Light-activated artificial synapses based on graphene hybrid phototransistors

Shuchao Qin, Yujie Liu, Xiaomu Wang, Yongbing Xu, Yi Shi, Rong Zhang, Fengqiu Wang*

School of Electronic Science and Engineering and Collaborative Innovation Center of Advanced Microstructures, Nanjing University, Nanjing 210093, China
E-mail address: fwang@nju.edu.cn

Abstract: A novel light-activated artificial synapse based on graphene/nanotube hybrid phototransistor is reported. Tunable synaptic weight and short-term synaptic plasticity behaviors are for the first time demonstrated using optical laser pulses.

OCIS codes: (230.0250) Optoelectronics; (200.4260) Neural networks; (160.1890) Detector materials

1. Introduction

Neurons are considered to be the computational engines of the brain. A neuron communicates with other neurons primarily through fast chemical synapses [1-3]. High-performance solid-state devices emulating synapse functionalities (such as short-term plasticity) are viewed as a key step towards hardware implementation of neuromorphic computation system, which has profound implications for a wide range of applications including visual image processing and auditory speech recognition [4]. Despite recent advancements, conventional neuromorphic circuits failed to implement two important functions of real neuron networks. First, in most of the artificial synapses, the neuromorphic computing is isolated from the data acquisition sensors (ocular or auditory stimuli), resulting in huge redundancy. Second, *in-situ* adjustment of synaptic weight has proved challenging. Synaptic weight represents the synapse efficacy between presynaptic and post-synaptic neurons, which is precisely adjusted by the neurotransmitter concentrations (such as Ca^{2+}, Na^{+}, K^{+} ions) [5]. Several artificial synaptic devices have been designed and fabricated based on common electronic components [6-8]. However, for a given artificial synapsis pair, the coupling coefficient of these devices is always fixed, while flexible tuning is desired to emulate real neuron operation. Some of these limitations are calling for new building blocks and architectures for the next-generation neuromorphic systems.

In this paper, we demonstrate that the charge transfer process at graphene/carbon nanotubes (CNTs) interface is an ideal analogue to ion transport between synapses. Accordingly, we propose and fabricate a novel neuromorphic phototransistor to simulate visual synaptic functions, by combining atomically thin two-dimensional graphene with one-dimensional CNTs. Our devices allow flexible tuning of synaptic strength by back-gate tuning, and synaptic plasticity behaviors under laser pulse excitation were for the first time successfully mimicked. The results show promise of incorporating active photonic functionalities in an artificial neural networks.

2. Graphene hybrid neuromorphic phototransistors

Figure 1(a) shows a biological synapse between a pre-neuron and a post-neuron. In our device, photocarriers generated by external laser light contribute to a photocurrent in the graphene/nanotube hybrid field-effect-transistor (FET) [9, 10]. After light activation, the source-drain current intensity gradually decay back to the level of resting current in dark, a process very similar to the characteristics of biological synapses. The incorporate of light pulses in such a synaptic device is expected to open up a much broad range of possible operation time scales.

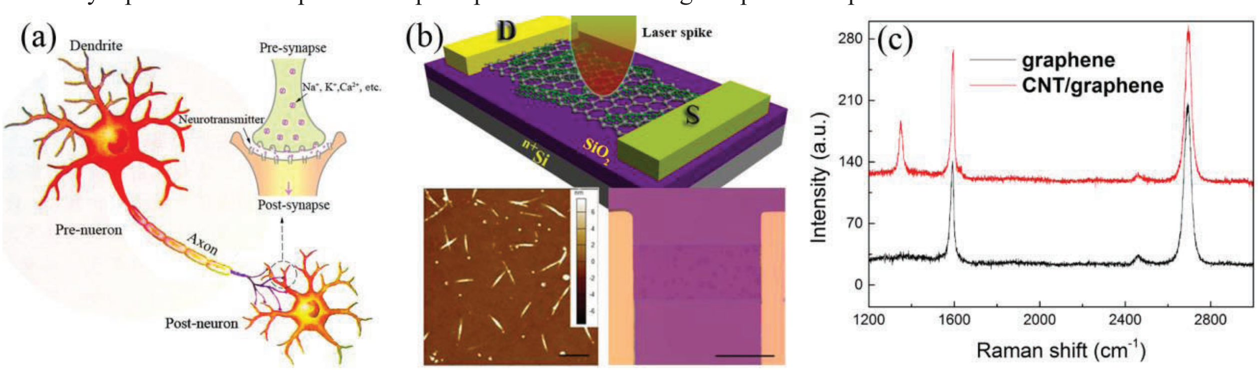

Fig.1 (a) Schematic illustration of the biological synaptic integration in a neuron,(b) Schematic diagram of an as-fabricated artificial synapse phototransistor, Insets: AFM of CNTs (scale bar:1 μm) and optical micrograph of a device (scale bar: 50μm). (c) Raman spectrum for the pristine graphene and graphene/nanotube hybrid films.

