

Sensing-storage-computing Integration of Multiterminal ReS_2 Neuromorphic Transistors with Sequence-dependent Responses for Dual-mode Authentication Systems

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Abstract

Dynamic and rapid temporal information processing is essential for sequence-critical artificial intelligence applications. While neuromorphic devices that integrate the functions of perception, memory, and processing with intrinsic temporal dynamics have attracted widespread attention, their development remains at an early stage. Here, we report ReS₂/PZT neuromorphic transistors capable of sensing-storage-computing integration via synergistic modulation of optical stimuli and in-plane (IP) and out-of-plane (OOP) ferroelectric polarization, building a basic block for sequence-dependent intelligent systems. Electric-field-tunable ferroelectric behavior in ReS₂ is induced via proximity coupling at the heterointerface. Through tailored signal control, the device achieved charge storage functionality and flexible transformation between volatile and nonvolatile states. Reconfigurable bionic functions and logic operations were implemented within a single unit. By leveraging the sequence-dependent memory characteristics and long-term synaptic plasticity of the transistors, we integrated crypto-lock and facial recognition to construct an intelligent security system with dual-mode authentication. This work provides a promising strategy for high-density, energy-efficient neuromorphic systems, advancing the development of sequence-critical intelligent technologies.

Introduction

Artificial intelligence (AI) and Internet of Things (IoT) technologies are driving the escalating demands for electronic devices capable of real-time sensing, efficient computation, and adaptive decision-making. Integrating temporal dynamics with perception and memory is essential for achieving high-fidelity and low-latency intelligent responses. Conventional complementary metal-oxide-semiconductor (CMOS) architectures face inherent limitations of the physical separation of their sensor, memory, and computing units.¹ Consequently, the transistor count in sequential circuits grows linearly or exponentially with functional complexity. For instance, basic units like D flip-flops typically require 10 ~ 12 transistors, whereas more complex systems like 16-bit counters demand hundreds, imposing critical bottlenecks in integration and time-delay.² These challenges are further exacerbated in sequence-critical AI application scenarios, e.g., the real-time perceiving and processing of continuous input streams from dynamic environments, where rapid response and precise decision-making are paramount. Inspired by the multimodal processing capabilities of biological neural networks, sensing-storage-computing integration has emerged as a revolutionary strategy to overcome these constraints.³

Multiterminal memristors provide an intriguing platform for sensing-storage-computing integration through hybridized physical and virtual terminals, supporting nonvolatile storage and multimodal co-processing while enhancing biomimetic fidelity.^{4–11} Among the different input terminals, the electrical inputs facilitate linear synaptic tuning,^{12,13} and optical inputs provide broadband and low-latency sensory mimicry.^{14,15} Cooperative control of optical and electrical inputs further expands the dynamic tuning freedom of synaptic plasticity.^{16,17} For instance, Sijie Ma et al. achieved spatiotemporal fusion by adopting floating-gate phototransistors with reconfigurable optical and electrical plasticity.¹⁸ Hong Fang

et al. proposed an $\text{In}_2\text{O}_3\cdot\text{SnO}_2/\text{Nb: SrTiO}_3$ optoelectronic synaptic device with optical/electrical multiple control over the interfacial barrier.⁴ These neuromorphic devices successfully realized spatiotemporal synchronization of signal storage and processing, not only simulating multilevel computation functions of biological neural networks but also improving parallel processing efficiency for complex tasks.¹⁹ Nevertheless, sensing-storage-computing integrated devices capable of processing sequence-dependent signals remain underexplored, thereby impeding progress in sequence-critical intelligent systems. Sequence-dependent response means that the device conductance is determined not only by signal parameters such as pulse amplitude, width, and number,^{20–23} but also critically by the temporal order of multiterminal input signals.^{24,25} This represents a high-order information encoding, significantly expanding the modulation dimensionality, going beyond conventional history-dependent effects for encoding temporal information.²⁴

Ferroelectric materials emerge as ideal synaptic units for neuromorphic chips due to analog conductance modulation through dynamic ferroelectric domain switching.^{24,26} Existing neuromorphic devices based on bulk ferroelectrics only employed the out-of-plane (OOP) polarization to modulate the carrier concentration, leaving the in-plane (IP) polarization unexplored or unused, and thus limiting the modulation degrees of freedom.^{27–29} $\text{Pb}(\text{Zr}_{1-x}\text{Ti}_x)\text{O}_3$ (PZT) exhibits exceptional promise for in-memory computing with low coercive field, high remnant polarization,³⁰ and CMOS compatibility.³¹ Crucially, its dual polarization degrees of freedom (IP³² and OOP^{33,34}) provide orthogonal dimensions for multimodal modulation. Nevertheless, the weak conductivity and photosensitivity of PZT limit its application in optically controlled nonvolatile memory-computing systems.^{35,36} Two-dimensional (2D) materials offer a unique platform for constructing high-performance neuromorphic devices owing to their atomic thickness, tunable bandgap, and weak interlayer van der Waals forces.^{37,38} ReS_2 from the 2D transition metal dichalcogenides (TMD) family exhibits a semiconductor bandgap with enhanced light absorption, positioning it as a promising candidate for optoelectronic applications.³⁹ Especially, the vacancies in ReS_2 could not only amplify the interfacial coupling effect but also provide trapping sites for photocarriers. These functions would promote persistent photoconductivity (PPC) phenomena,^{40,41} thereby enriching the regulatory mechanisms for sensing-storage-computing integrated architectures and building a block for multimodal sequence-dependent signal processing. Meanwhile, this framework combining photosensitive 2D materials with orthogonally polarized ferroelectric substrates enables multimodal regulation, mimicking the heterogeneous synaptic integration in biological neural networks.⁴²

In this work, we demonstrated a multifunctional synaptic transistor of ReS_2 on a PZT substrate with sequence-dependent responses. The proximity coupling at the heterogeneous interface induces ferroelectric behavior in 2D ReS_2 , achieving reconfigurable sensing-storage-computing integration via tri-terminal cooperative modulation (transverse current, gate voltage, and optical excitation). The spatiotemporal encoding of multiterminal input signals enables diverse functionalities, from biomimetic applications (light adaptation, conditioned learning) to logic operations. Notably, the synaptic transistor

combines sequence-dependent storage characteristics with long-term synaptic plasticity, permitting the innovative merger of hardware-dependent crypto-locks and deep learning-based biometric recognition to develop dual-mode authentication systems. This study establishes a new design strategy for developing optoelectronic ferroelectric memory devices with advanced in-sensor computing capabilities in sequence-critical intelligent systems.

Results

Design of ferroelectric-optoelectronic neuromorphic transistor for integrated sensing-storage-computing functionality

Pursuing integrated sensing-storage-computing functionality, we designed a ReS_2 -based multiterminal neuromorphic transistor on a PZT substrate. The ReS_2 layer serves dual roles as a photoactive layer and charge transport channel. The ferroelectric oxide PZT, crystallizing in an ABO_3 -type orthorhombic structure, exhibits two polarization degrees of freedom in OOP and IP orientations. Under external electric fields, longitudinal or transverse displacement of Zr/Ti atoms can generate residual polarization fields that regulate the ReS_2 conductivity in a non-volatile manner.³⁴ Fig. 1a illustrates the design concept of the neuromorphic transistor for multifunctional integration. First, gate voltage modulates the OOP orientation of ferroelectric domains in PZT, enabling control over the carrier density in ReS_2 (Fig. 1a, left panel). A negative (positive) voltage induces downward (upward) polarization that confines positive (negative) charges at the ReS_2 /PZT interface, thereby accumulating (depleting) electrons in the channel to establish a low-resistance (high-resistance) state (LRS and HRS). This polarization-stabilized nonvolatile resistive state enables the synaptic-mimetic memory functionality. Second, transverse current tunes the IP polarization component of PZT, which in turn modifies the band alignment between the channel and electrodes (Fig. 1a, right panel). The IP polarization induces compensating electrons and holes that are separately captured at different interface regions, facilitating multilevel resistance states in ReS_2 , which emulate history-dependent synaptic weight update.⁴³ Third, photonic excitation above the bandgap energy of ReS_2 produces persistent nonvolatile photoconductivity (Fig. 1a, middle panel). The photocarriers can be trapped at defect states, exhibiting slow release kinetics impeding electron-hole recombination after optical stimuli cease and consequently producing unique optoelectronic memory effects.⁴⁴ Analogous to heterosynaptic plasticity (Fig. 1b, left panel), the multistate nonvolatile memory characteristics will support adaptive learning and network stability (Fig. 1b, right panel),³ enabling multimodal signal sensing, storage, and computation within a single device. This triple-modulation strategy furnishes a unique platform for sequence-dependent signal manipulation and is expected to incorporate contextual states into decision-making for sequence-critical AI application.

