Extended Abstracts of the 2018 International Conference on Solid State Devices and Materials, Tokyo, 2018, pp895-896

Artificial neuron enabled by a three-terminal memristive device

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Abstract

Neuromorphic computing shows great potentials of improving the computational efficiency over conventional von-neumann based computing paradigms in terms of cognitive capability, such as learning and decision making. To construct large scale neural network in hardware, developing efficient artificial synapses and neurons are criticial. Till now, significant progress has been made in mimicking the behaviors of biological synapses by using memristive devices. However, little work on artificial neuron has been reported. Here we report an artificial neuron based on a three-terminal memrisitve device, which can emulate the leaky integration and firing neural functions. More importantly, through the third terminal, this artificial neuron can generate spikes passively and manipulate its refractory time, leading to a bio-plausible behavior with high energy and area efficiency. This demonstration provides a promising approach for constructing large scale neural network.

1. Introduction

Neuromorphic computation - inspired by the working principles of biological brains - has emerged as one of the most promising technologies to continue the advancement of computing systems in the post Moore's Law's era[1]. Recently, a drastic paradigm shift toward memristive device opens a new approach in mimicking neurons and synapses – the basic building block of neural network in human brain - on hardware in a more efficient way. Memristive device possesses unique analogue properties that the resistance state is dependent on the history, which is suitable for emulating neural activities observed in the brain at the device level. Significant progress has been made on the emulation of synapses, which have demonstrated rich synaptic learning functionalities on a single nano-device. In contrast, artificial neurons are less explored despite of its importance. Recently, some attempts have been made to emulate neural behaviors like leaky integration and threshold firing based on Mott memristors and phase change memory[2]–[4]. However, in these works external circuits are required to assist the spike generation, which is not bio-plausible, consumes high power and occupies large area.

In this work, we propose a three-terminal memristive device which exhibits transient switching behaviors. By utilizing the transient switching behavior, we successfully mimic the neural behaviors including the leaky integration and firing neural functions. More importantly, by introducing the third terminal, our artificial neuron can generate spikes passively and manipulate its refractory time. This approach enables the possibility to design artificial neuron with high power/area efficiency for large scale neural network development.

2. Objectives and Methods

This work aims to develop a bio-plausible neuron by a novel three-terminal memristive device and investigate its neural functions.

The memristive devices were constructed on a p-type (100) Silicon wafer with a 1 μm thermal oxide. The device was composed of a sandwich structure with a bottom electrode, a switching layer and a top electrode. The schematic of device structure is shown in Fig. 1. The 70-nm silver (Ag) bottom electrode was sputtered in a vacuum system as the input terminal. A 60-nm thick insulating silicon oxide (SiO_2) was then deposited and patterned with a 2×2 μm^2 window exposing the bottom electrode. Subsequently, an oxide switching layer with ~30 nm thickness was sputtered followed by a layer of 70 nm thick platinum (Pt) top electrode as a ground terminal. Finally, 10 nm SiO_2 and 70 nm titanium tungsten (TiW) were sequentially deposited at the top square area as the output terminal. All the films were formed by using AJA sputtering machine and patterned by lithography and a lift-off process.

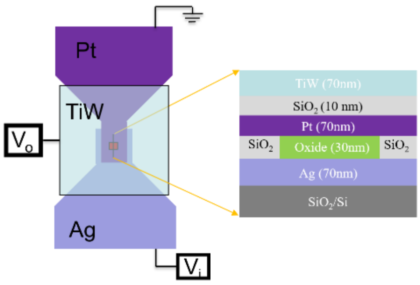

Fig.1 Schematic illustration of three-terminal memristive device.

3. Results

We first investigated the behavior of normal two-terminal memristive device. A typical current-voltage sweeping was applied on the two terminals of Ag/Oxide/Pt memristive device with Pt grounded and Ag as the input electrode, as exhibited in Fig. 2a. A compliance current of 1 μA was set to aviod damaging the device. Under postive sweeping, the current initially kept flat, revealing that the current was below the detection limit of measurement machine (<10 pA). When the DC voltage went beyond a threshold voltage, an obvious current jump from low conductance state to high conductance state was observed. But once the sweeping voltage was below 0.1 V, a sharp decrease in current could be observed and device was recovered to low conductance state (10 pS). The recovery speed of memrisitive was found to be dependent on the compliance current (CC) as shown in Fig. 2b. With increasing CC, the two-terminal device took longer time to recover from high conductance state to low conductance state.

