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Spike Pattern Dependent Characteristics of Artificial Neuron using Proton Conductive SiO_2 Electrolyte and InZnO System

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Abstract

An artificial neuron constructed with proton conductive SiO_2 electrolyte and InZnO was proposed. Spike signal, formed by a waveform generator, were introduced into the neuron. Spike pattern dependent characteristics of the neuron were studied, from the aspects of time, rate and shape. A schematic model was established by considering the field driven ion migration, polarization and thermal recovery.

1. Introduction

Synapses and neurons dominate the architecture of the brain and are responsible for the massive parallelism, structural plasticity and robustness [1]. To mimic the biologic system, important synaptic learning rules such as spike-timing-dependent plasticity and short term memory to long term memory have been demonstrated [2]. However, for artificial neurons, the spike pattern dependent characteristics of are rarely reported. The change of membrane potential of neuron occurs after the neurons are stimulated, and the change of potential on both sides of the membrane behaves like a capacitor. Therefore, following from our previous study [3], an artificial neuron is proposed based on a capacitor structure with proton conductive SiO_2 electrolyte and InZnO (IZO) system. And the spike pattern dependent characteristics were systematically investigated.

2. Experimental

Artificial synaptic transistor and neuron were prepared by the following process: 800 nm P-doped nanogranular SiO_2 (P-SiO_2) films were deposited on ITO coated glass substrate by PECVD using SiH_4/PH_3 (95%/5%) and O_2 as the reactive gases with RF power of 100W and working pressure of ~30 Pa, followed by sputtering of IZO with a shadow mask [3]. Agilent 33250A wave form generator was used for signal generation, and connected to the gate electrode. Keithley 4200SCS with a shared common ground with 33250A was used for dc measurement. Due to the limitation sampling frequency and integration time, the upper frequency limit is 7 Hz to obtain the neuron response correctly. The schematic of the test configuration is shown in Fig. 1.

3. Discussion

Fig.2 shows the frequency-dependent capacitance of the IZO/P-SiO_2/ITO structure. A capacitance of ~5.2 $\mu F/cm^2$ can be obtained at 1.0 Hz. This large value is due to the electrical double layer formation at the P-SiO_2/IZO electrode interface. Proton conductivity of the P-SiO_2 was estimated to be 10^{-3}-10^{-4} S/cm at room temperature due to the sequence of proton hopping between hydroxyl groups and water molecules under applied electrical field [4]. Transfer characteristics of the synaptic transistor are shown in Fig. 3, an on/off ratio of over 10^5 is obtained, indicating the powerful modulation of the proton conductive SiO_2 electrolyte. Figs. 4(a)-(d) show the spike pattern dependent characteristics with square waveform. In Fig. 4(a), by applying 0.1 Hz /1.5 V square wave to the gate, the response shows an upward spike and a downward one alternatively. We attribute this process to the hyperpolarization and depolarization of the electrolyte due to proton migration. In Fig. 4(b), by elevating the frequency, the current through the neuron membrane becomes lower, indicating that the ion migration cannot catch up with the external stimuli. As shown in Fig. 4(c), by fixing the hold time and varying the 0 V interval, the response current shifts upward gradually, suggesting that the intensity of the stimulus becomes more difficult for neurons to excite. While for the case with fixed interval and varied hold time, as depicted in Fig. 4(d), the response current shifts downward gradually, suggesting that high frequency stimulation makes nerves difficult to respond to. Fig. 5 shows the spike rate dependent behavior with triangle waveform. The current is found to increase with the increase in the rate of voltage sweep. The working mechanism of the artificial neuron is schematically shown in Fig. 6 by considering the field driven ion motion (hyperpolarization) and thermal recovery (depolarization). By varying spike shape, rate, and time, since ion migration cannot respond to the external field immediately, and the competition between field driven ion migration and thermal recovery results in various abovementioned response.

4. Conclusions

An artificial neuron constructed with P-SiO_2 and InZnO system was successfully mimicked. Spike pattern dependent behavior of the neuron were studied through two terminal tests. A model by considering the competition between field driven ion migration and thermal recovery was proposed, which could well explain the working mechanism of the neuron, strengthening the fundamental of neural network learning for future bionic applications.

References

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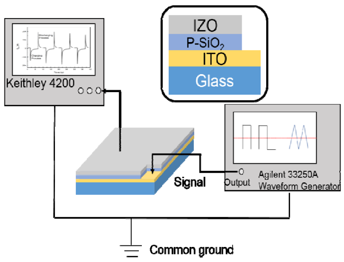

Fig. 1 Schematic of device structure and equipment connection. 800 nm P-doped nanogranular SiO_2 films were deposited on ITO coated glass substrate.