Based on the design concept, a three-terminal device was fabricated. Piezoresponse force microscopy (PFM) demonstrated the intrinsic ferroelectricity of PZT (**Fig. S1**) and also revealed a ferroelectric response in both the OOP and IP directions for the ReS₂ upon transferred on PZT substrate (Fig. 1c). This indicates an interfacial effect that produced polarization in ReS₂, which enabled nonvolatile charge trapping, thereby contributing to resistive switching memory. Control experiments of ReS₂ on SiO₂ substrate exhibited transient paraelectric response in the OOP direction and no ferroelectric response in the IP direction (Fig. 1d), further validating that the novel ferroelectric polarization in ReS₂ was exclusively induced by the PZT substrate.

Independent and collaborative regulations of gate and optical stimuli

To investigate the gating effects, interference from the IP polarization of PZT was excluded by limiting readout voltages to < 1 V (**Fig. S2a**). The window width of the ferroelectric transfer curve broadened with increasing sweeping voltage range (**Figs. S2b-c**), directly reflecting the OOP polarization characteristics and demonstrating the feasibility of synaptic weight modulation via gate voltage (V_{gs}).⁴⁵ Fig. 2 depicts the systematic exploration of the ReS₂/PZT device in emulating biological synaptic functions under electrical/optical encoding. Negative V_{gs} pulses induced excitatory postsynaptic currents (EPSCs), elevating conductance post-stimulus (Fig. 2a), whereas positive V_{gs} pulses triggered inhibitory postsynaptic currents (IPSCs), causing conductance depression. Conductance modulation intensified with increased pulse amplitude, number, width, and reduced interval (Figs. 2b-e), closely aligning with biological synaptic plasticity rules. The transition from short-term plasticity (STP) to long-term plasticity (LTP) mirrored memory consolidation through increased learning intensity, frequency, duration, and shortened review intervals.⁴⁶ Additionally, sequential V_{gs} pulses further replicated biological long-term potentiation (LTP) and long-term depression (LTD) characteristics (Fig. 2f).

Intrinsic photosensitivity of ReS₂ in the device enabled biological-like perception of environmental stimuli through wavelength-selective responses. Under 690 nm optical stimuli, the magnitude of photocurrent increased with laser power, pulse number, and duration (**Fig. S3**), yet exhibited volatility. Similar photocurrent modulation trends occurred under 532 nm excitation (Figs. 2g-i), but with a critical distinction: the current first rose sharply, then decayed slowly, and eventually saturated without recovering to baseline level within hundreds of seconds. This nonvolatile optoelectronic response originated from the fact that 532 nm photon energy (2.33 eV) exceeds the bandgap of ReS₂ (1.65 eV), enabling intraband transitions that generated abundant carriers. Conversely, 690 nm photons (1.80 eV) only induced ground-state transitions with lower carrier yield. As demonstrated, ReS₂ possesses abundant sulfur vacancies, which act as shallow and deep trap sites.⁴⁴ The deep-level traps retarded the recombination of carriers excited by the 532 nm laser, establishing a nonvolatile photocurrent.⁴⁷ This mechanism provides a foundation for light-controlled ferroelectric devices with wavelength selectivity. Through spectral programming, shorter wavelengths (e.g., 532 nm) enable nonvolatile responses for static spatial information storage, while longer wavelengths (e.g., 690 nm) produce volatile responses

suitable for dynamic spatiotemporal processing. Moreover, multiple-device measurements confirm the device-to-device reproducibility of pulse-dependent synaptic responses (**Figs. S4-5**).

Mirroring human perception through visual-tactile integration, the ReS₂/PZT device demonstrated tunable synaptic plasticity and enhanced response efficiency under synergistic optical-electrical stimulation, mitigating temporally-spatially correlated information loss in unimodal processing.¹⁸ As shown in Fig. 2j, 532 nm laser pulses induced EPSC that was further enhanced by increasing voltage amplitude under negative gating ($V_{gs} < 0$ V). Here, the negative V_{gs} induced upward polarization in PZT that directionally separated photocarriers. Holes migrated to the ReS₂/PZT interface while electrons accumulated in the ReS₂ channel, forming a low-resistance state. This spatial charge separation suppressed carrier recombination, boosting the conductance. Conversely, positive gating ($V_{gs} > 0$ V) reversed polarization downward, increasing electron trapping at the interface to suppress photocurrent and produce IPSC characteristics (Fig. 2k). Figure 2l illustrates the dynamic modulation of ferroelectric transfer curves by laser power. Increasing the power from 0.5 to 6 mW narrowed the hysteresis window due to the enhanced shielding effect of photocarriers on ferroelectric polarization. High-power irradiation generated abundant electron-hole pairs that were separated by the polarization field. The carriers migrated to the ReS₂/PZT interface to neutralize polarized charges, reducing the remanent polarization field. This process aligns with the "photo-ferroelectric coupling" model, where carriers disrupt domain wall pinning through Coulomb interactions, modulating the threshold field for polarization reversal.⁴⁸ The ReS₂/PZT neuromorphic transistor successfully emulates the synaptic dynamics under independent or collaborative optical/electrical operations, which paves the way for neuromorphic networks with multimodal signal processing capabilities.

Transverse current-regulation for memristive and memcapacitive applications

Owing to the IP ferroelectricity of PZT, the device exhibited unique memristive behavior without gate control. As shown in Fig. 3a, bidirectional V_{ds} sweeping revealed significant hysteresis loops, where both forward and backward sweeps progressively decreased the conductance from LRS to HRS. Unlike the "Fig.-eight" single-loop characteristic of traditional memristors, this "double LRS-HRS" switching originates from the back-to-back series-connected Schottky barriers produced by the two symmetric electrode configurations.⁴⁹ Within this symmetric metal-semiconductor-metal contact system, any V_{ds} polarity increases the Schottky barrier at the electrode with reverse-biased conditions, impeding carrier transport via space-charge limitation. Absence of hysteretic behavior in pure PZT and ReS₂ devices confirmed proximity-coupling-induced ferroelectric characteristics in ReS₂, expanding the generation mechanism of ferroelectricity from intrinsic crystallinity to heterointerface engineering (**Fig. S6**). Moreover, the proximity-induced polarization was critically modulated by the thickness of Ti interfacial layer, with an optimal 2 nm Ti for enhancing polarization (adopted in device fabrication, **Fig. S7**).

