Saturation Behavior for a Comb-Like Light-Induced Synaptic Transistor

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***Abstract*—We propose and fabricate a comb-like light-induced synaptic transistor composed of two InGaN/GaN multiple-quantum-well diodes (MQWDs) with a common base. One InGaN/GaN MQWD is used as an emitter of light, and another InGaN/GaN MQWD is used as a collector. When a presynaptic voltage is applied to the emitter to generate light, the collector absorbs the emitted light and demonstrates an excitatory postsynaptic voltage (EPSV). Saturated EPSV behavior occurs at the collector when multiple pulse signals are continuously applied to the emitter. The saturated EPSV value is increased and the saturated pulse number is reduced as the amplitude of the applied pulse signal increases. Experimental results indicate that continuous stimuli with a high pulse intensity will greatly improve the memory effect during the learning process.**

***Index Terms*—InGaN/GaN multiple-quantum-well diode, light-induced synaptic transistor, excitatory postsynaptic voltages, memory effect, saturation behavior.**

I. Introduction

THE development of neural networks is currently of great interest to various branches of research. In neural circuits, synapses can conduct critical computational functions by receiving excitatory stimuli and transmitting signals from one neuron to another [1]–[3]. Three-terminal ionic/electronic hybrid transistors have been treated as biological synapses to mimic the behavior of neurons in the human brain [4]–[6]. This type of transistor with synaptic functions is promising for the construction of blocks for neuromorphic systems and brain-inspired computing [7]. Synaptic functions include paired-pulse facilitation behavior, where the magnitude of the second postsynaptic potential is larger than that of the first postsynaptic potential [7], [8], spike-timing dependent plasticity [7], [9], [10] and long-term/short-term plasticity [11]. Non-associative learning, in which an animal learns about the occurrence or characteristic of a single stimulus, has been implemented by single memristor-based multi-terminal synaptic devices [12]. It is well known that continuous practice can strengthen memory effects during the learning process. Multiple pulse signals can be applied to artificial synaptic transistors to investigate the memory effect through saturation behavior.

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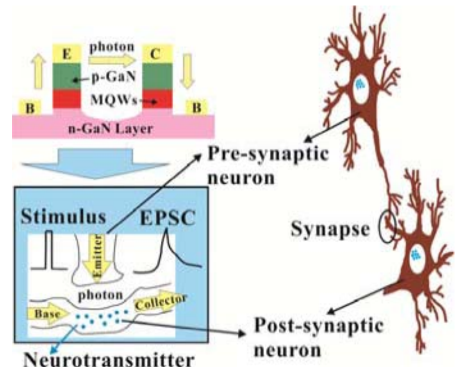

Fig. 1. The schematic diagram of the light-induced synaptic transistor.

Here, we propose and fabricate a comb-like light-induced transistor on a GaN-on-silicon platform. The transistor is composed of two InGaN/GaN multiple-quantum-well diodes (MQWDs) with a common n-contact as the base [13]. One InGaN/GaN MQWD is used as an emitter to emit light, and another InGaN/GaN MQWD serves as a collector to absorb the emitted light. When a presynaptic voltage is applied to the emitter to generate light, the collector absorbs the emitted light and demonstrates an excitatory postsynaptic voltage (EPSV), as shown in Fig. 1. Compared with the low-power synaptic transistors, our proposed light-induced synaptic transistor uses photon rather than electron or proton to induce EPSV behavior for artificial synapse applications. The saturation behavior of EPSV is characterized to investigate the memory effect for the light-induced synaptic transistor. Experimental results indicate that continuous stimuli with a high pulse intensity will greatly improve the memory effect.

II. Experimental Results and Discussion

The comb-like light-induced synaptic transistor is constructed on a commercial GaN-on-silicon wafer [14]. The total thickness of top epitaxial films is approximately 4.97 μm and the InGaN/GaN MQWs layer is 120 nm thick. A double-sided fabrication technique is used to prepare suspended comb-like light-induced synaptic transistor. Comb-like mesas are firstly defined by photolithography and etched using Cl_2 and BCl_3 hybrid gases at the flow rates of 10 sccm and 25 sccm, respectively. In association with evaporation and lift-off techniques, the 20 nm Ni/ 180 nm Au bilayers are generated and then annealed at 500°C in a N_2 atmosphere, leading to a formation of p- and n-contacts. Silicon removal and back

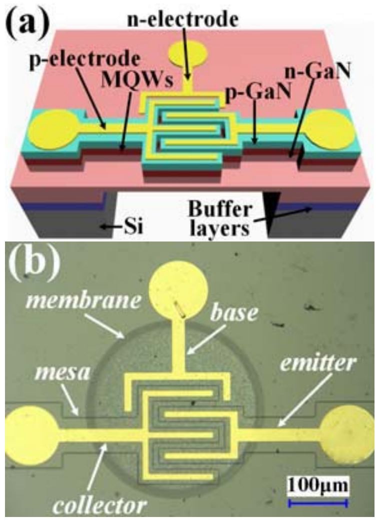

Fig. 2. (a) Schematic cross section of the comb-like light-induced synaptic transistor; (b) Optical micrograph of the fabricated comb-like transistor.

