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Reconfigurable multi-state photonic encryption

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Abstract

A bias-switchable van der Waals phototransistor demonstrates reconfigurable transitions between photovoltaic and photoconductive modes, generating four current states within a single device. This multi-state functionality advances on-chip optical logic and image encryption. It offers a promising route towards secure, low-power, and highly integrated photonic communication systems.

Keywords: Multi-state image encryption, Van der Waals heterostructure, Mode switchable phototransistor, Optical communications, Optoelectronics

Encryption plays an important role in mobile communication networks, the Internet of things, and other modern communication systems because information security is indispensable for safely transmitting large amounts of data every day[1,2]. This imposes a higher demand on the devices in terms of both security and performance. Optical encryption has emerged as a promising strategy[3–5]. However, conventional optical-encryption technologies remain limited in terms of flexibility and adaptability at the hardware level. Silicon-based encryption devices still struggle to achieve high sensitivity[6], low power consumption[7], and dynamic encryption capability[8]. In particular, binary-state operations restrict the modulation diversity and limit the implementation of adaptive encryption schemes[9,10]. These challenges have motivated the exploration of alternative device platforms capable of multi-state operation.

Owing to their high carrier mobility and strong electrical tunability, two-dimensional van der Waals (vdW) heterostructures provide a versatile platform for advanced optoelectronic devices[11–13]. This enables the dynamic control of the photo-response. Simultaneously, weak interlayer coupling facilitates heterogeneous integration with CMOS-compatible circuits[14,15]. Band alignment engineering further allows the effective suppression of the dark current, improving both the on-off ratio and signal-to-noise performance. Because of these advantages, various modulation strategies have been explored. These strategies include gate voltage control[16], polarisation-sensitive response[17], and multi-wavelength excitation[18], as well as multi-state photodetectors based on stacked structures or interfacial engineering. However, several of these approaches rely on complex external components or multiple light sources, whereas others require a relatively high operating bias. Such requirements increase the system complexity and limit the scalability. Consequently, achieving a compact, low-power, and intrinsically reconfigurable device that supports multi-state operations and secure optical encoding remains a significant challenge.

Yu et al. have recently demonstrated a dual-mode vdW phototransistor based on a $PtTe_2/WS_2$ heterostructure[19]. The schematic of the $PtTe_2/WS_2$ vdW device is shown in Fig. 1a, in which the optical response can be reconfigured

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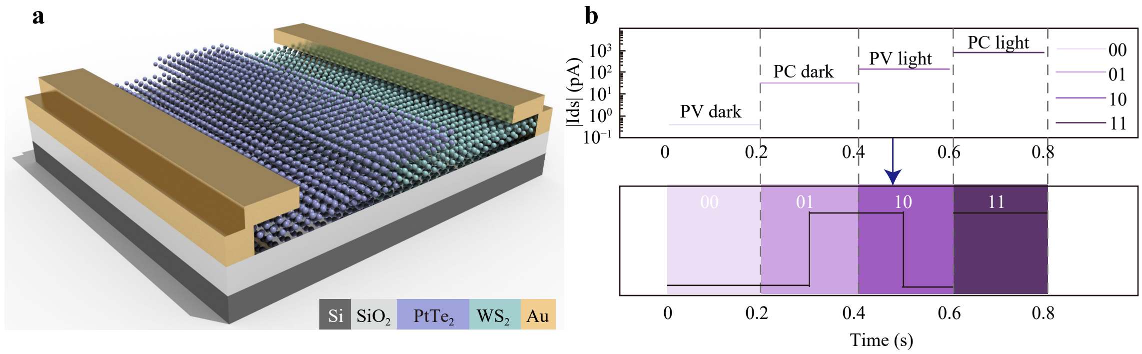

Fig. 1 a Schematic of $PtTe_2/WS_2$ dual-mode switchable vdW phototransistor. **b** Different current levels generated by dual-mode phototransistor and the corresponding quaternary numbers. "00" and "10" represent the dark and source–drain currents under light illumination in the PV mode, whereas "01" and "11" indicate the dark and source–drain currents under light illumination in the PC mode[19].

by tuning the bias. This bias-controlled operation enables the transition between the photoconductive (PC) and photovoltaic (PV) modes within a single device. In the PC regime, carrier trapping prolongs carrier lifetime and leads to a large photo-gain, yielding a responsivity of up to 1.37 $A \cdot W^{-1}$. In contrast, the PV regime is governed by a widened depletion region that suppresses dark current and promotes fast carrier separation, resulting in a high specific detectivity of 9.42×10^{14} Jones and a response time on the order of tens of microseconds (rise time ~26.3 μs, fall time ~22.6 μs). The ability to switch between these two mechanisms allows the device to combine high sensitivity and fast operation[20].

Beyond the performance metrics, a key advancement in this study lies in the generation of four current states from a single device. By using light illumination and bias polarity as independent inputs, the phototransistor moves beyond conventional binary operation and enables multi-level signal encoding with an on-off ratio approaching 10^5. As illustrated in Fig. 1b, these four states can be mapped to the binary pairs 00, 01, 10, and 11. This mechanism allows the direct translation of image information into sequences of electrical signals through controlled light modulation and bias switching. The resulting sequences can be reconfigured into encrypted outputs according to predefined rules, thereby providing a hardware-level route for multi-state image encryption. This approach highlights how simple physical inputs can be leveraged to achieve complex information-processing functionalities within a single photonic device.

This multi-state functionality enables the implementation of optical logic operations, including XNOR, XOR, and NOR, by directly linking physical inputs to logical outputs. Thus, the device bridges optoelectronic response and information processing within a unified platform. The availability of multiple current levels also improves the robustness of signal discrimination compared with conventional binary systems. Consequently, the device could perform multi-state image encryption with an average adjacent-pixel correlation coefficient as low as 0.03, demonstrating enhanced security and reduced data redundancy at the hardware level.

This study highlights a broad direction for optical encryption and integrated photonic systems. Instead of relying on external modulation schemes or complex system architectures, functional diversity can be achieved through intrinsic device physics and reconfigurable operations. The reported energy consumption at the femtojoule level further underscores the potential for low-power applications[21]. This demonstration of multi-state reconfigurable photonic encryption represents an important step towards developing more versatile, energy-efficient, and secure optical communication technologies.

Data availability

All data are available from the corresponding authors upon reasonable request.

Conflict of interest

The author declares no competing interests.

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