Figure 3 Memristive, memcapacitive behaviors and synaptic performance of the ReS₂/PZT device. **a** Bidirectional tests of the I_{ds} - V_{ds} characteristics (the solid lines indicate the progressively decreased current with the number of sweeps, while the dashed lines represent the results of subsequent tests after a reverse scan). **b** Bidirectional tests of the I_{ds} - V_{ds} characteristics with different V_{ds} sweeping ranges. **c** The I_{ds} - V_{ds} curves obtained through continuous sweeping. **d** Schematic of the four-terminal configuration (the inner electrodes measure output I_{ds} - V_{ds} characteristics under another bias applied across peripheral electrodes). **e** Corresponding I_{ds} - V_{ds} variations during peripheral bias sweeping from 0 V to 7 V (insert: magnified region of 6.2-7 V). **f** I_{ds} - V_{ds} response under reverse peripheral bias from 0 V to 65 V (insert: magnified region of 50–65 V). **g** Optical power-dependent synaptic plasticity with IP polarization (532 nm laser, 10 s irradiation duration). **h, i** Negative and positive V_{gs} amplitude-dependent synaptic plasticity with IP polarization, respectively (V_{gs} duration of 40 s). **j** Irradiation duration-dependent synaptic plasticity with IP polarization (532 nm laser, 8 mW optical power). **k, l** Negative and positive V_{gs} duration-dependent synaptic plasticity with IP polarization, respectively (V_{gs} amplitude of 10 V). All data were obtained through V_{ds} pulse testing (pulse width, interval, and amplitude of 1 s, 1 s, and 5 V, respectively, read voltage of 1 V) after the removal of optical irradiation or gate voltage.

Given that the V_{ds} polarity affects both the carrier transport direction and the IP polarization field, we designed a multiterminal architecture with functionalities of separate regulation (Fig. 3d, optical image in **Fig. S8a**). Applying constant bias across peripheral electrodes locks the polarization orientation, while inner electrodes monitor the ReS₂ channel current. As shown in Fig. 3e, when the peripheral transverse voltage increased from 0 V to 7 V, the conductance of ReS₂ showed a decay trend, demonstrating the suppression of carrier mobility by the enhanced polarization. Local magnification (insert in Fig. 3e) reveals a unique "duck-shaped" I_{ds} - V_{ds} characteristic arising from dynamic competition between carrier migration and interfacial localization during V_{ds} sweeping, producing a capacitor-like current response. This capacitive effect vanished without peripheral bias (**Fig. S8b**), confirming its origin in ferroelectricity-induced space charge rearrangement. Reverse-bias testing (0–65 V) further validated the polarization regulation on the formation of the electric double layer (Fig. 3f). The enhanced reverse fields drove the carriers in ReS₂ to accumulate at the ReS₂/electrode interface, significantly increasing charge storage density (**Figs. S8c-d**). These results suggest that the electrical reconfigurability endowed by the IP polarization enables a switching from memristive to memcapacitive state, which could not only be used for information storage but also serve as the computational core of many brain-inspired computing architectures.⁵²

Utilizing input V_{ds} pulses to emulate the stimulation from presynaptic neurons, the output signal corresponding to the postsynaptic current was recorded, which confirmed tunable inhibitory synaptic plasticity via IP polarization dynamics (**Fig. S9**). In biological neural networks, neurons employ normalization mechanisms mediated by neuromodulators to prevent unconstrained potentiation/depression of synaptic weight.⁵³ Analogously, the multimodal tunability of IPSCs/EPSCs based on IP polarization was demonstrated in this artificial neural network. Additional optical stimuli can

modulate the stepwise conductance decay induced by IP polarization accumulation, thereby effectively regulating the synaptic performance (**Fig. S10**). Figures 3g and 3j show enhanced IPSCs with elevated optical power (P) or extended irradiation duration (Δt), which is attributable to the photocarriers that redistribute internal charges, reconstruct the polarization fields, and amplify the inhibitory responses. In terms of electrical regulation, the negative gating voltage with increasing amplitude and duration enhanced the device conductivity (Figs. 3h and 3k) through Fermi level modulation, which reduced the Schottky barrier and promoted carrier injection. Conversely, positive gating suppressed conductivity by exacerbating carrier depletion (Figs. 3i and 3l), which established the bidirectional and electrical tunability of synaptic behavior.

Bionic functions and logical operation applications

Biological light adaptation constitutes photoreceptor-mediated inhibitory dynamics that prevent retinal damage under extreme luminance levels.⁵⁴ Inspired by this mechanism, the ReS₂/PZT device emulated light adaptation through optoelectronic synergy. As shown in Fig. 4a, under a low-intensity optical stimulation (532 nm, 0.5 mW, 10 s), the photocurrent remained below the threshold of 0.4 nA (red dashed line), corresponding to comfortable vision in mild light environments. Increasing the power to 2 mW elevated the photocurrent to 0.9 nA (supra-threshold), eliciting neural responses. A subsequent positive V_{gs} pulse (1 V) was applied to reduce the photocurrent below the threshold again, mimicking pupillary constriction for intense-light adaptation. This functionality arises from the combined effect of optical-carrier density modulation and electrical-interfacial barrier modulation, demonstrating the potential of ReS₂/PZT as an artificial pupil in artificial vision systems. Beyond light adaptation, associative learning constitutes a fundamental cognitive operation in biological neural systems.⁵⁵ Here, spatiotemporally correlated optical-electrical operation implemented classical Pavlovian conditioning, emulating associative learning-memory functions. As illustrated in Fig. 4b, electrical pulses (V_{gs}) served as unconditioned stimuli (food), while optical pulses (532 nm, 3 mW, 5 s) acted as conditioned stimuli (bell), with a 1.5 nA current threshold (red dashed line) representing an unconditioned response. For pretraining, single optical pulses yielded sub-threshold PSC, whereas isolated electrical pulses (-3 V, 5 s) evoked PSC to 5.4 nA (supra-threshold). For subsequent post-training, optical pulses alone triggered supra-threshold responses, demonstrating a conditioned-to-unconditioned stimulus conversion. During extinction, continuous optical pulses without electrical reinforcement gradually decayed PSC below the threshold, replicating biological forgetting and completing an associative learning-forgetting cycle.

Furthermore, the ReS₂/PZT neuromorphic transistor demonstrated significant potential for real-time logic operations (Fig. 4c). The absence and presence of optical stimuli were defined as logic input "0" and "1", respectively, while a V_{ds} of 0.5 V (low logic level) and 1.5 V (high logic level) represented independent input "0" and "1". The PSC exceeded a predefined threshold (red dashed line) and output a logic "1" only when both optical stimuli and high V_{ds} were present simultaneously, thereby implementing a Boolean AND gate function. This device enables logic operation within a single element relying on

optoelectronic co-modulation, which exhibits great potential to boost integration density and lower signal latency as well as power consumption in future optoelectronic logic systems. The introduction of V_{gs} as a selector further enabled advanced AND logic operation (Fig. 4d). At $V_{gs} = -5$ V ($EN = 0$), the device exhibited normal AND behavior under optical stimuli and V_{ds} co-regulation. In contrast, at $V_{gs} = 5$ V ($EN = 1$), a persistently high-resistance state was maintained, effectively decoupling the optical stimuli and V_{ds} inputs. Additionally, this gate-voltage programmability endowed multistate memory functionality and enabled multiterminal reconfigurability. As shown in Fig. 4e, maintaining negative V_{gs} permitted programmable multistate storage through tri-terminal synergy, facilitating letter encoding (e.g., "A" to "F") for hardware-level encrypted communication.

