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Electron-transport polymeric gold nanoparticles memory device, artificial synapse for neuromorphic applications

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ABSTRACT

In this paper, we demonstrate the charge storage in nanoparticles “NPs” organic memory field-effect transistor using an electron-transport polymeric semiconductor layer, poly{[N,N0-bis(2-octyldodecyl)-naphthalene-1,4,5,8-is(dicarboximide)-2,6-diyl]- alt - 5,50-(2,20-bithiophene)} [P(NDI2OD-T2)n], known as its commercial name PolyeraTM N2200. The device exhibited good programmable memory characteristics with respect to the program/erase operations, leading to a reversible threshold voltage (Vth) shifts. Results revealed that OFET based NPs exhibited larger hysteresis and showed a facilitating and a depressing drain current mimicking the behavior of biological synapses, the building block responsible of action potentials transmission between neurons.

1. Introduction

Recently, great researches have been devoted to develop high-performance nanoparticles organic memory field effect transistor (NOMFET), that has arisen for use as biological synapses, with reliable data storage, low-power consumption, and low-manufacturing cost [1].

One of the most popular MOSFET technologies which undergo intense researches, is Complementary MOS or CMOS technology [2,3]. Its capability to bring adaptability and robustness in circuits beyond the conventional Von Neumann architecture is a great interest to develop new neuromorphic circuits [4].

However, CMOS technology have not the capacity to be at the same scale as the biological one, since the huge number of transistors required to emulate the dynamic behavior of the biological synapse and neuron [5,6].

The human brain contains more than a billion of neuron cells, each cell works like a simple processor. The massive interaction between all cells and their parallel processing only makes the brain's abilities possible. The synapse is the point of connection between neurons, and its basic principle is to perform the following two functions: modifying connection strength and storing weights.

Previous studies show that mixing nanoparticles (NPs) and molecules to implement computation and memory in a single synapse-like device is a powerful approach towards such objectives. This approach was resolved by demonstrating a new kind of memristive compound and synaptic transistor [7,8].

The NPs embedded into organic semiconductor are used as nanoscale capacitors to store the electrical charges. They accumulate electrons when a positive DC gate voltage is applied (programming phase). Afterward, a pulse drain current is facilitated with increasing time when a positive gate voltage is applied. Besides, in the erasing phase, they lose electrons when a negative gate voltage is applied. Then, a drain current is depressed with increasing time when a positive gate voltage is applied. This behavior is obtained by virtue of the combination of two principal properties of the NOMFET: the memory effect and the transistor transconductance gain [9,10].

In this paper, we have demonstrated a charge storage in nanoparticles organic memory field effect transistor, using an electron-transport polymeric semiconductor layer [P (NDI2OD-T2)$_n$] (Polyera™ ActivInk N2200) [11,12]. We also showed that we can adapt

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the dynamic behavior of the NOMFET in the frequency/time domain (0.5 Hz–5 Hz) leading to a facilitating and a depressing drain current mimicking the behavior of biological synapses, which can be also a starting point to realize complementary circuits and bring as the capability of studying neural networks made only with NOMFET.

2. Experiments

NOMFET devises are based on a bottom gate, bottom contact (BG/BC) OFET configuration Fig. 1a and b. The fabrication process is described below: a highly-doped p-type silicon covered with a thermally grown 200 nm thick silicon dioxide was used as the bottom gate electrode and blocking dielectric layer, respectively. 50 nm of Au drain and source contacts were thermally evaporated on top of the dielectric layer. Substrates were then cleaned by sonication in ethanol, isopropanol, for 10 min followed by ultraviolet irradiation in an ozone atmosphere (Ozonolysis) for 30 min. We use a piranha solution (H_2SO_4/H_2O 2, 2:1v/v) for 15 min (caution: preparation of the piranha solution is highly exothermic and reacts violently with organics).

Samples were then immersed into a solution of **(3-Aminopropyl) triethoxysilane** (APTS) forming a positively charged self-assembled monolayer (SAM) [13], they are subsequently transferred into a negatively charged citrate-reduced Au NP's solution to obtain an Au NP's matrix acting as a floating gate layer [14]. To improve device performance, the surface was treated with a thin layer of **Octadecyltrichlorosilane** (OTS) [15]. Finally, [P(NDI2OD-T2)$_n$] film, was spin coated through a 0.45-μm PTFE filter (solution concentration, 10 mg/mL in chloroform, spin rate 2500 rpm, annealed at 120 °C overnight) [10].

