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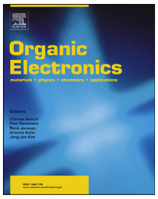

Spatially-correlated neuron transistors with ion-gel gating for brain-inspired applications

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ABSTRACT

In this paper, ion-gel gated transistors based on solution-processed indium-gallium-zinc-oxide (In-Ga-Zn-O) semiconductors were fabricated. These transistors consisted of a spatial distribution configuration of multi-in-plane gates. Spike pluses applied on multi-in-plane gates are analogy to massive synaptic inputs from various dendritic positions. The basic neuromorphic functions, such as potentiation or depression behaviors, synaptic plasticity and frequency-dependent filtering, were demonstrated in these devices by applied a spiking on an in-plane gate. The output signal of neuromorphic devices is greatly relevant to the gate position-correlated input signal and the spatially-correlated information processing could advance the capacity of neuromorphic performance. Orientation selectivity was a broadly investigated phenomenon. More importantly, by using the spatial summation functions of dendritic integration, the orientation identification was successfully realized in our transistor with multi-in-plane gates. The spatially-correlated neuromorphic devices are exceedingly promising for the neural information processing and sensing.

1. Introduction

The ability of human brain to convert input information from multi-path ways into specific output patterns is important for learning, memory, executing event-driven behaviors and enabling parallel computations [1]. Neuron is a basic unit of the brain structures. The most intricate property of a neuron is that a tree distributed dendrites and axonal sprouts used to connect with other neurons [2–4]. Through the specific structure of dendrites, neurons can receive tens of thousands of inputs from other neurons and transmit and process signals to determine outputs via the axons [2–4]. The various characteristics of neuronal morphology and properties all play significant roles in determining the functional capabilities of human brain [5]. Furthermore, synaptic junctions between neurons permit the correlation of a presynaptic neuron connected with other postsynaptic neurons, conveying electrical or chemical signals and influencing the spiking behavior of neighboring neurons, which give rise to a large-scale synchrony [6,7].

Many sciences and technology challenges could benefit from the developing bio-inspired neural systems. Over the past few years, the fabrication of neuromorphic devices has attracted much attention [8–12]. Emulating neuromorphic behaviors is the most important step toward neuromorphic applications. Some groups have made great progress on the research of artificial synapses by using two-terminal memristors and three-terminal transistors [8–10,13–16]. Important temporal dynamic behaviors, including synaptic plasticity and learning rules, were demonstrated in single synaptic device level [12,17–19]. However, neural information processing of the feature-detecting neurons (such as visual functions) is also incredibly important for the human interaction with the real-world environment. In neurobiology, the visual cortex shows a specific response to image edges or orientations [20]. Realization of the orientation-tuning-dependent dynamic respond of the neuromorphic devices is the first step for bio-inspired cognitive systems. Previous studies on this field are relatively scarce. Prof. Wong et al. have applied more than 16000 memristor-based synapses for the fabrication of a neuromorphic visual system with orientation detection functions [21]. Prof. Wan group have fabricated an artificial visual system which consist of a

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photodetector connected to the gate of a vacuum-deposited oxide neuromorphic transistor and orientation tuning was also mimicked based on the paired-pulse facilitation (PPF) rule [22]. Very recently, Prof. Malliaras et al. have demonstrated that an orientation selectivity function was reproduced in liquid electrolyte gated organic electrochemical transistors with multi-gates [23]. However, the liquid electrolyte modulating of these devices may be hard to ingrate into complicated neural circuits.

Potentiation or depression synaptic information input and process from distributed trees are a complex biophysical process and incorporating nonlinear dendritic summation effects [24]. It is reported that the dendritic integration is thought to enrich signal transmit and increases the computational ability of neural systems [25]. Herein, we demonstrate the fabrication of ion-gel electrolyte gated transistors based on solution-processed indium-gallium-zinc-oxide (In-Ga-Zn-O) semiconductors. These transistors consisted of a spatial distribution configuration of multi-in-plane gates, which was a novel approach to realize neuromorphic devices. Spike pluses applied on multi-in-plane gates are analogy to massive synaptic inputs from various dendritic positions. Important neural behaviors and spatially-correlated information processing were demonstrated. Moreover, dendritic integration were used for the emulation of orientation tuning, which may pave the way for neural information processing and sensing and bioinspired cognitive systems.