Functioning as a dynamic system whose output is determined by the temporal sequence of input signals, sequential circuits consist fundamentally of combinatorial modules for real-time logic operations and storage units for recording historical states. The ferroelectric/semiconductor heterostructure here allows the emulation of sequence-dependent responses through the sequential application of electrical and optical fields. Each new external stimulus was applied after the previous one was removed, with no reinitialization between transitions. By precisely controlling the input signals across the three terminals, the device achieved dynamic and nonvolatile conductance modulation, where signal sequence critically governed the output state (Fig. 4f). Cycling and environmental fluctuation tests of cases 1–6 show negligible conductance drift and performance degradation, demonstrating excellent stability, robustness, and environmental adaptability (**Figs. S11–12**). By integrating pulse-parameter modulation with multimodal sequence regulation, a novel extension of the conventional "parameter-only dependent" modulation scheme for synaptic devices can be developed. Such integration of sequential logic and memory functions within a single device offers a new strategy for constructing highly integrated and efficient sequential circuits. Meanwhile, the multiterminal neuromorphic transistor holds unique advantages for timing-sensitive intelligent systems such as neuromorphic computing and real-time adaptive processing.

Digital passwords stored in software are vulnerable to cracking or tampering, whereas temporal sequence authentication relies on the physical conductance states of transistors, offering superior security for authenticated access control. Facial recognition, on the other hand, possesses a unique advantage rooted in the non-replicability of biometric features.⁵⁶ To achieve this classification functionality, an optoelectronic synapse array and peripheral circuits were designed (Fig. 5a). Synaptic weights were updated through inner products between the input signal vectors and the synaptic matrix, with optical or electrical pulses providing feedback for weight updates.⁵⁷ The classification accuracy of a facial recognition system could be incrementally enhanced after the deep learning process. Through the integration of hardware-dependent crypto-lock and deep learning-enabled biometric recognition, an intelligent authentication system characterized by "high security, high efficiency, and high adaptability" was developed.

Figure 5b illustrates the circuit diagram of the crypto-lock module. An input interface captures user-triggered sequential signals, emulating the keystroke operations for $Q_0/Q_1/Q_2$ and converts them into device-recognizable stimuli, optical stimuli, V_{ds} , and V_{gs} , respectively. These modulated signals drive the ReS_2/PZT tri-terminal device, dynamically generating a real-time drain current (I_{out}) that reflects the input history. A comparator continuously evaluates I_{out} against the reference threshold (I_{th}): a logic high (1) triggers the unlocking actuator upon sequence matching, while a logic low (0) activates an error alert for mismatched inputs. Concurrently, a reset circuit generates positive gate pulses to rapidly restore the device conductance to its initial value, erasing all historical data and re-locking the system. Furthermore, in the event of an intermediate input error, a manual reset can be initiated via a "Reset" button, which triggers the generation of positive gate pulses to clear the existing states. Besides, a multi-cycle input protocol across the three terminals can effectively boost system security against unauthorized decryption. As evidenced in Fig. 5c, even minor variations in input sequences can yield distinguishable output responses, and formulating more input cycles significantly enhances the complexity of password combinations, thereby better addressing the demands of practical application scenarios.

To verify the learning capability of the artificial synapses and the feasibility of their application in facial recognition, we constructed a convolutional neural network (CNN) for training and inference simulations.⁵⁸ The training was conducted using the Olivetti Research Laboratory (ORL) face database, which contains 35 categories of facial images with 10 grayscale images (112×92 pixels) per category, covering different angles and expressions. The training/test sets were randomly split at a ratio of 7:3, and cross-validation was performed to avoid training–testing overlap. The input layer received a $1 \times 112 \times 92$ grayscale input, processed it by a 5×5 convolutional layer (32 channels, padding = 2), followed by ReLU activation and two rounds of 2×2 max-pooling (Fig. 5d). After flattening into a 20608-dimensional vector, the data was fed into a fully connected layer to output classification results for 35 categories. For decision-making, the highest-probability category was extracted from the model output, passing authentication if this category matches an authorized user and failing otherwise. As shown in Fig. 2f, we have realized controllable modulation of synaptic weights via electrical potentiation-electrical depression (EPED) under alternating negative and positive V_{gs} pulses. Furthermore, we also achieved weight modulation through optical potentiation-electrical depression (OPED) by utilizing 532 nm optical pulses combined with positive V_{gs} pulses (Fig. 5e, **upper panel**). After 100 training epochs, the electrical-electrical synaptic configuration reached 88.3% recognition accuracy, while that of the optical-electrical approach was further improved to 93.8% (Fig. 5e, **lower panel**). Confusion matrices corresponding to the network classification performance of synapses under both training regimes (Figs. 5f-g) show that correct classifications are all located on the diagonal, while off-diagonal entries represent misclassifications. This intuitively confirms that the CNN achieved superior recognition performance for the optical-electrical mode, verifying the excellent learning capability of the artificial synapses in neuromorphic computing. This intelligent security system adopts a complementary mode that combines physical sequential authentication and biometric facial recognition, establishing a dual-mode verification mechanism that significantly enhances robustness against spoofing, thereby elevating the security and reliability of intelligent authentication systems.

Discussion

In this work, we developed ReS₂/PZT-based neuromorphic transistors that integrate sensing-storage-computing functionalities via multiterminal modulation involving optical stimuli, IP, and OOP ferroelectric polarization. Dynamic modulation of synaptic weights through independent tuning or coupled interplay of physical signals faithfully replicated the heterosynaptic plasticity in neuromorphology. The device effectively harnessed IP polarization for charge storage and accomplished wavelength-programmable volatile/nonvolatile conductance transitions for specific application scenarios. Besides, the multiterminal transistor has demonstrated reconfigurable synaptic behaviors and executed logic operations through spatiotemporal encoding of tri-terminal inputs within a unified architecture. By leveraging the complementary scheme of physical sequential authentication and biometric facial recognition, a secure and reliable intelligent authentication system was realized using the synaptic transistors. The ferroelectric-semiconductor framework here provides new avenues for highly integrated and energy-efficient neuromorphic circuits with high-fidelity discrimination of sequence-dependent dynamic signals, delivering robust hardware support for real-time adaptive AI architectures.

Materials and methods

Material Synthesis. The ReS₂ samples used in this experiment were synthesized via CVD. A quartz boat loaded with 5 mg of ReO₃ powder was positioned in the middle of the tube furnace, and the powder was covered with molecular sieves. At one or two molecular sieves away from the end of the powder, freshly exfoliated mica sheets were placed on the upper end of the quartz boat with the confined space stacking method. A quartz boat containing 250 mg of S powder was placed at the upstream end of the tube furnace. High-flow-rate Ar gas was introduced to purge the tube furnace, after which the flow rate was set to 90 sccm for growth. The S powder zone was heated to 250°C in 35 minutes and held for 30 minutes. Simultaneously, the ReO₃ zone was heated to 650°C in 30 minutes and held for 10 minutes, followed by natural cooling for both zones to room temperature. The PZT thin film was prepared on a Pt/SiO₂/Si substrate by the sol-gel method. The precursor sol was formulated from lead nitrate, zirconium nitrate, and tetrabutyl titanate in ethylene glycol monomethyl ether, with the molar ratio of Pb: Zr: Ti adjusted to 1.1: 0.52: 0.48. After stirring at 60°C and aging at room temperature, the sol was spin-coated on the cleaned substrate surface. Following stepwise pre-baking and annealing at 650°C in an oxygen atmosphere, the process was repeated to obtain a PZT thin film with a thickness of approximately 2 μm.