We note that the Au NP's density can be controlled by the concentration of NPs in the solution and by the duration of the chemical reaction. To observe the synaptic behavior (short term plasticity effect) the optimum NPs density reported in Ref. [9] for a NOMFET based pentacene, it is between 10^{11} and 10^{12} cm^{-2}. For a low density less than 10^{11} NP cm^{-2}, the memory effect is observed [16], but the synaptic behavior of the NOMFET appears too weak. At high density, more than 10^{12} NP cm^{-2}, the device is affected by short circuit that occurs between source and drain, and NPs film screen the gate voltage from the channel. In our case, the scanning electron microscopy (SEM) image, Fig. 1c and d, shows an average density of the Au nanoparticles embedded in the channel [P(NDI2OD-T2)$_n$] about 2.1 × 10^{11} NP.cm^{-2} with well separated nanoparticles (presence of some aggregations). The separation of the Au NP's from each other is maintained averagely larger than 5 nm which limits any lateral flow of charge.

3. Results and discussion

In this section, first, we present the experimental performance of the device as electrically programmable and erasable memory cells and then we will examine the biological synapse behavior of NOMFET.

The transfer curves of the initial, the programmed and the erased states are typical of a short-channel electron-transport MOSFET. Fig. 2a shows an important shift ΔV_{th} in the transfer curves of the memory device defined as the change in the threshold voltage V_{th} with respect to the applied program/erase bias pulses.

At the erasing state, after applying a gate voltage of 70 V for 10 s, the drain current becomes more important. While at the programming state, it decreases after a gate voltage of −70 V was applied for 10 s. The threshold voltages after programming and erasing are 7 V and 23 V, respectively. In this study, the memory window was around 16 V with program/erase bias pulses of (70 V for 10 s). These results indicate that the Au nanoparticles

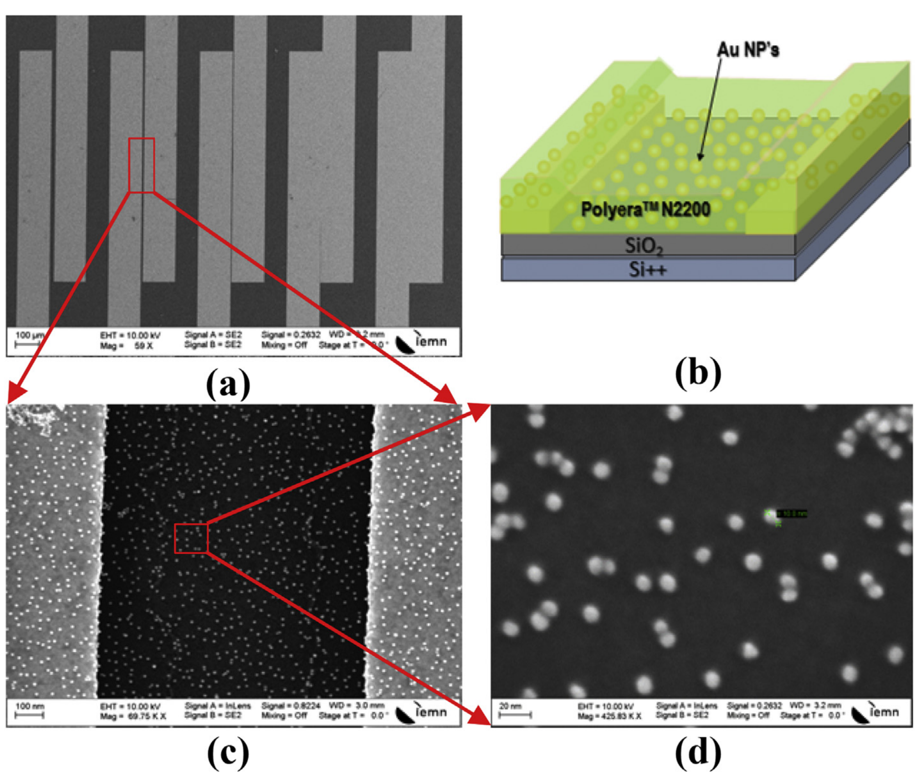

Fig. 1. NOMFET 3D schematic structure with scanning electron microscope image of the NP's arrays before the [P(NDI2OD-T2)$_n$] deposition. (NP's have 10 nm of diameter with a density of 5.6 × 10^{10} NP.cm^{-2}).