DOI 10.5162/IMCS2018/AP2.2

Artificial Synapse and Neuron Combining the Ion-Sensitive Field-Effect Transistor and Memristor

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Abstract :

Implementations of artificial synapse and neuron are presented by combining the silicon nanowire ion-sensitive field-effect transistor (ISFET) and the indium-gallium-zinc-oxide (IGZO) memristor. Chemical and electrical operations of synapse are emulated by the pH sensor operation of ISFET and by the long-term potentiation of IGZO memristor, respectively. The concentration of hydrogen ions in electrolyte is successfully transformed via the voltage-controlled oscillator (VCO)-based neuron into the modulation of synaptic strength, i.e., the current of memristor. Proposed synapse and neuron show the feasibility of emulating the brain-inspired computing along with taking into accounts both chemical and electrical operation of synapse.

Key words: human-like sensory circuit, Silicon nano wire, pH, memristor,

Introduction

Recently, great efforts have been made to overcome the limit of energy-efficiency of von-Neumann computing system by employing the human brain-inspired neuromorphic computing system. Here, the emulation of biological systems is an indispensable step toward the design and verification of large-scale integrated neuromorphic system and architecture. Noticeably, the chemical as well as the electrical function of synapse needs to be considered for systematic emulation. The latter means not only the long-term potentiation (LTP) and short-term depression (STD) but also the spike timing–dependent plasticity (STDP) in persepctive of spiking neural network [1] and while the former needs to detect the concentration of neurotransmitter agents, i.e., glutamate, γ-Aminobutyric Acid (GABA), and glycine, with the functionalization of their specific-binding receptors [2]. However, both the chemical and electrical synaptic behaviors have been seldom demonstrated in a single platform. In this work, artificial synapse and neuron are demonstrated by combining the silicon nanowire (SiNW) ion-sensitive field-effect transistor (ISFET) and the amorphous indium-gallium-zinc-oxide (IGZO) memristor.

Experiment

The biological system consisting of synapses and neurons is illustrated in Fig. 1(a) and correspondingly, artificial synapse and neuron are implemented in Fig. 1(b). The action potential at the presynaptic neuron is transformed into an ejected neurotransmitter. Then, this neurotransmitter diffuses and binds at the receptor in the postsynaptic neuron and converts to action potentials again. These chemical synapse is emulated by SiNW ISFET. Its fabrication details can be found in [3]. In addition, the electrical synapse is emulated by the two-terminal IGZO memristor. The neuron is implemented with VCO and amplifiers.

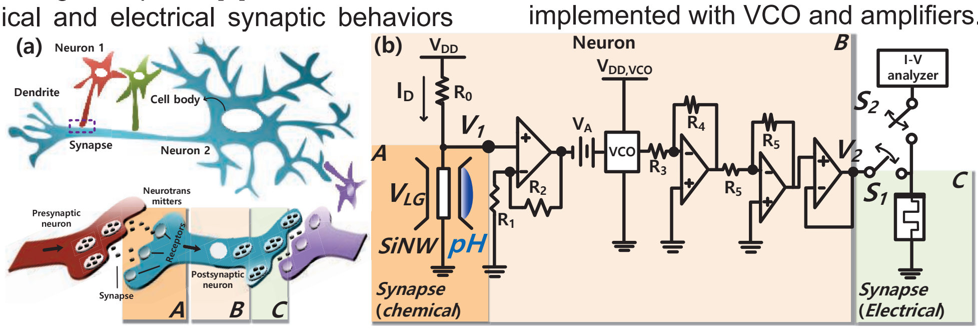

Fig.1. (a) Biological synapse and neuron. (b) Artificial synapse and neuron.

Result and Discussion

The SiNW ISFET, IGZO memristor, and neuron circuit were characterized using an I-V analyzer (Keithley-4200). Used voltages were V_{DD}=2 V, V_{GS}=1.4 V, $V_{DD,VCO}$=12 V, and V_A=10 V. Resistors of R_0, R_1, R_2, R_3, R_4, and R_5 having the values 500 kΩ, 2 kΩ, 5 kΩ, 12 kΩ, 5 kΩ, 12 kΩ were used. The V_1 is determined with varying the pH-dependent ISFET current I_D as:

$$V_1 = V_{DD} - I_D \times R_0 \quad (1)$$

On the other hand, the current of IGZO memristor (I_{mem}) shows the LTP and STD operation depending on the frequency/interval of programming pulse (Fig. 2).