Device Fabrication and Measurements. The ReS₂ film was first detached from the mica substrate using polymethyl methacrylate (PMMA) spin-coating and hydrofluoric acid (HF) etching. It was then transferred onto a PZT/Pt/SiO₂ substrate in deionized water. After removing the PMMA by soaking in acetone, the film was annealed in an Ar atmosphere at 180°C for 2 hours. A standard electron beam lithography technique (Sigma300 + ELPHY Quantum) was employed to define electrical contact pads on the ReS₂ using a 950 K PMMA resist, creating a channel width of 1 μm. Subsequently, Ti/Au (2/50 nm)

electrodes were deposited via electron beam evaporation (DE Technology DE400), followed by a lift-off process. A 150 nm-thick Pt layer was employed as the bottom-gate electrode of the device. Electrical characterizations were performed at ambient conditions utilizing a Keysight B1505A semiconductor parameter analyzer connected to a probe station. The voltage pulses were generated by an Agilent B2901A voltage source.

Declarations

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

1. Wang, Y. F. et al. Boolean logic computing based on neuromorphic transistor. *Adv Funct Mater.* 33, 2305791 (2023).
2. Marthi, P. et al. Design and analysis of high performance ballistic nanodevice-based sequential circuits using monte carlo and verilog AMS simulations. *IEEE Trans Circuits Syst I Regul Pap.* 63, 2236 (2016).
3. Wang, S. B. et al. Memristor-based intelligent human-like neural computing. *Adv Electron Mater.* 9, 2200877 (2023).
4. Fang, H. et al. Multimodal in-sensor computing implemented by easily-fabricated oxide-heterojunction optoelectronic synapses. *Adv Funct Mater.* 34, 2409045 (2024).
5. Feng, X. W. et al. Self-selective multi-terminal memtransistor crossbar array for in-memory computing. *ACS Nano.* 15, 1764 (2021).
6. Kim, D. et al. PZT ferroelectric synapse TFT with multi-level of conductance state for neuromorphic applications. *IEEE Access.* 9, 140975 (2021).
7. Nguyen, D. A. et al. Electrically and optically controllable p-n junction memtransistor based on an Al₂O₃ encapsulated 2D Te/ReS₂ van der Waals Heterostructure. *Small Methods.* 5, 2101303 (2021).
8. Ranganathan, K., Fiegenbaum-Raz, M., Ismach, A. Large-scale and robust multifunctional vertically aligned MoS₂ photo-memristors. *Adv Funct Mater.* 30, 2005718 (2020).
9. Soliman, M. et al. Photoferroelectric all-van-der-Waals heterostructure for multimode neuromorphic ferroelectric transistors. *ACS Appl Mater.* 15, 15732 (2023).

10. Wang, X. W. et al. Van der Waals engineering of ferroelectric heterostructures for long-retention memory. *Nat Commun.* 12, 1109 (2021).
11. Zhou, J. C. et al. Multimodal 2D ferroelectric transistor with integrated perception-and-computing-in-memory functions for reservoir computing. *Nano Lett.* 24, 14892 (2024).
12. Kwon, K. C. et al. In-plane ferroelectric Tin Monosulfide and its application in a ferroelectric analog synaptic device. *ACS Nano.* 14, 7628 (2020).
13. Wang, Y. N. et al. A gate-tunable artificial synapse based on vertically assembled van der Waals ferroelectric heterojunction. *Journal of Materials Science & Technology.* 128, 239 (2022).
14. Xie, D. D. et al. Porous metal-organic framework/ReS₂ heterojunction phototransistor for polarization-sensitive visual adaptation emulation. *Adv Mater.* 35, 2212118 (2023).
15. Yang, H. Y. et al. Near-infrared optical synapses based on multilayer MoSe₂ moire superlattice for artificial retina. *Adv Funct Mater.* 34, 2308149 (2024).
16. Das, B. et al. Artificial visual systems fabricated with ferroelectric van der Waals heterostructure for in-memory computing applications. *ACS Nano.* 17, 21297 (2023).
17. Mukherjee, S., Dutta, D., Ghosh, A., Koren, E. Graphene-In₂Se₃ van der Waals heterojunction neuristor for optical in-memory bimodal operation. *ACS Nano.* 17, 22287 (2023).
18. Ma, S. J. et al. Bioinspired in-sensor multimodal fusion for enhanced spatial and spatiotemporal association. *Nano Lett.* 24, 7091 (2024).
19. Leng, Y. B. et al. Recent progress in multiterminal memristors for neuromorphic applications. *Adv Electron Mater.* 9, 2300108 (2023).
20. Deng, Y. et al. Intrinsic defect-driven synergistic synaptic heterostructures for gate-free neuromorphic phototransistors. *Adv Mater.* 36, 2309940 (2024).
21. Guo, Z. Q. et al. High-performance neuromorphic computing and logic operation based on a self-assembled vertically aligned nanocomposite SrTiO₃:MgO film memristor. *ACS Nano.* 17, 21518 (2023).
22. Huh, W. et al. Synaptic barristor based on phase-engineered 2D heterostructures. *Adv Mater.* 30, 1801447 (2018).
23. Liu, Y. Q. et al. CuInP₂S₆-based electronic/optoelectronic synapse for artificial visual system application. *Adv Funct Mater.* 34, 2306945 (2024).
24. Cao, Y. et al. Physical reservoir computing using van der Waals ferroelectrics for acoustic keyword spotting. *ACS Nano.* 18, 23265 (2024).
25. Peng, J. et al. A self-powered polarization-sensitive neuromorphic vision device enabled by laser-induced symmetry engineering. *ACS Nano.* 20, 5146 (2026).
26. Liu, Z. R. et al. In-plane charged domain walls with memristive behaviour in a ferroelectric film. *Nature.* 613, 656 (2023).
27. Jiang, Y. R. et al. Asymmetric ferroelectric-gated two-dimensional transistor integrating self-rectifying photoelectric memory and artificial synapse. *ACS Nano.* 16, 11218 (2022).

28. Meng, G. D. et al. Polarizable nonvolatile ferroelectric gating in monolayer MoS₂ phototransistors. *ACS Appl Mater Interfaces*. 16, 10316 (2024).
29. Song, C. M., Kim, D., Lee, S. B., Kwon, H. J. Ferroelectric 2D SnS₂ analog synaptic FET. *Adv Sci*. 11, 2308588 (2024).
30. Besleaga, C. et al. Ferroelectric field effect transistors based on PZT and IGZO. *J-EDS*. 7, 268 (2019).
31. Xie, Y. J. et al. PZT photonic materials and devices platform. *J Semicond*. 45, 120501 (2024).
32. Qiu, X. X. et al. In-plane polarization-triggered WS₂-ferroelectric heterostructured synaptic devices. *ACS Appl Mater Interfaces*. 17, 7027 (2025).
33. Lipatov, A., Sharma, P., Gruverman, A., Sinitskii, A. Optoelectrical molybdenum disulfide (MoS₂)-ferroelectric memories. *ACS Nano*. 9, 8089 (2015).
34. Wang, L. H. et al. The domain and domain wall structure of Pt/PZT/Pt ferroelectric thin film. *Acta Physica Sinica*. 55, 2590 (2006).
35. Ganapathi, K. L., Rath, M., Rao, M. S. R. Polarization induced switching in PZT back gated multilayer MoS₂ FETs for low power non-volatile memory. *Semicond Sci Tec*. 34, 055016 (2019).
36. Ko, C. et al. Ferroelectrically gated atomically thin transition-metal dichalcogenides as nonvolatile memory. *Adv Mater*. 28, 2923 (2016).
37. Huh, W., Lee, D., Lee, C. H. Memristors based on 2D materials as an artificial synapse for neuromorphic electronics. *Adv Mater*. 32, 2002092 (2020).
38. Wang, M. et al. Robust memristors based on layered two-dimensional materials. *Nat Electron*. 1, 130 (2018).
39. Chen, Y. J. et al. Wrinkled rhenium disulfide for anisotropic nonvolatile memory and multiple artificial neuromorphic synapses. *ACS Nano*. 18, 30871 (2024).
40. Chen, Y. B. et al. Energy-efficient ReS₂-based optoelectronic synapse for 3D object reconstruction and recognition. *ACS Appl Mater*. 15, 58631 (2023).
41. Dang, Z. Y. et al. Ferroelectric modulation of ReS₂-based multifunctional optoelectronic neuromorphic devices for wavelength-selective artificial visual system. *Adv Funct Mater*. 34, 2400105 (2024).
42. Huh, W. et al. Synaptic barristor based on phase-engineered 2D heterostructures. *Adv Mater*. 30, 1801447 (2018).
43. Cai, Y. C. et al. Molecular ferroelectric/semiconductor interfacial memristors for artificial synapses. *Npj Flexible Electronics*. 6, 16 (2022).
44. Jung, K. H. et al. Polyvinylalcohol (PVA)-assisted exfoliation of ReS₂ nanosheets and the use of ReS₂-PVA composites for transparent memristive photosynapse devices. *ACS Appl Mater Interfaces*. 13, 8919 (2021).
45. Lu, H. Y., Wang, Y., Han, X. C., Liu, J. An ultrafast multibit memory based on the ReS₂/h-BN/Graphene heterostructure. *ACS Nano*. 18, 23403 (2024).

