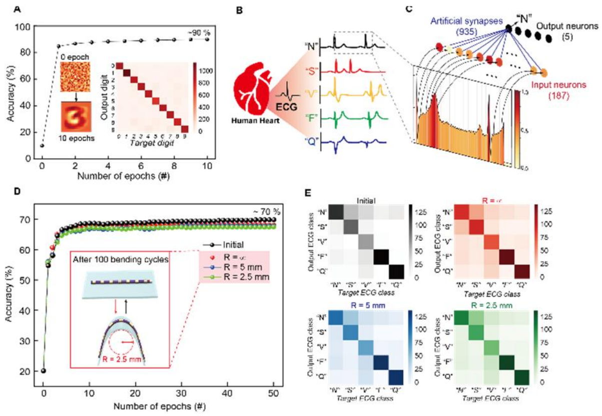

Fig.3. (A) Recognition accuracy for MNIST pattern as a function of number of learning epochs. (B) Schematics of 5 ECG classes of the human heart representing "N", "S", "V", "F", and "Q" class (C) Constituents of a single-layer neural network for "N" ECG pattern recognition process. Reproduced with permission.[2] Copyright 2020 AAAS

original one. This I_{PSC} behavior analogs to STP of
Owing to the excellent flexibility and the multi-synaptic channels, our 1D device could be easily weaved in the form of the wearable textile array structure, like NOR-type synaptic array as the ANNs (Fig. 3G). This textile array resembles a biological neural network because the I_{PSC} determined by the *w* (synaptic weight) on each channel can be transmitted and integrated. As shown in Fig. 2A, we extended and reconstituted our device as a wearable textile 10 × 12 array structure containing 30 synapses using 10 1D devices and 12 Ag wires. Ag metal wires are utilized as source/drain lines and then connected to the 1D multi-synaptic devices in parallel. Figure 3H shows the change of the I_{PSC} integrated from the inner 2 × 2 array when alternately applying potentiating V_{G1} and V_{G2} pulses (–30 V for 500 ms) with Δt = 5 s at each pre-neuron. This demonstrates that our 1D multi-synapses can extend to the array architecture enabling the integration of multiple postsynaptic responses.
To evaluate the learning capability of the textile array comprising of 1D multi-synapses, we simulated the MNIST pattern recognition based on the fitting results of our device switching characteristic. After only 10 learning epochs, ~90 % recognition accuracy is achieved, which is a bit higher than other synaptic device platforms when considering a single-layer neural network (Fig. 3A). However, beyond above simple digit recognition, in order to apply the wearable and healthcare intelligent device on the human body, diverse biometric sensing information should be able to be immediately and successfully classified even under the bending condition. As proof of concept, we selected the heartbeat dataset comprising of five different arrhythmias electrocardiograms (ECG) categorized by different waveforms and morphologies. As a result of the ECG pattern recognition, we were able to achieve a recognition rate of approximately 70% (Fig.3, B-E).

3 Conclusion

In summary, we reported flexible 1D artificial multi-synapses based on organic ferroelectric materials. Using the ferroelectric switching characteristic, the 1D organic artificial synapses exhibited excellent and reliable synaptic functionalities including reproducible LTP and LTD even under repeated pulse cycles and bending. Owing to the electrical and mechanical durability, our 1D device could weave to form the wearable textile array structure, like NOR-type synaptic array as artificial neural network (ANN). Also, we demonstrated from the back-propagation learning algorithm that the 1D artificial multi synapses can have ~90 and ~70 % recognition accuracy for each MINST digit and ECG patterns, respectively, in the pattern recognition simulation. We believe our proposed 1D artificial multi-synaptic device will provide the potential of an e-textile neuromorphic device for wearable and flexible electronics.

References

[1] Y. Park, M.-J Park, J.-S. Lee, "Reduced Graphene Oxide-Based Artificial Synapse Yarns for Wearable Textile Device Applications" *Adv. Funct. Mater.* vol. 28, pp. 1804123, 2018.

[2] S. Ham, M. Kang, S. Jang, J. Jang, S. Choi, T.-W. Kim, G. Wang, *Sci. Adv.* vol. 6, pp. eaba1178, 2020.