Photonic synaptic device capable of optical memory and logic operations

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Abstract: We demonstrate an optically-driven artificial synapse based on a graphene hybrid phototransistor. Both optical memory function (long-term plasticity) and logic operations are achieved, which adds important new capabilities to photonics enabled neuromorphic computing.

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

1. Introduction

Signal processing, memory, and learning are key functions performed by neurons in our brain. Neurons communicate with each other primarily through anatomically identifiable cellular regions called synapses [1]. One important theme in neuromorphic computing and engineering is hardware implementation of devices with functionalities exhibit by biological synapses, such as short-term and long-term plasticity [2]. Inspired by the brain's structure, electronic materials, devices, and circuits are being extensively explored to emulate synapses [3]. Despite remarkable advancements, conventional neuromorphic circuits based on electronic components still suffer from some drawbacks. For example, signal processing is usually isolated from the data acquisition sensors (ocular, olfactory or auditory stimuli), resulting in huge hardware redundancy. On the other hand, photonics offers significantly faster signal processing speed and can provide multiple degrees of freedom in terms of enabling high throughput data processing [4]. Thus, novel neuromorphic functional devices that can provide coupling mechanisms with light, e.g. optical spike processing, are expected to enable new capabilities for future photonics-driven neuromorphic architectures. Previously, we showed that a graphene hybrid phototransistor can be used to process light stimuli, emulating the functionality of short-term plasticity of an artificial synapse [5].

In this paper, we further employ the atomically thin two-dimensional graphene with one-dimensional carbon nanotubes (CNTs) and demonstrate that the photonic synapse exhibit optical memory behavior that well emulates long-term plasticity, and a full set of optical logic operations are also successfully achieved in the same integrated device. The results show that a hybrid phototransistor may be employed as a multifunctional, conceptually novel device for implementing photonics based artificial neural networks.

2. Long-term plasticity/optical memory

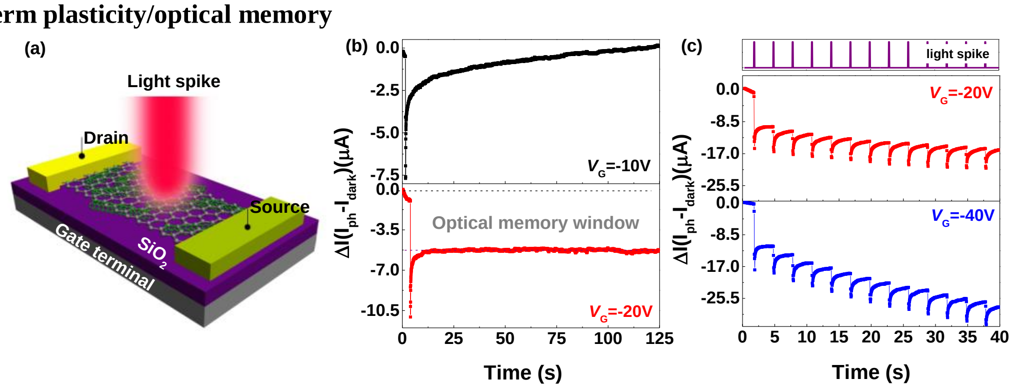

Fig.1 (a) Schematic illustration of a graphene-CNT phototransistor functioning as an optically-driven artificial synapse. (b) The amplitude of IPSC triggered by a pre-synaptic light spike (50 μW, 100 ms duration) under different gate bias. (c) The enhancement of LTP upon consecutive spike excitation.

To fabricate the proof-of-concept artificial synapse, CNT suspensions are produced by ultrasonicating 2 mg nanotube in 20 mL NMP, and then the resulting suspensions are ultra-centrifuged with 10,000 g for 1h and 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. An artificial synapse is shown as Fig. 1(a). In the synaptic transistor, the input light pulses applied onto the device could generate photocarriers to alter the channel conductance [6-7], which can be regarded as the synaptic weight. In this case, light pulses are taken to be pre-synaptic spikes or external stimuli. The incorporation of light pulses in such a synaptic device is expected to open up a much broad range of possible operation time scales.