46. Qu, S. D. et al. An artificially-intelligent cornea with tactile sensation enables sensory expansion and interaction. *Nat Commun.* 14, 7181 (2023).
47. Huang, F. H. et al. Controllable resistive switching in ReS₂/WS₂ heterostructure for nonvolatile memory and synaptic simulation. *Adv Sci.* 10, 2302813 (2023).
48. Xue, F. et al. Optoelectronic ferroelectric domain-wall memories made from a single van der Waals ferroelectric. *Adv Funct Mater.* 30, 2004206 (2020).
49. Wang, L. et al. Exploring ferroelectric switching in α -In₂Se₃ for neuromorphic computing. *Adv Funct Mater.* 30, 2004609 (2020).
50. Chen, L. et al. Unlocking the electro-optic potential of ferroelectrics: advanced domain and phase manipulation. *J Adv Ceram.* 14, 9221180 (2025).
51. Xue, F. et al. Gate-tunable and multidirection-switchable memristive phenomena in a van der Waals ferroelectric. *Adv Mater.* 31, 1901300 (2019).
52. Bessonov, A. A. et al. Layered memristive and memcapacitive switches for printable electronics. *Nat Mater.* 14, 199 (2015).
53. Zhou, Z., He, G., Zhang, X., Lv, X., Jia, Z. NGPF2 triggers synaptic scaling up through ALK-LIMK-cofilin-mediated mechanisms. *Cell Reports.* 36, 109515 (2021).
54. Liu, Y. Q. et al. CuInP₂S₆-based electronic/optoelectronic synapse for artificial visual system application. *Adv Funct Mater.* 34, 2306945 (2024).
55. Dong, L. Y. et al. Highly promising 2D/1D BP-C/CNT bionic opto-olfactory co-sensory artificial synapses for multisensory integration. *Adv Sci.* 11, 2403665 (2024).
56. Niu, J. Z., Fang, Z. L., Liu, G. J., Zhao, Z., Yan, X. B. Multilevel state ferroelectric La:HfO₂-based memristors and their implementations in associative learning circuit and face recognition. *Sci China Mater.* 66, 1148 (2023).
57. Chen, Y. N. et al. Revolutionizing neuromorphic computing with memristor-based artificial neurons. *J Semicond.* 46, 061301 (2025).
58. Debnath, T. et al. Four-layer ConvNet to facial emotion recognition with minimal epochs and the significance of data diversity. *Sci Rep.* 12, 6991 (2022).

Figures

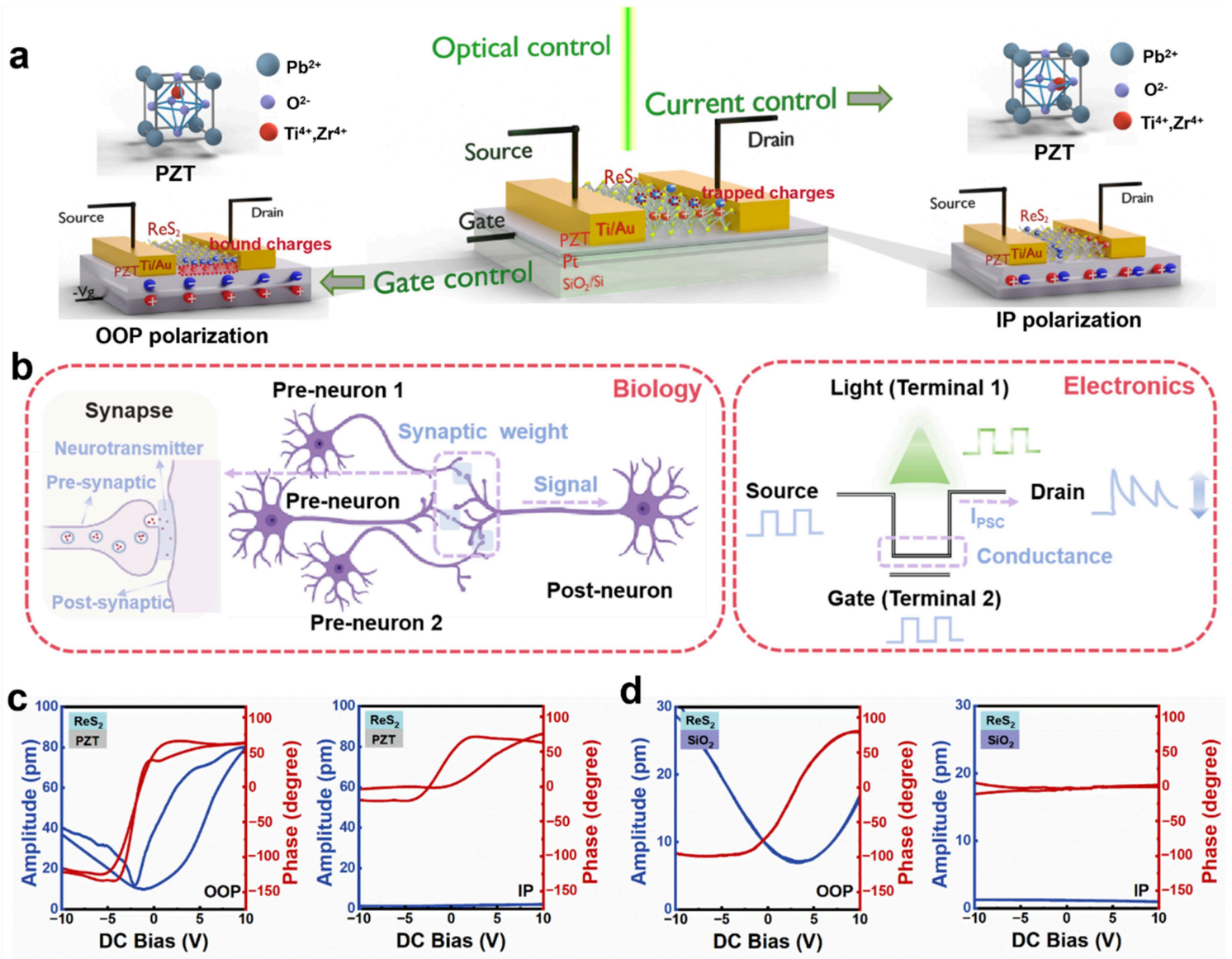


Figure 1

Design of the multimodal neuromorphic transistor based on ReS_2/PZT heterostructure. **a** Schematic of the multiterminal neuromorphic transistor enabling nonvolatile conductance modulation through gate, current, and optical modulations. **b** Comparison of the operational paradigms between the biological neural system (left panel) and the multiterminal neuromorphic transistor (right panel). **c** OOP/IP PFM responses of the ReS_2 on SiO_2 substrate. **d** OOP/IP PFM responses of the ReS_2 on PZT substrate.