2. Experimental methods

2.1. *Precursor solution preparation*

The precursor solution of indium-gallium-zinc-oxide (In-Ga-Zn-O) was prepared by dissolving 0.833 M of indium nitrate hydrate ($In(NO_3)_3 \cdot xH_2O$), 0.167 M zinc nitrate hydrate ($Zn(NO_3)_2 \cdot 6H_2O$) and quantitative gallium nitrate hydrate ($Ga(NO_3)_3 \cdot 6H_2O$) into 2-methoxyethanol (2ME) solvent of 1.2 mL in air environment. All nitrates were purchased from Sigma-Aldrich and the purity was 99.999%.The concentration ratio of In/Zn was kept as 1: 0.2, while the concentration of Ga varied according to the following: 0, 0.25, 0.583, and 0.833 M (*i.e.* concentration ratio of Ga/In was 0, 0.3, 0.7, and 1). After the In-Ga-Zn-O solutions were constant stirring for 6 h, they were passed through a 0.22 μm syringe filter to remove precipitated material and form homogeneous as well as transparent solutions. The ion-gel dielectric layer (P(VDF-HPF)+[EMI][TFSA]) was prepared by previous methods [18,26,27]. The details about the preparation of the ion-gels could be found in the supplementary information.

2.2. *Device fabrication and characterization*

For eliminating the organic substances and improving the wettability, the glass substrates were cleaned by successively sonicating for 20 min each in acetone, deionized water, and isopropanol, then dried by N_2 stream and treated by UV-ozone for 20 min. Subsequently, the In-Ga-Zn-O stock solution was spin-coated on a substrate at 600 rpm for 9 s and 3500 rpm for 30 s. After spin-coating, the samples were moved to the preheated hot plate at 100 °C for 10 min in atmospheric environment to remove residual organic solvents. The aforementioned processes were repeated twice by the same method for a final thickness of about 25 nm, and then the samples were passed through rapid annealing at 400 °C in a box furnace for 1 h, the temperature ramping rate was 5 °C/min. For fabricating the transistor with multi-in-plane gates, source/drain (S/D) and gate(G) Al/Au electrodes of with a thickness of 50/30 nm were deposited by thermal evaporation (pressure ~5×10^{-4} Pa) through a shadow mask. The device dimension with a channel width (W)/length (L) ratio of 1600 μm/80 μm was obtained.

The electrical performances and synaptic functions of the neuron transistors were analyzed by a semiconductor parameter analyzer (Keithley 4200-SCS). The surface topography and film thickness were characterized by Atomic Force Microscopy (5500 AFM, Agilent Technologies) at room temperature in a dark shock-proof shielding box. The Hall mobility of the thin-films was measured by using a Hall-effect Measurement System (Ecopia HMS-3000) with a magnetic field of 0.55 T at room temperature. The crystallinity of In-Ga-Zn-O thin-films was investigated by using X-Ray Diffraction (XRD). The chemical components of thin-films were analyzed in an ultrahigh vacuum (UHV) system by X-ray Photoelectron Spectroscopy (XPS) (ESCALAB 250Xi, Thermo Fisher-VG Scientific). The impedance spectroscopy of the ion-gels with frequency ranging from 4.0 Hz to 1.0 MHz was taken across the Au/ion-gel/Au in-plane electrode structure by using impedance analyzer (IM 3536 LCR Mental).

3. Results and discussion

In human nervous systems, neurons can receive massive synaptic inputs reaching from various dendritic positions, and these inputs unify through the neurons and manage local outputs [28,29]. As shown in Fig. 1 (a), the purple dots indicate approximate locations of the stimulation that are used for the distributed input pattern. A large number of synaptic inputs from different dendritic positions are integrated in the neurons and form a specific pattern of postsynaptic output and establish fundamental information

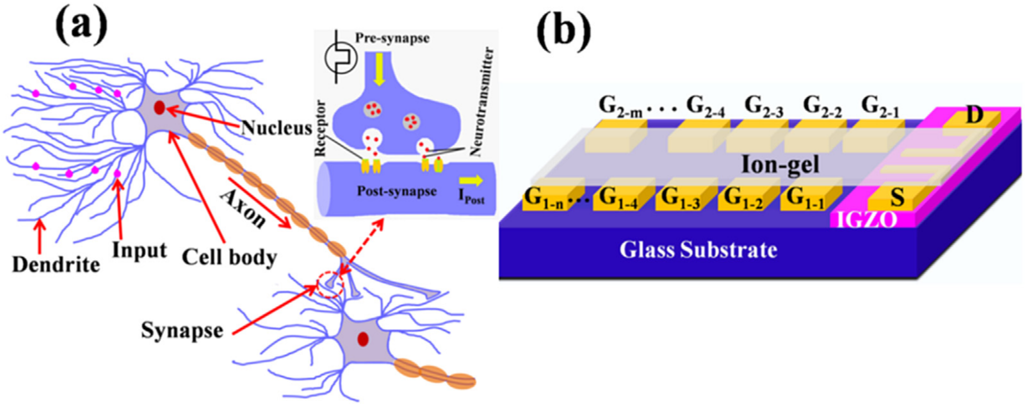

Fig. 1. (a) Schematic illustration shows the synaptic network connected two neurons. A typical biological neuron composes of a nucleus, cell body, axon and massive dendrites. Inset presents the schematic diagram of the biological synapse. (b) The diagrammatic sketch shows an ion-gel gated In-Ga-Zn-O neuron transistor with multi-in-plane gates.