wafer thinning are finally conducted to obtain suspended comb-like light-induced synaptic transistor. Figure 2(a) shows a schematic of the comb-like light-induced synaptic transistor. Two InGaN/GaN MQWDs with a common base were used as an emitter and a collector to form a light-induced transistor. The comb-like device architecture is proposed to increase the light coupling between the emitter and the collector. Silicon removal and backside thinning are conducted to generate a suspended membrane with a diameter of 300 μm on which the device is fabricated (except for the contact pad), as shown in Fig. 2(b). The 10-μm-wide gap between the comb teeth is photolithographically defined and generated by inductively coupled plasma-reactive ion etching, and the comb teeth are 140 μm long. Suspended device architecture can directly sense the out-of-plane incoming light, which means that the light-induced synaptic transistor can simultaneously detect the in-plane pulse signals and the out-of-plane signals to achieve multiple-dimensional synaptic emulation.

The emitted light from the comb-like emitter depends on the forward current. The InGaN/GaN MQWD collector absorbs the incident light and completes the photon-to-electron conversion, leading to an induced photocurrent. The photocurrent amplitude is dependent on the light energy and is thus modulated by the forward current applied to the emitter. The photocurrent is characterized by a combination of an Agilent B1500A semiconductor device analyzer and a Cascade PM5 probe station. The dependence of the photocurrent amplitude on the forward current is shown in Fig. 3(a). The photocurrent is obtained by subtracting the measured current values of the collector at the various forward currents of the emitter using the measured current values without light absorption. The collector, regarded as a photodiode, exhibits two light detection modes. The induced photocurrent of the collector increases with increasing forward current of the emitter. Figure 3(b) shows a dynamic photocurrent as a function of the forward current of the emitter. Correspondingly, the photocurrent of the collector varies in response to the dynamic fluctuation of the forward current. These results suggest the good photocurrent response and stability of the light-induced synaptic transistor.

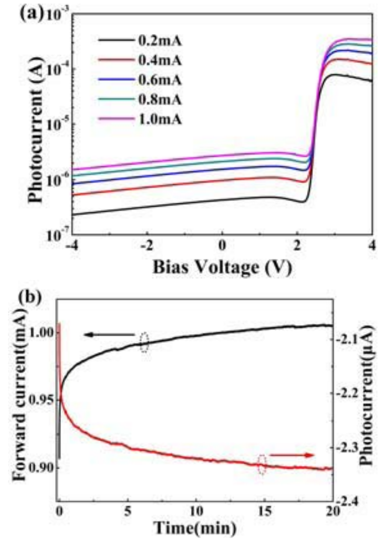

Fig. 3. (a) Induced collector photocurrent versus forward current of the emitter; (b) Dynamic photocurrent as a function of the forward current of the emitter.

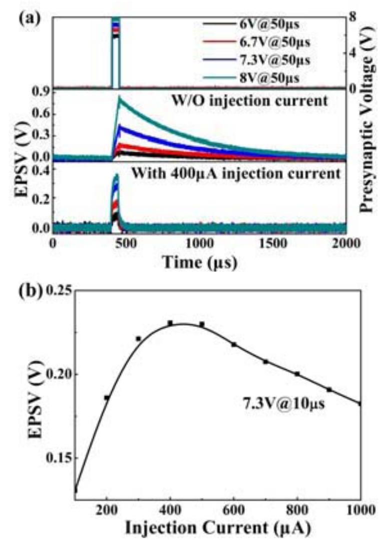

Fig. 4. (a) Dependence of EPSV on pulse signal amplitude; (b) EPSV versus collector injection current operating under light detection and emission mode.

During animal learning, a single stimulus will induce an EPSV, which reaches a peak and is forgotten as time goes by. This process is known as the memory effect. The EPSV behavior is measured by a combination of a Keysight 81160A pulse function arbitrary generator and an Agilent DSO9254A digital storage oscilloscope. Figure 4(a) shows the measured EPSV as a function of the amplitude of the pulse signal. The EPSV amplitude increases and memory time extends as the applied pulse signal increases from 6V@50μs to 8V@50μs. When the collector operates only in light-detection mode, the memory time distinctly increases and the EPSV amplitude is higher compared to its light-emission and detection counterpart. The EPSV amplitude is dependent on the injection current of the collector when it operates under light-emission and detection mode, as illustrated in Fig. 4(b). A 7.3V@10μs pulse signal is applied to the emitter, and the EPSV amplitude approaches a maximum value with increasing injection current

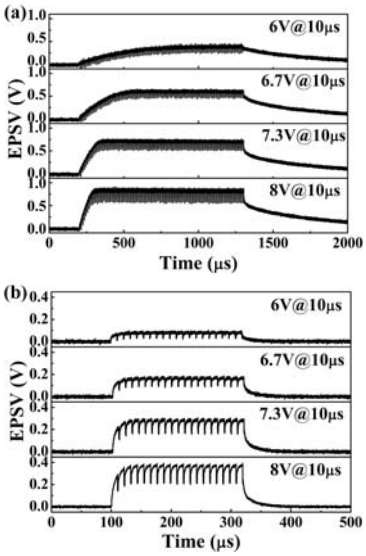

Fig. 5. (a) Pulse number-dependent EPSV versus the pulse signal amplitude in light-detection mode; (b) pulse number-dependent EPSV amplitude of pulse signal in light-emission and detection mode.