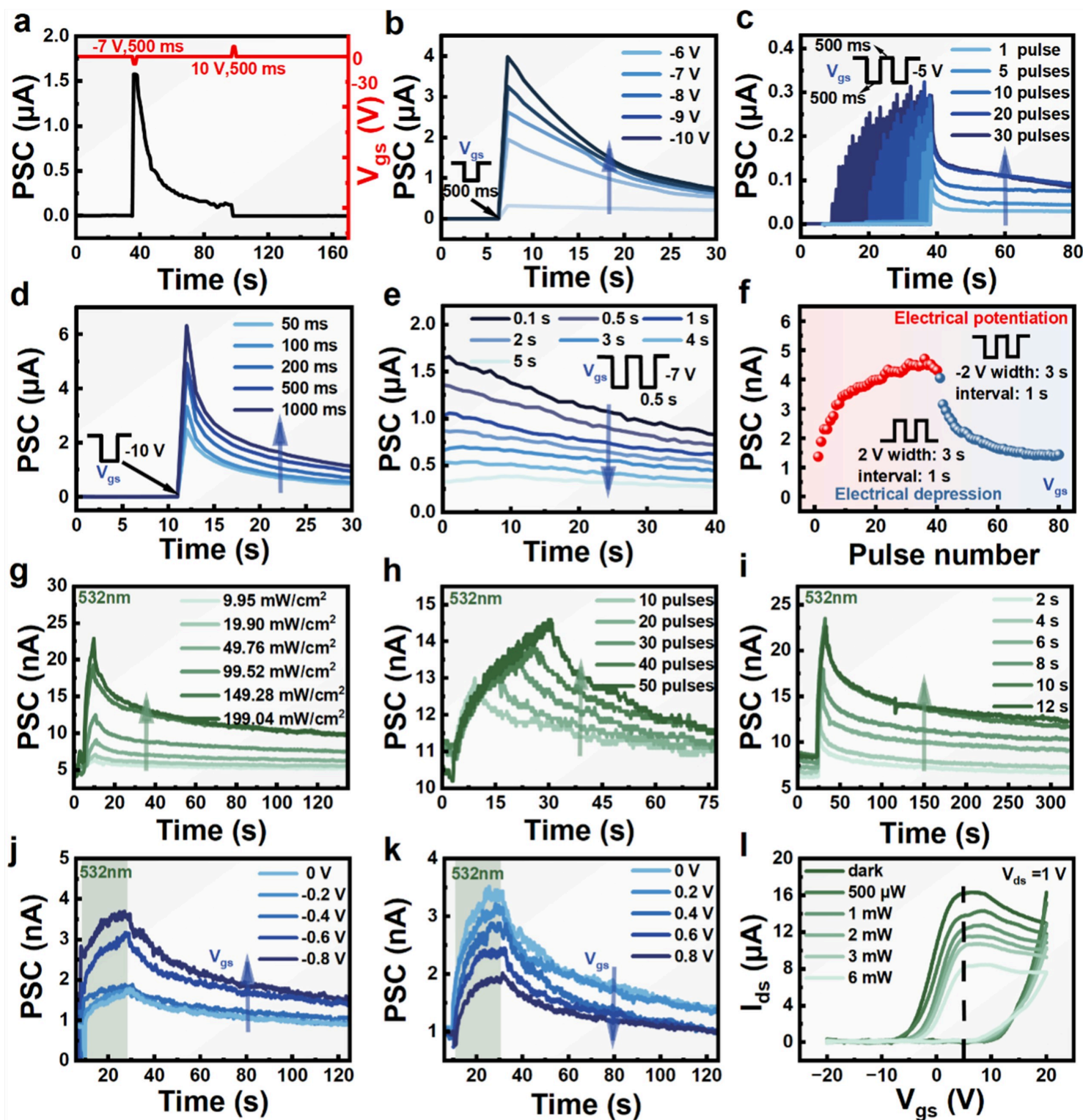


Figure 2

Independent and collaborative modulations of synaptic weights by electrical and optical signals. **a** Gate regulation of synaptic performance. **b** PSC response dependent on V_{gs} pulse amplitude (pulse width = 500 ms). **c** PSC response dependent on V_{gs} pulse number ($V_{gs} = -5$ V, pulse width/interval = 500 ms). **d** PSC response dependent on V_{gs} pulse width ($V_{gs} = -10$ V). **e** PSC response dependent on V_{gs} pulse interval ($V_{gs} = -7$ V, pulse width = 500 ms). **f** Dynamic current changes under V_{gs} pulse stimulation (40 interval ($V_{gs} = -7$ V, pulse width = 500 ms).

continuous negative and positive pulses). **g-i** PSC responses dependent on laser pulse power, pulse number, and duration under 532 nm optical stimuli, respectively. The readout voltage for all tests was 0.5 V. **j, k** Optical (532 nm, 1 mW, 20 s) synaptic plasticity under negative and positive gate regulations, respectively. **l** Modulation on transfer curves with various laser powers at $V_{ds} = 1$ V.

