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GaN-based artificial optoelectronic neural circuit with multilevel synapses cascade for neuromorphic computing

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The "synapse-neuron-synapse" (SNS) structure represents the most fundamental neural circuitry for brain information transmission (Figure 1(a)), highlighting the necessity of integrating cascaded synaptic devices in neuromorphic systems. However, existing studies have only demonstrated input synapses (IS) or output synapses (OS) individually, with no reports of integrated implementations incorporating both. Moreover, monolithic integration of synaptic devices remains challenging. Optoelectronic synaptic devices have emerged as promising candidates due to their high bandwidth, low crosstalk, and low power consumption [1]. Benefiting from the exceptional photoelectric properties of GaN-based materials and their compatibility with standard semiconductor fabrication processes [2], the monolithic integration of multiple optoelectronic synaptic devices on a single platform is becoming feasible.

In this work, we propose a GaN-based all-optical modulated synaptic cascade structure comprising a circular-gate synaptic metal-oxide-semiconductor field-effect transistor (MOSFET) and a large thin film synaptic diode, as shown in Figures 1(b) and (c). The synaptic characteristics of both devices arise from the trapping and releasing of photogenerated carriers. Specifically, the synaptic diode exploits defect states introduced in the p-type region by ion bombardment during inductively coupled plasma etching, while the synaptic MOSFET introduces interface trap states at the gate-channel interface. The fabrication process, morphology characterization, energy band structure, and essential optoelectronic and synaptic characteristics of the proposed devices are presented in Appendixes A and B. To our best knowledge, it is the first time to realize two types of synaptic devices on a single chip based on the homogeneous material, which is an important advance in the field of neuromorphic photonics. Moreover, by connecting the synaptic diode in series with a resistor to form a voltage divider circuit, the postsynaptic current is converted into a gate voltage for the synaptic MOSFET, establishing cascaded information transmission between synaptic devices. Figure 1(d) presents the equivalent circuit of the proposed cascade structure. This structure successfully emulates spike-timing-dependent plasticity (STDP), associative learning, and logic operation, providing a novel platform for intra-dendritic computing and highly integrated neuromorphic chips.

The synaptic diode and synaptic MOSFET are selectively stimulated by 375 and 405 nm ultraviolet light, respectively, enabling the synaptic cascade structure to realize more advanced neuromorphic computation. STDP is an advanced neuromorphic learning rule derived from Hebbian learning theory. STDP modulates synaptic strength based on the temporal difference between neuronal spikes, with the synaptic weight determined by the time interval ($\Delta t_{\text{pre-post}}$) between presynaptic and postsynaptic spikes. When the device is stimulated by two optical spikes with different $\Delta t_{\text{pre-post}}$, the resulting change in postsynaptic current (PSC) is measured. The resulting STDP curve follows the classical model:

$$\Delta S = \begin{Bmatrix} A^+ \times \exp(\frac{\Delta t}{\tau^+}) + \omega_0 & \Delta t > 0 \\ A^- \times \exp(\frac{\Delta t}{\tau^-}) + \omega_0 & \Delta t < 0 \end{Bmatrix}, \tag{1}$$

where A^+, A^-, τ^+, and τ^- are the amplitudes and the time constants of potentiation and depression, respectively. Figure 1(e) shows that the dependence of ΔS on $\Delta t_{\text{pre-post}}$ exhibits an antisymmetric distribution, reflecting the characteristic Hebbian learning rule governed by STDP.

Pavlov's dog experiment is a form of associative learning involving higher-order cognitive functions and is widely used to evaluate neuromorphic computing capabilities [3]. In this study, the 375 nm light serves as the "bell", while the 405 nm light represents "food". As shown in Figure 1(f), the simultaneous application of ten pairs of 375 and 405 nm light pulses to the IS and OS, respectively, generates suprathreshold PSC, signifying salivation and the formation of an association between the two stimuli. After a forgetting period, the PSC decays below the threshold (salivation ceases). When the 375 nm light is reapplied alone, the PSC exceeds the threshold and exhibits potentiation, confirming that the previous stimulus (ringing bell) now independently triggers the conditioned response (salivation), just as the unconditioned stimulus (feeding) did originally.

Moreover, we have successfully demonstrated a logical operation using cascaded synaptic devices. An input of "0" corresponds to the absence of optical stimulation, while "1" represents the presence of a light pulse. An inhibitory postsynaptic current is defined as output "0", whereas an excitatory postsynaptic current (EPSC) corresponds to output "1". Figure 1(g) demonstrates that when