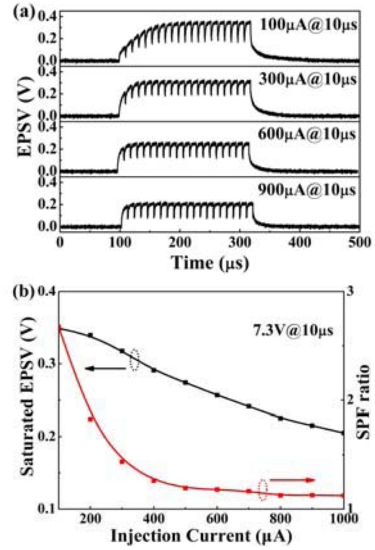

Fig. 6. (a) Pulse number-dependent EPSV versus collector injection current; (b) Saturated EPSV amplitude and SPF ratio versus injection current.

to 400 μA. Amplitude gradually decreases with increasing injection current, indicating a nonlinear response process.

For a light-induced synaptic transistor, presynaptic stimuli coincide with postsynaptic stimuli, leading to a superimposed EPSV at the collector. Hence, saturation effects of the EPSV will occur when multiple pulse signals are continuously applied to the emitter. Figure 5(a) shows pulse number-dependent EPSV versus various signal amplitudes. The injection current of the collector is 0 μA, and the pulse number is 100 with a fixed pulse interval of 1 μs. The EPSV amplitude reaches saturation with increasing pulse number. The saturated EPSV value clearly increases and the saturated pulse number is reduced as the applied pulse signal increases from 6V@10μs to 8V@10μs. Higher signal amplitudes can achieve better memory effects. In other words, the same pulse signal can realize higher EPSV amplitudes with shorter stimuli cycles, indicating that high intensity training are superior to moderate intensity exercise training for practical applications. Figure 5(b) illustrates the saturation behavior of the light-induced synaptic transistor, which operates in light-detection and emission mode with an injection current of 400 μA. Amplitude-dependent saturation behavior is distinctly observed, indicating that continuous learning with higher learning intensity will greatly improve the memory effect.

Moreover, saturation behavior is influenced by the injection current of the collector when it operates in light detection and emission mode. As illustrated in Fig. 6(a), both the saturated value and the saturated pulse number decrease at a pulse signal of 7.3V@10μs with increasing injection current from 100 μA to 900 μA. Figure 6(b) shows the saturated EPSV amplitude and saturated-pulse facilitation (SPF) ratio as a function of injection current. The saturated EPSV amplitude is approximately 2.67-fold higher than the first EPSV amplitude at an injection current of 100 μA, and approximately 1.12-fold higher than the first EPSV amplitude at an injection current of 900 μA. The saturation amplitude is decreased when higher injection current is applied to the collector, indicating that, under an excited state, one responds rapidly to external stimulus but with low memory effect.

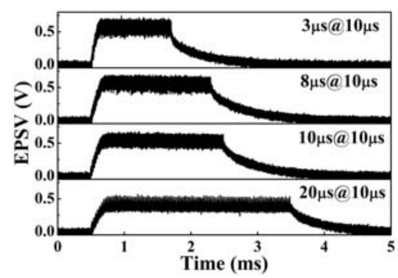

Fig. 7. Pulse number-dependent EPSV versus the interval time $\triangle$t.

Figure 7 shows pulse number-dependent EPSV versus various interval time $\triangle$t when the collector operates under light detection mode. The applied pulse signals are 7.3V@10μs with different interval time $\triangle$t. The saturated EPSV amplitudes are 0.62 V, 0.60 V, 0.57 V and 0.45 V at the interval times of 3 μs, 8 μs, 10 μs and 20 μs, respectively. Experimental results demonstrate that the saturation amplitudes are improved when the interval time $\triangle$t of the applied pulse signal is decreased, suggesting that repetitive learning with short-interval time can effectively strengthen the memory effect.

III. Conclusion

In conclusion, we propose and fabricate a comb-like light-induced synaptic transistor to investigate the memory effect. The saturation behavior of the EPSV amplitude occurs when continuous pulse signals are applied. The memory effect is dependent on the amplitude, interval time and number of the pulse signal. As pulse signal amplitude increases, the saturated EPSV value increases and the saturated pulse number is reduced, leading to an improved memory effect. The saturation behavior of the EPSV is influenced by the injection current of the collector when it operates in light-detection and emission mode. Moreover, experimental results suggest that the saturation EPSV amplitude will be improved with decreasing the interval time of the applied pulse signal.

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