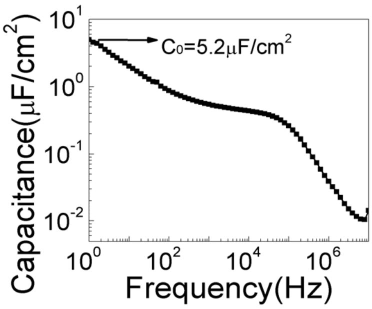

Fig. 2 Frequency-dependent capacitance of the P-doped SiO_2 electrolyte films using IZO/SiO_2/ITO structure.

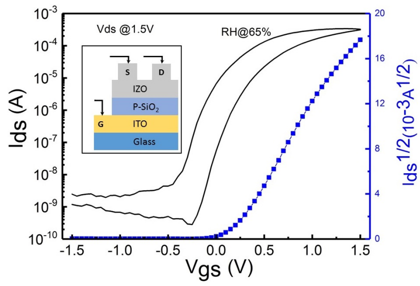

Fig. 3 Transfer characteristics of the synaptic transistor, an on/off ratio of over 10^5 is obtained, indicating the powerful modulation of the proton conductive SiO_2 electrolyte.

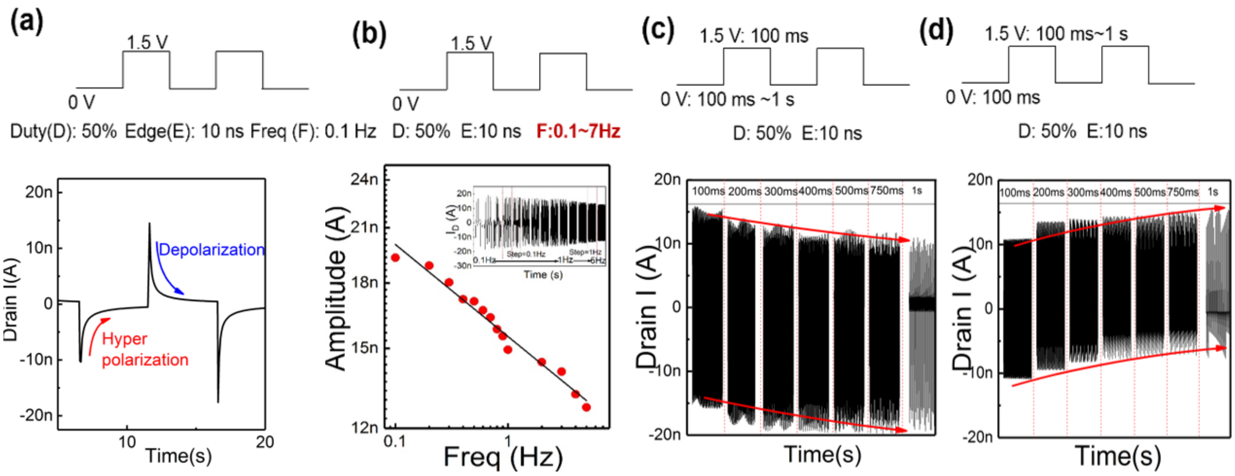

Fig. 4 Spike pattern dependent characteristics of the artificial neuron with square waveform. (a) Hyperpolarization and depolarization behavior with 0.1 Hz /1.5 V square waveform. (b) By varying frequency from 0.1 Hz to 7 Hz. (c) By varying 0 V interval from 100ms to 1 s while fixing 1.5 V hold time as 100 ms. (d) By varying 1.5 V hold time from 100ms to 1s while fixing 0V interval as 100 ms.

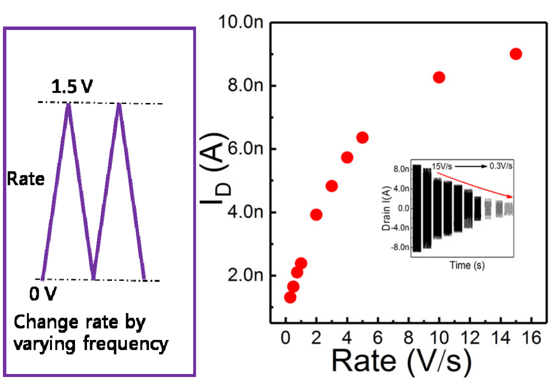

Fig. 5 spike rate dependent behavior with triangle waveform. The current is found to increase with the increase in the slope of voltage sweep.

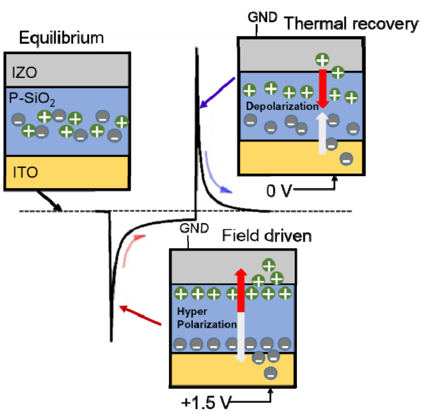

Fig. 6 Schematic model of hyperpolarization and depolarization of IZO/P-SiO_2/ITO artificial neuron by considering proton migration, polarization and thermal recovery.