A-3-02
Extended Abstracts of the 2019 International Conference on Solid State Devices and Materials, Nagoya, 2019, pp31-32

Organic Material-based Artificial Synaptic Device for Neuromorphic Applications

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Abstract

Organic-based artificial synaptic devices that can learn and store massive non-structured information with extremely low-power on purpose have attracted as a practical candidate for the intelligent electronic device due to its inherent mechanical flexibility, relatively inexpensive and functional diversity. Here, we review the development of two organic neuromorphic devices. First, inspired by light-assisted dopamine-facilitated, which achieves rapid learning and adaptation by lowering the threshold of the synaptic plasticity, we fabricate a organolead halide perovskite (OHP)-based photonic synapse in which the synaptic plasticity is modified by both electrical pulses and light illumination. Owing to the accelerated migration of the iodine vacancy inherently existing in the OHP film under light illumination, It is showed that the threshold of the long-term potentiation decreases and synaptic weight further modulates when light illuminates the device. Second, we fabricated a fiber-shaped artificial synapse based on a ferroelectric organic transistor that could capable of the integrated flexible NOR-type array. The fiber-shaped artificial synapse can exhibit excellent and reliable synaptic functionalities.

1. Introduction

Neuro-inspired computing architectures have been attracting considerable attention because of the potential to solve unstructured problems, such as recognition and learning tasks, at extremely low powers compared with typical digital computers.[1] In this view, designing and fabricating an artificial synapse that replicates the plasticity fundamentals of its biological counterpart are essential prerequisites for implementing a neuro-inspired computing system. Organic-based artificial synaptic devices that can learn and store massive non-structured information with extremely low-power on purpose have attracted as a practical candidate for the intelligent electronic device due to its inherent mechanical flexibility, relatively inexpensive and functional diversity.

Here, we review the development of two organic neuromorphic devices. First, inspired by light-assisted dopamine-facilitated, which achieves rapid learning and adaptation by lowering the threshold of the synaptic plasticity, we fabricate a organolead halide perovskite (OHP)-based photonic synapse in which the synaptic plasticity is modified by both electrical pulses and light illumination. Owing to the accelerated migration of the iodine vacancy inherently existing in the OHP film under light illumination, this phenomenon showed that the threshold of the long-term potentiation decreases and synaptic weight further modulates when light illuminates the device. Second, we fabricated a fiber-shaped artificial synapse based on a ferroelectric organic transistor that could capable of the integrated flexible NOR-type array. The fiber-shaped artificial synapse can exhibit excellent and reliable synaptic functionalities such as short-term plasticity (STP) and long-term plasticity (LTP).

2. Experiment and results

2.1 OHP-based synaptic device

2.1.1 Fabrication and resistive switching characteristics

To obtain the crystallized $CH_3NH_3PbI_3$ film, we prepared the OHP precursor solution by adding a 1:1:1 molar ratio for PbI_2, CH_3NH_3I, and DMSO, respectively. After that, a diethly ether (DME) was dropped for the rapid crystallization of the film during the spin-coating process of the precursor solution on the ITO bottom electrode. Then, the patterned Ag top electrode was deposited on OHP/ITO layer to complete the two-terminal OHP junction (Fig 1(a)). The fabricated Ag/OHP/ITO synaptic device shows a representative current–voltage (I-V) characteristic, exhibiting a bipolar switching feature with an ~10^4 ON-OFF ratio at V_r = 0.05 V driven by sweeping with different voltage polarities (Fig 1(c)). The observed bipolar switching behavior originated from the formation/annihilation of electric-field-driven $V_I^{\cdot}$ (iodine vacancy) through the GBs or several defect migration pathways in the OHP film.

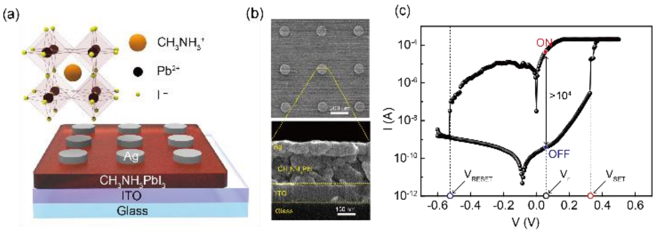

Fig. 1 (a) Schematics of the Ag/CH3NH3PbI3(OHP)/ITO synaptic device and OHP structure. (b) The top and cross-sectional views of the SEM images of the completed OHP synaptic device The representative I-V characteristic of the OHP synaptic device.