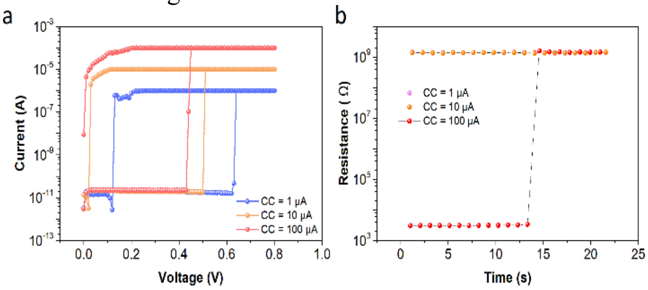

Fig. 2 (a) DC voltage sweeping on two terminal Ag/Oxide/Pt memristive device under different compliance current (CC). (b) CC dependent recovery time from high conductance state to low conductance.

To emulate the spikes input to biological neuron, voltage pulse train was used to test the two-terminal device. The current response with continous voltage pulse train was plotted in Fig. 3a. The current initially remained almost zero before an obvious current surged at the 16^{th} pulse. The process before resistance switching can be regarded as integration of spikes. Similar to biological neuron, once the integrated spikes reach a threshold, the two-terminal memristive device can switch to a high conductance state. Depending on the stimulation strength, the recovery time was varied.

As two-terminal memristive device can only integrate spikes but cannot generate spikes, three terminal memristive device was introduced in this work. By stacking a layer of SiO_2 with appropriate thickness on top of the two terminal memristive device, action potential can be generated when two terminal memristive device was switching to high conductance state. Moreover, the Pt/SiO_2/TiW can serve as a resistor which can clamp the current, which reduces the power consumption significantly during firing. A schematic comparison between memristive neuron and biological neuron is shown in Fig. 3b. Similar to the biological neuron's behavior, the three terminal memristive device integrates incoming pulses and generates an action potential as a result. Aftermath, as clamped by the Pt/SiO_2/TiW resistor, the memristive device quickly returns back to its resting state, namely low conductance state.

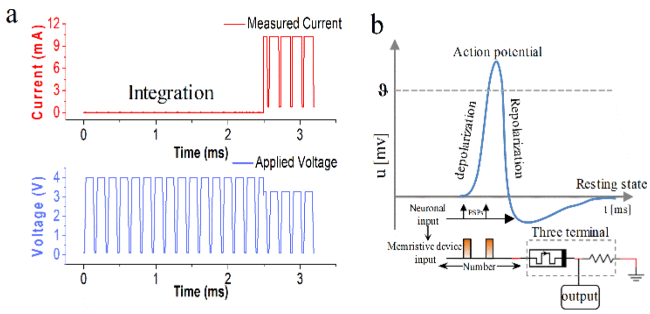

Fig. 3 (a) current response with continuous pulses stimulation on two-terminal device (b) Comparison between three terminal memristive neuron and biological neuron.

To demonstrate this idea, our three terminal memristive device was tested under the FPGA board with continuous pulse stimulation. The input and output data were recorded through a high-speed oscilloscope (see Fig. 4). The input pulse amplitude, width and interval was 3.3 V, 0.2 ms and 1 ms, respectively. With continuous input pulse trains, the output terminal initially kept zero voltage. Once a threshold was met, an action potential was generated and the device quickly returned to its initial low conductance state and restarted to integrate the next wave of input spikes.

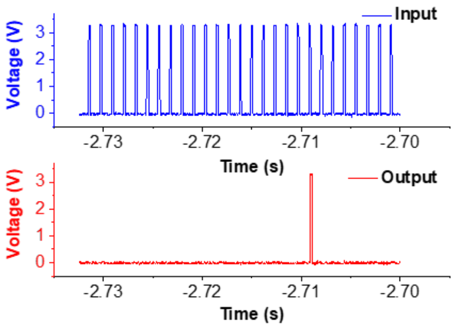

Fig. 4 Demonstration of integrate-and-fire behavior under continuous voltage pulse train on three terminal memristive device.

4. Conclusions

In summary, with utilization of transient switching dynamics, we demonstrated a bio-plausible artificial neuron based on a novel three-terminal memristive device. The three-terminal memristive artificial neuron exhibits neural functions on a single nano-device, including leaky integration and firing. With the introduction of third terminal, this artificial neuron can generate spikes passively, leading to a bio-plausible behavior in a highly power and energy efficiency manner. This work provides a promising technique to construct large scale artificial neural network in hardware.

The details of this work will be presented in the conference.

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