To fabricate a proof-of-concept artificial synapse, CNT suspensions are produced by ultrasonicating 2 mg nanotube in 20 mL NMP, and then resulting suspensions ultra-centrifuged with 10,000 g for 1h are coated onto a Si/SiO_2 (285 nm) wafer. CVD graphene is transferred on top of the CNT layer using the poly(methyl methacrylate) supported procedures. Subsequently, different electrodes (Ti/Au and Pd/Au) are patterned by standard photolithography, as depicted in Fig. 2(b). The insets show AFM image of the CNTs on the substrate and optical micrograph of the finished device. External laser pulses are regarded as the synaptic spikes to trigger an excitatory postsynaptic current (EPSC), with channel conductance acting as synaptic weight. Such architecture can significantly simplify the simulation system and can make the entire device more compact and efficient. Raman spectrum of the top pristine graphene and hybrid films is shown in Fig.1(c). The bio-simulation measurements are carried out under vacuum (10^{-6} Torr) at room temperature.

3. Results for photoresponsivity enhancement

A laser spike (100 μW, 150 ms) that mimics a pre-synaptic or ocular stimuli was applied on the channel using a 532 nm visible diode laser and a V_{DS} of 50 mV was applied between the source and drain electrodes for EPSC measurement. The EPSC reached a peak value at the end of the spike at V_G=10 V, and gradually decayed back to the resting current within around 400 ms after the laser pulse diminishes in Fig. 2(a). Upon photoexcitation, electron-hole pairs can be generated and one type of charge carrier (according to graphene chemical potential) transfer into the channel, leading to photocurrent. Inspiringly, the relative change of synaptic weight (ΔW, defined as $\Delta I/I_0$) can be modified by the gate voltage [inset of Fig. 2(a)], realizing the *in-situ* adjustment of synaptic weight. Paired-pulse facilitation (PPF) is a phenomenon whereby EPSC is increased when the second spike closely follows a previous spike, which embodies long-term plasticity and is essential to decode temporal information in auditory or visual signals [5]. In our synaptic phototransistor, this temporal analog logic function has also been realized by a pair of laser spikes with a pulse interval (Δt) of 200 ms at V_G=10 V, as shown in Fig. 2(b). Fig. 2(c) shows the PPF index (A2/A1×100%) as a function of the interval between the paired pulses, which can be well fitted by a double-exponential function. It is notable that the synaptic weight is facilitated when the interval is shorter than the relaxation time of charge carries.

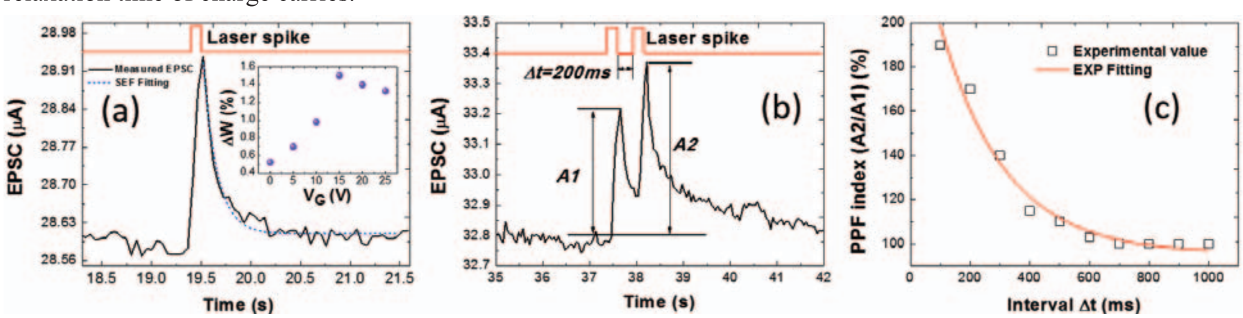

Fig.2 (a) EPSC triggered by a pre-synaptic laser spike, which is fitted by a stretched exponential function. (b) PPF behaviors. (c) PPF index (A2/A1) plotted as a function of laser spike interval time Δt between two consecutive laser spikes.

4. Conclusion

We have for the first time demonstrated a novel, light-activated artificial synapse with gate-tunable synaptic weight based on a phototransistor. Short-term synaptic plasticity behaviors are successfully achieved. Such a novel device is envisaged to be important for large-scale integrated artificial synaptic network, and paves the way for hybridizing photonic functions with conventional proton or electron based neuromorphic devices.

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