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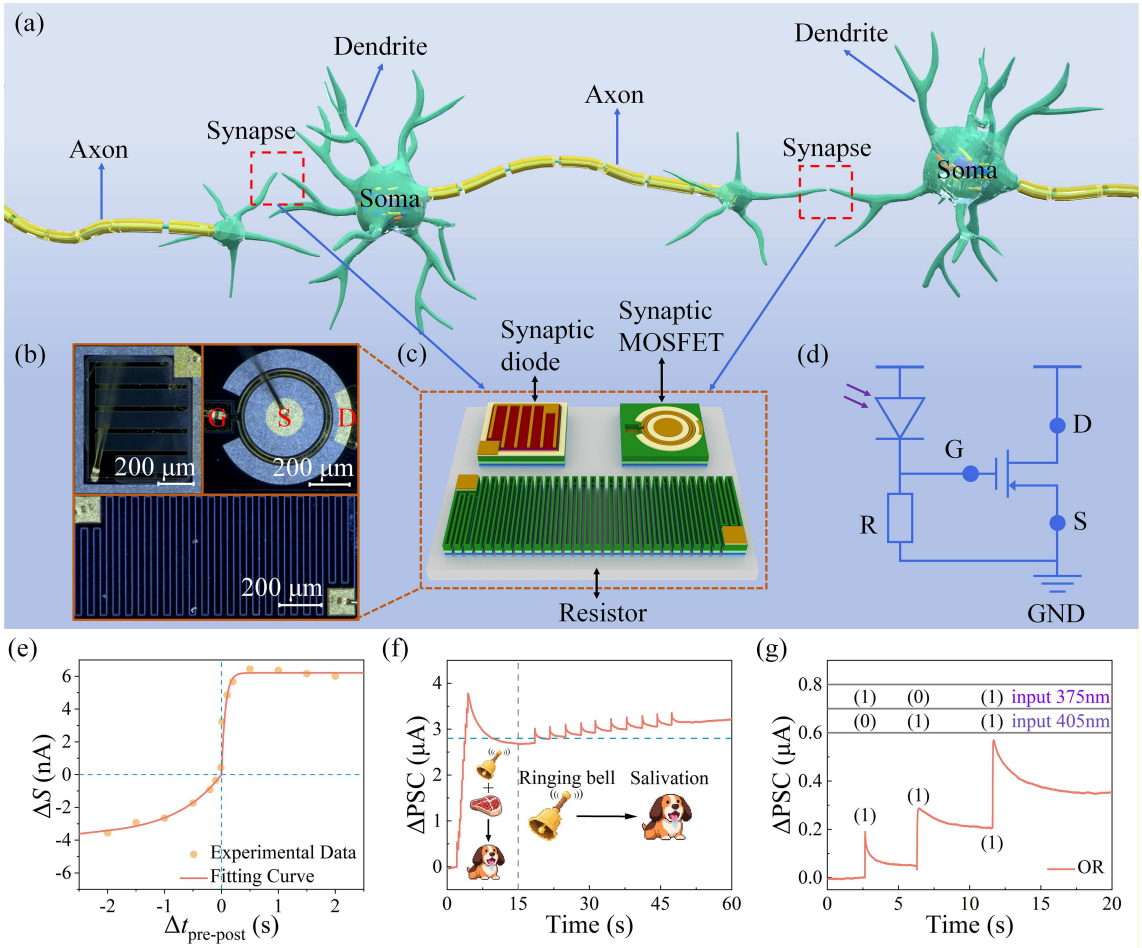


Figure 1 (Color online) (a) Synaptic connections in a biological neural system; (b) top-view optical image of the proposed devices; (c) schematic diagram of synaptic cascade structure; (d) circuit implementation of the synaptic cascade structure; (e) STDP induced synaptic weight changes (ΔS) relative to $\Delta t_{\text{pre-post}}$ changes; (f) the phenomenon resulting from the simultaneous modulation of two stimuli in Pavlov's dog experiment; (g) the logical operation of OR gate.

both the 375 and 405 nm inputs are "1", or when either input is "1", the OS output generates an EPSC, thereby implementing an OR logic function. The detailed process of neuromorphic computing based on the synaptic cascade structure is presented in Appendix C.

Conclusion. In summary, inspired by the SNS structure, we realize a GaN-based cascaded structure integrating a synaptic diode and a synaptic MOSFET, enabling brain-inspired synaptic functionalities through GaN's superior optoelectronic properties. The proposed structure demonstrates advanced neuromorphic capabilities, including STDP, Pavlovian associative learning, and logic operation. This work offers significant potential for the development of next-generation sensor-memory-processor integrated systems and large-scale neuromorphic computing chips.

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Supporting information Appendixes A–C. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

References

1 Zhu C, Liu H, Wang W, et al. Optical synaptic devices with ultra-low power consumption for neuromorphic computing. Light Sci Appl, 2022, 11: 337
2 Liu X, Wang D, Chen W, et al. Optoelectronic synapses with chemical-electric behaviors in gallium nitride semiconductors for biorealistic neuromorphic functionality. Nat Commun, 2024, 15: 7671
3 Chen M, Wei G, Yuan S, et al. Low-power plasmonic SiC nanowire network-based artificial photo-synaptic device for musical classification neural network systems. Sci China Mater, 2025, 68: 3703–3714