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Electrolyte-gated organic synapse transistor interfaced with neurons

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ABSTRACT

We demonstrate an electrolyte-gated hybrid nanoparticle/organic synapstor (synapse-transistor, termed EGOS) that exhibits short-term plasticity as biological synapses. The response of EGOS makes it suitable to be interfaced with neurons: short-term plasticity is observed at spike voltage as low as 50 mV (in a par with the amplitude of action potential in neurons) and with a typical response time in the range of tens milliseconds. Human neuroblastoma stem cells are adhered and differentiated into neurons on top of EGOS. We observe that the presence of the cells does not alter short-term plasticity of the device.

1. Introduction

There is a growing interest to emerging or alternative logic architectures beyond the Boolean architecture based on silicon CMOS technology (see a review in Ref. [1]). In this context, the organic synapse transistor (termed synapstor) has been initially designed and studied [2,3] as the basic element for neuro-inspired computing architectures (namely artificial neural networks). These devices are based on the trapping/detrapping of charges by an ensemble of gold nanoparticles (NPs) placed at the gate dielectric/organic semiconductor (OSC) interface. The presence of NPs embedded in the OSC at the interface with the gate dielectric confers memory effects in a single transistor. For this reason, this device was also named Nanoparticle Organic Memory Field-Effect Transistor (NOMFET) [2,3]. Organic synapstor mimics the two main synaptic plasticity behaviors of biological spiking synapses [2,3]: STP - Short Term Plasticity - and STDP - Spike Timing Dependent Plasticity. STP is characterized by the fact that the output signal of the synapse decreases with the number of spikes (depressing behavior) for spikes at the highest frequencies of operation, whereas a facilitating behavior (increase of the output signal with the number of pulses) is observed for the lowest operational frequency. The synaptic weight (i.e. the signal transmission efficiency) of the biological synapse is tuned by the density of input spikes (frequency coding of information). Depending on the frequency of a sequence of input spike voltages with respect to the typical charging/discharging dynamics of the NPs in the OSC channel, we demonstrated that the output drain current of the synapstor can be also modulated by the frequency of the input spikes [2,4]. Thus, the transconductance of the organic synapstor mimics the STP behavior of the synapse. Recently, we have reported that organic synapstors can be optimized to work with low voltage spikes (1 V), with a typical response time of about 100 ms and a low energy dissipation of about 2 nJ/spike [5].

In the field of bioelectronics, organic transistors like electrolyte-gated organic field effect transistor (EGOFET) [6–12] and Organic Electro-Chemical Transistor (OECT) [13–16] have been interfaced with neuronal cells for biochemical signal recording and transduction of bio-electrical signals from cells and tissues [17–24]. Synaptic behavior (STP) has also recently been demonstrated for OECTs made with PEDOT:PSS films with a quite different principle since this STP behavior is driven by the dynamics of ions diffusion between the electrolyte and the PEDOT:PSS layer [25,26].

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In this paper, we demonstrate electrolyte-gated organic synapstor (EGOS) with performances suitable to be interfaced to neurons. STP is demonstrated at spike voltage as low as 50 mV (in a par with the amplitude of action potential in neurons) and with a dynamic response down to tens milliseconds. We report the adhesion of Human Neuroblastoma cells (SH-SY5Y) and their differentiation into neurons on top of the EGOS. We demonstrate that EGOS STP is not altered throughout the cell growth and differentiation protocol. Interfacing neural cells to EGOS is attractive for synapse prosthesis application because the device could mediate the signal transmission between adjacent cells that are not connected through synapses. In this sense, the device might replace a chemical synapsis with an electronic synapsis gated by a frequency dependent input supplied by the action potential of the transmitting neuron.

2. Results and discussion

2.1. EGOS without neurons

Fig. 1 shows representative output characteristics I_D-V_D of the devices measured in air (silicon bottom gate, NOMFET configuration) and in saline aqueous solution (Pt wire top gate, EGOS configuration). Devices have a channel length L = 1–50 μm, channel width W = 1000 μm, SiO_2 thickness 200 nm, Au NPs 10 nm in diameter, 40 nm thick pentacene, electrolyte 0.1 M NaCl in deionized water, see details in section "Methods". Noticeably, EGOS displays field-effect below 0.8 V due to the high capacitive coupling between the OSC and the electrolyte, whereas the organic synapstor operating in air requires few tens V. We limited the voltage range below 0.8 V to avoid water electrolysis and faradaic current. These characteristics are similar to the ones already reported for electrolyte gated organic field effect transistor (EGOFET) [10,11,20,27,28], that consists of the same device structure as EGOS without the NPs embedded in the pentacene film. From the transfer I_D-V_G curves in the saturation regime (not shown), we extracted the hole mobility for the EGOS assuming a gate-voltage independent double layer capacitance C_{DL} of 14 μF/cm^2 as measured for pentacene EGOFET with a similar saline aqueous solution [12]. We obtain $\mu_{EGOS} \approx 1–5 \times 10^{-4}$ cm^2/V.s for devices with L between 1 and 50 μm (see Fig. S5 of SI). The hole mobility for the same device operated in air with the bottom silicon gate is 10^{-2}–10^{-1} cm^2/V.s, as already reported for these organic synapstors [5]. This decrease