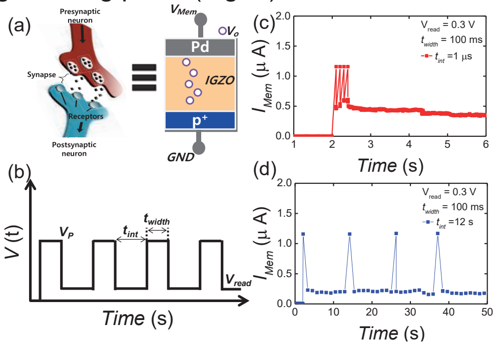

Fig. 2. (a) The electrical synapse based on IGZO memristor. (b) Pulse condition applied to memristor and the measured (c) LTP and (d) STD characteristics.

Measured V_1 is modulated with the variation of pH value (Fig. 3), which mimics the chemical synaptic behavior because this result suggests that the ISFET can transform the concentration of neurotransmitter agents into the input voltage V_1 of neuron circuit with the functionalization of their specific-binding receptors.

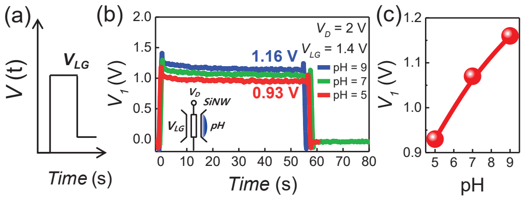

Fig. 3. (a) Time-varying condition of liquid gate voltage V_{LG}. (b) Measured time-varying V_1 (inset: the chemical synapse based on SiNW ISFET) and (c) the pH-dependent V_1.

The output voltage of VCO, i.e. V_2, successfully converts the concentration of hydrogen ions to the consecutive pulse trail with the pH-dependent frequency (Fig. 4), which emulates the trail of output spikes out of post-synaptic neuron, i.e. the group of dendrite-cell body-axon, including the function of integration & fire.

Finally, the post-synapse current (I_{PSC}) is written to the IGZO memristor when the S_1 is closed and the S_2 is open and it is read when the S_2 is closed and the S_1 is open. The level of read I_{PSC} is programmed depending on the pH value (Fig. 5), which duplicates the electrical synaptic operation, i.e. LTP and STD.

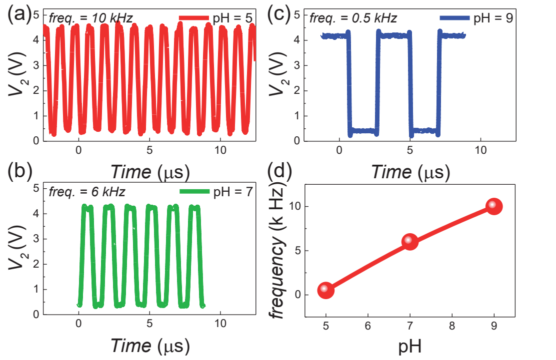

Fig. 4. Measured V_2 when (a) pH = 5, (b) pH =7, and (c) pH = 9. (d) The pH-dependent frequency of V_2.

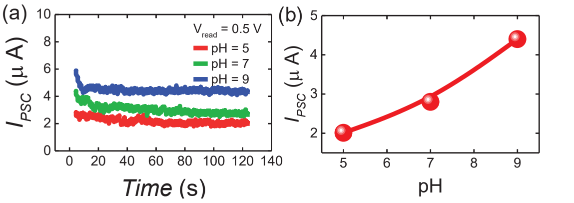

Fig. 5. (a) Measured I_{PSC} when V_{read} = 0.5 V. (b) The pH-dependent I_{PSC}.

Conclusion

Chemical and electrical operations of synapses were implemented by combining the pH sensing of ISFET and the LTP of IGZO memristor, respectively. The concentration of ions was successfully transformed via a simple neuron circuit block, into the modulation of the post-synapse current of memristor. Although they were not integrated, they did not directly detect neurotransmitters, nor did they use sophisticated neuron circuits, but the proposed artificial synapse and neuron can simulate the chemical and electrical behaviors of synapse at the same time. Therefore, our results are potentially useful for emulating the brain-inspired computing along with taking into accounts both chemical and electrical operation of synapse.

Acknowledgment

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (Ministry of Education, Science and Technology, MEST) (Nos. 2016R1A5A1012966, 2016R1A6A3A01006588, and 2016M3A7B4909668).

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