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A nanoparticle organic memory field-effect transistor behaving as a programmable spiking synapse

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Molecule-based devices are envisioned to complement silicon devices by providing new functions or already existing functions at a simpler process level and at a lower cost by virtue of their self-organization capabilities, moreover, they are not bound to von Neuman architecture and this may open the way to other architectural paradigms. Neuromorphic electronics is one of them. Here we demonstrate a device made of conjugated molecules and metal nanoparticles which behaves as a biological spiking synapse. We have built a nanoparticle organic memory filed-effect transistor (NOMFET) and we demonstrate that this device exhibits the main behavior of a biological spiking synapse. Facilitating and depressing synaptic behaviors can be reproduced by the NOMEFT and can be programmed. The NOMFET exhibits short term plasticity, as a biological synapse, and can be shrunk to nanometric size. These results open the way to rate coding utilization of the NOMFET in neuromorphic computing circuits. We can also envision the NOMFET as a building block of neuroelectronics for interfacing neurones or neuronal logic devices made from patterned neuronal cultures with solid-state devices and circuits.

The device (Fig. 1) consists of a bottom-gate, bottom source-drain contact organic transistor configuration. The gold NPs (20 and 5 nm in diameter) were immobilized into the source-drain channel using surface chemistry (self-assembled monolayers) and they were subsequently covered by a thin film (35 nm thick) of pentacene. Scanning electron microscope (SEM) images, Fig. 1, show a random distribution of the 20 nm NPs, with the formation of some aggregates. From an image analysis, we deduce an average density of ~ 2-5x10^{10} NP/cm^2. For the 5 nm NPs, we obtain a rather uniform distribution of NPs (no NP aggregation) with a density of ~ 6.5x10^{11} NP/cm^2.

The synaptic behavior is obtained by virtue of the combination of two properties of the NOMFET: the transconductance gain of the transistor and the memory effect due to charges stored in the NP. We previously demonstrated that this type of device works as a non-volatile memory [1] but with a “leaky” behavior. The retention time was in the range of few 10 s to few 1000 s, and this behavior is used here to implement the synapic weight w_{ij} with a possible dynamic working in this range, a mandatory condition to obtain the training/learning of a spiking neural network [2]. A transistor is basically a multiplier, thus it is used to realize the basic function of the synapse described as $S_j=w_{ij}S_i$, where S_i and S_j are the pre- and post-synaptic signals (here the source/drain current and voltage of the NOMFET). We demonstrate that we can tailor the dynamic behavior of the NOMFET in the frequency/time domain (0.01-10 Hz) by adjusting the size of both the NPs (5-20 nm in diameter) and the NOMFET (50 nm to 12 µm). In a biological synapse, short term plasticity induces a dynamical processing of pulses pattern that depend on the timing between pulses and on the past history of the synapse [3]. This behavior is exactly what we demonstrated for the NOMFET (figure 2). We also demonstrate that models developed to explain and simulate the behavior of biological synapse [4] can be successfully adapted to the NOMFET behavior. These results open the way to rate coding utilization [5] of the NOMFET in neuromorphic computing circuits [6].

References:

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Figures:

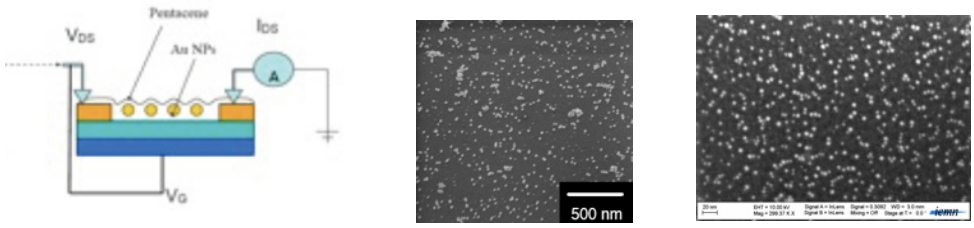

Figure 1: Schematic view (left) of the NOMFET, and SEM of the 20 nm NP (middle) and 5 nm NP (right) network on the gate dielectric surface.

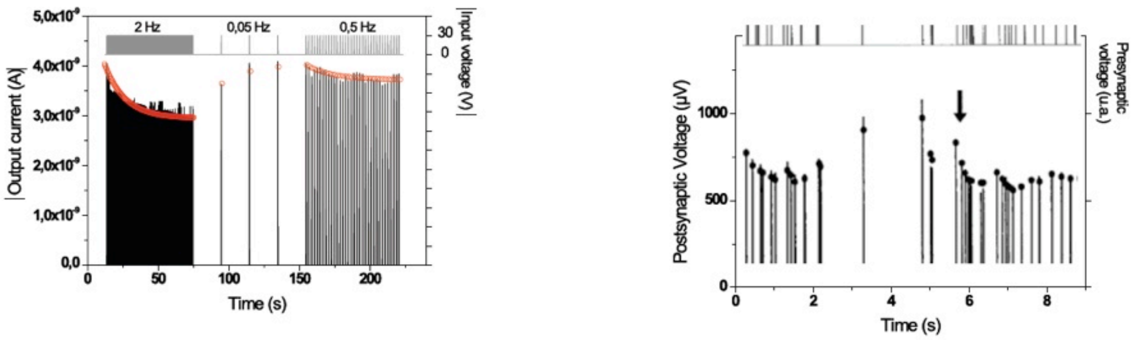

Figure 2: Typical synaptic behaviour of the NOMFET (left) and comparison with the response of a biological synapse (right). The open circles and dots correspond to the modelisation of the NOMFET and of a biological synapse, respectively.