When a pre-synaptic light spike (50 μW, 100 ms) from a 405 nm visible diode laser is applied onto the channel, a typical inhibitory post-synaptic current (IPSC) is directly triggered but does not relax back to its initial state at V_G=-20 V, which emulates the LTP mechanism, as shown in Fig. 1(b). Meanwhile, LTP may be mitigated by applying a -10 V (or zero) gate voltage. Its physical mechanism originates from charge injection into the interface or bulk SiO_2 trap centers (such as dangling bonds, intrinsic defects and local structural distortions, Ref. 8) at high gate voltage. The trap sites density can be tuned by the gate bias. In Fig. 1(c), the enhancement and saturation of long-term memory upon consecutive spike irradiation are both observed at V_G=-20 V and -40 V. These results demonstrate that such hybrid synapses go beyond purely mimicking synaptic biological characteristics, and may also be designed to gate-tunable nonvolatile optical memory.

3. Optical logic operations

Optical signal processing is widely present in real biological systems. For example, biological retina executes a number of signal processing tasks to make human vision highly adaptive [9]. By properly choosing the gate bias, 2-input AND/OR light-driven logic operations are obtained through charge-trap-mediated optical coupling in a single synaptic transistor. Two pre-synaptic lasers represent binary logic inputs A & B (as the logic inputs 1/0) and the photocurrents play as logic outputs (high current as ON and low current as OFF). Fundamentally, the device obeys two summation rules of multi-laser inputs, namely super-linear summation rule and sub-linear power summation rule. Applying a gate bias at V_{cross} (crossover of the transfer curves in dark and in light), a very low level output current is kept under individual pre-synapse spike. However, if both pre-synapses trigger simultaneously, super-linear summation rule would guarantee a significant output, as shown in Fig. 2(a). On the other hand, setting the gate bias to be at V_G=20 V, the device enters the IPSC saturation regime. Sub-linear power summation rule validates that the output current does not change much even both of the pulses are applied, which results in the OR operation, as plotted in Fig. 2(b). These functions achieved in our neuromorphic device provide important interface to photonic computing capabilities and may lead to fundamental upgrade of conventional neuromorphic network architecture [4].

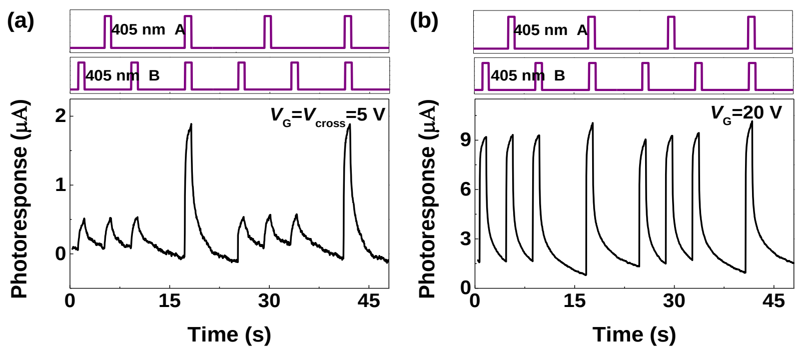

Fig.2 (a) AND logic operation by utilizing two 405 nm light spikes (10 μW, 1 s) at V_G=V_{cross}. (b) OR logic operation at V_G=20 V with (50 μW, 1 s) light spikes.

4. Conclusion

We have for the first time demonstrated a novel, optically-driven artificial synapse based on a phototransistor. Gate-tunable long-term plasticity (optical memory) and AND/OR optical logic operations are successfully achieved. Such a novel device is envisaged to be important for large-scale integrated artificial synaptic network, and paves the new way for brain-inspired ultrafast computation using photonics enabled platforms.

5. References

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