2.1.2 Synaptic function and pattern simulation

To investigate the voltage-driven synaptic plasticity, the change in the PSC was monitored when the diverse input electrical pulses were applied to the pre-neuron. According to condition of input stimuli, our device mimic a short-term plasticity, long-term potentiation (LTP) in synaptic plasticity. Under light exposure, our OHP synaptic device can similarly mimic dopamine-facilitated synaptic functions. Owing to the accelerated migration of the iodine vacancy inherently existing in the OHP film under light illumination, the OHP synaptic device exhibits light-tunable synaptic functionalities with very low programming inputs (~0.1 V). It is also demonstrated that the threshold of the long-term potentiation decreases and synaptic weight further modulates when light illuminates the device. Consequently, owing to the effect of light illumination on the $V_I^{\cdot}$ migration in the OHP synaptic device, it is possible to minutely modulate the synaptic plasticity even when insufficient electrical input pulses are applied, thus supplying the needed neural amplification with a low power. Notably, under light exposure, the OHP synaptic device achieves rapid pattern recognition with ~82.7% accuracy with a low power consumption (4.82 nW/the initial update for potentiation), which is ~2.6 $\times 10^3$ times lower than when the synaptic weights are updated by only high electrical pulses (Fig. 2)

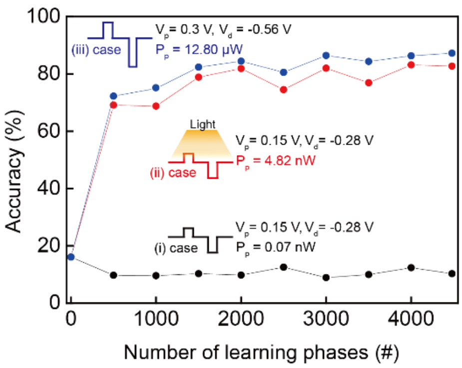

Fig. 2 Recognition accuracy for the MNIST patterns and energy consumption

2.2 Fiber-shaped organic artificial synapse

Organic-based artificial synaptic devices that can learn and store massive non-structured information with extremely low-power on purpose have attracted as a practical candidate for the wearable intelligent electronic device due to its inherent mechanical flexibility and functional diversity [2-3].
Here, we fabricated a fiber-shaped artificial synapse based on a ferroelectric organic transistor that could capable of the integrated flexible NOR-type array. Fig. 3 shows the fiber-shaped synaptic devices designed to be TFT-type NOR structure consisting of Ag wire as the common gate, Au source/drain electrode, and pentacene active channel. The organic ferroelectric film (PVDF-TrFE) was deposited on the 100 μm-diameter of metallic Ag wires as the gate dielectric layer by dip-coating methods using a capillary tube and a printing speed controller.

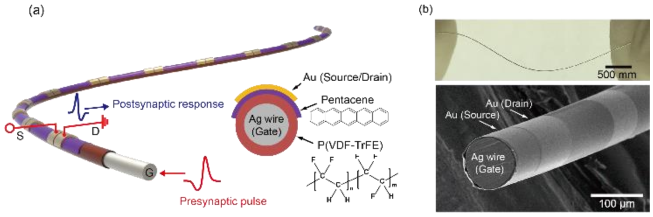

Fig. 3 (a) Schematics of the fiber-shaped synaptic device. (b) photographic image(top) and SEM image(bottom) of the fiber-shaped synaptic device.

To examine the voltage-driven synaptic plasticity of the device, the change in the PSC was observed when the diverse electrical stimuli was applied to pre-neuron (gate electrode). The artificial synapse device exhibits excellent and reliable synaptic functions of biological synapses, including excitatory postsynaptic current (EPSC), spike rate dependent plasticity (SRDP), spike timing dependent plasticity (STDP), and a transition from STP to LTP. This phenomenon can be interpreted in the residual polarization of the PVDF-TrFE layer based on different gate voltage pulses. Furthermore, we demonstrated reliable transition of LTP and LTD operation using 30 potentiation/depression pulses during 100 cycles.

3. Conclusions

In summary, we review the development of two organic neuromorphic devices. First, we have fabricated a two-terminal OHP-based photonic synapse whose the synaptic plasticity could be modulated by both electrical and light stimuli, which can mimic the dopamine-facilitated synaptic activity. Notably, the onset threshold of the LTP was further lowered and the available number of intermediated states was increased when the light illuminated the OHP synaptic device. Second, we fabricated a fiber-shaped artificial synapse based on a ferroelectric organic transistor that could capable of the integrated flexible NOR-type array. The fiber-shaped artificial synapse can exhibit excellent and reliable synaptic functionalities such as short-term plasticity (STP) and long-term plasticity (LTP). We believe our proposed photonic/wearable synaptic device could offer a new route to significantly improve the learning and memory capability in a neuro-inspired computing system.

Acknowledgements

This work was supported by the National Research Foundation of Korea (NRF-2016R1C1B2007330), KU-KIST Research Fund, Samsung Electronics, and a Korea University Future Research Grant.

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