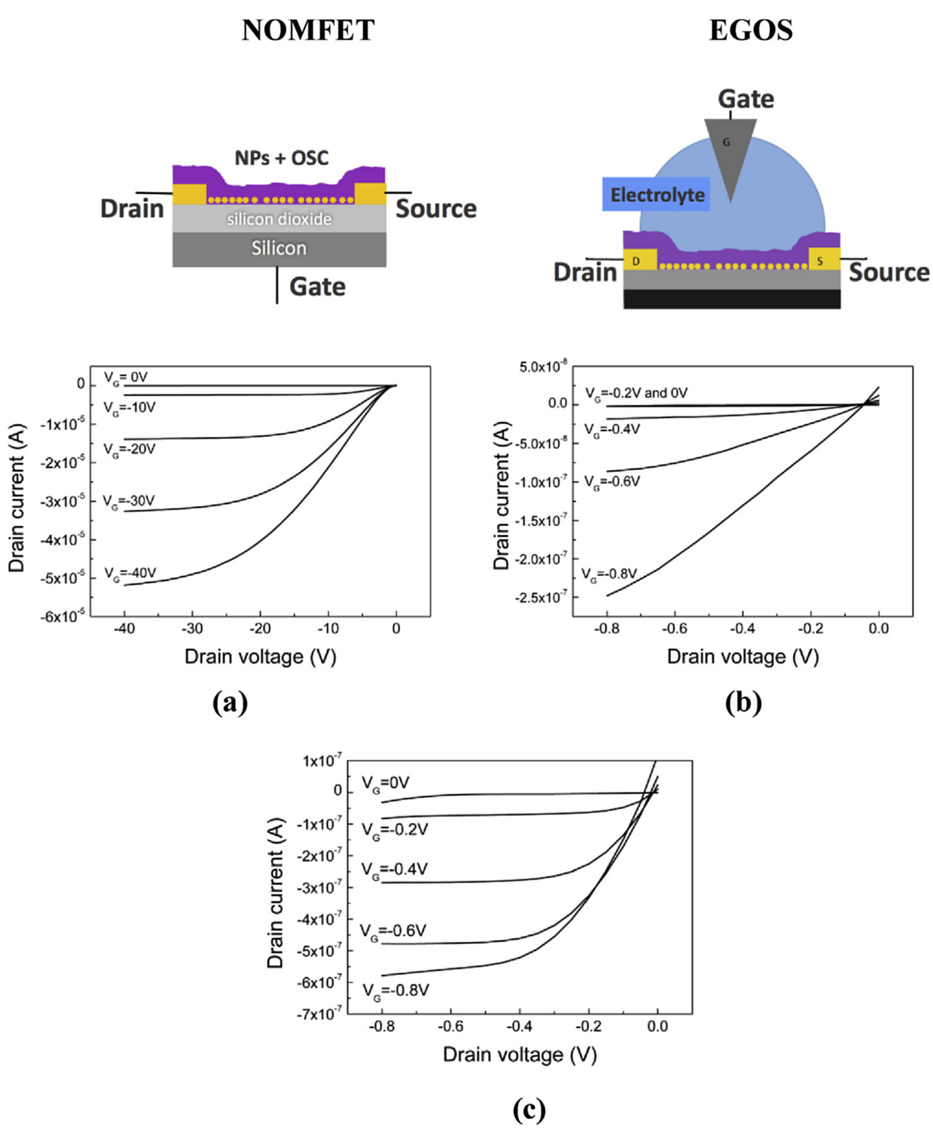

Fig. 1. (Top, left) Schematics of a NOMFET and (top, right) EGOS. Output curves I_D-V_D of (a) NOMFET (L = 5 μm) on Si/SiO_2 substrate in air, (b) EGOS (L = 5 μm) on Si/SiO_2 substrate and (c) EGOS (L = 15 μm) on quartz. Both EGOSs on Si/SiO_2 and quartz substrates are measured in 0.1 M of NaCl in deionized water.