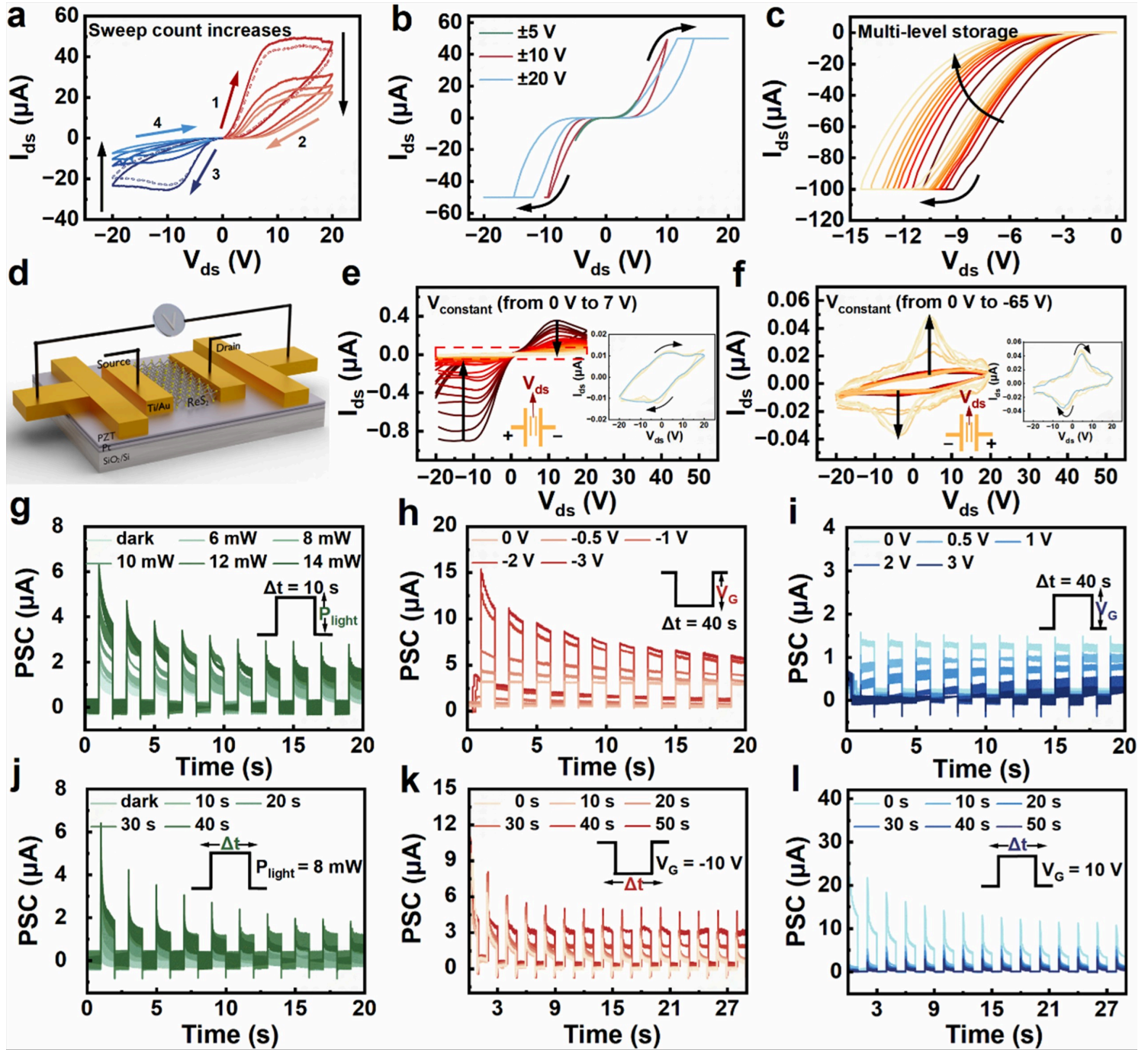


Figure 3

Memristive, memcapacitive behaviors and synaptic performance of the ReS₂/PZT device. **a**

Bidirectional tests of the I_{ds} - V_{ds} characteristics (the solid lines indicate the progressively decreased current with the number of sweeps, while the dashed lines represent the results of subsequent tests after a reverse scan). **b** Bidirectional tests of the I_{ds} - V_{ds} characteristics with different V_{ds} sweeping

ranges. **c** The I_{ds} - V_{ds} curves obtained through continuous sweeping. **d** Schematic of the four-terminal configuration (the inner electrodes measure output I_{ds} - V_{ds} characteristics under another bias applied across peripheral electrodes). **e** Corresponding I_{ds} - V_{ds} variations during peripheral bias sweeping from 0 V to 7 V (insert: magnified region of 6.2-7 V). **f** I_{ds} - V_{ds} response under reverse peripheral bias from 0 V to 65 V (insert: magnified region of 50-65 V). **g** Optical power-dependent synaptic plasticity with IP polarization (532 nm laser, 10 s irradiation duration). **h, i** Negative and positive V_{gs} amplitude-dependent synaptic plasticity with IP polarization, respectively (V_{gs} duration of 40 s). **j** Irradiation duration-dependent synaptic plasticity with IP polarization (532 nm laser, 8 mW optical power). **k, l** Negative and positive V_{gs} duration-dependent synaptic plasticity with IP polarization, respectively (V_{gs} amplitude of 10 V). All data were obtained through V_{ds} pulse testing (pulse width, interval, and amplitude of 1 s, 1 s, and 5 V, respectively, read voltage of 1 V) after the removal of optical irradiation or gate voltage.

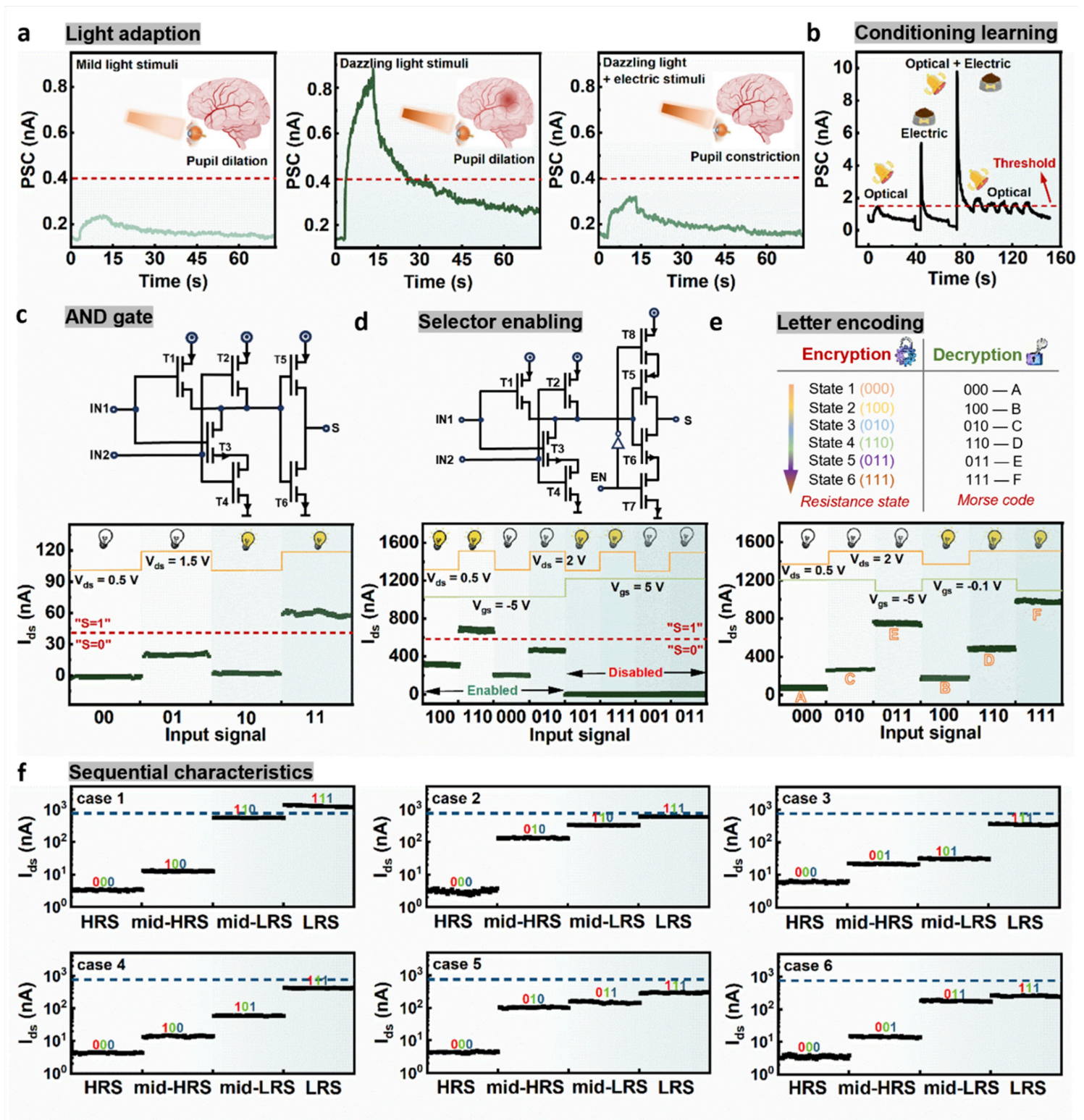


Figure 4

Bionic functions and logical operations of the ReS₂/PZT neuromorphic transistor. **a** Emulation of light adaptation of the human visual system at 532 nm optical stimuli. **b** Emulation of the Pavlovian conditioning experiments (optical pulse: conditioned stimulus, electrical pulse: unconditioned stimulus). **c** AND gate operation based on optical stimuli and V_{ds} regulation (the values above the red dashed line represent a high logic level). **d** Selector-enabled AND gate operation (optical stimuli, V_{ds} , and V_{gs}

regulation). **e** Letter encoding through the synergistic regulation of optical stimuli, V_{ds} , and V_{gs} . **f** Sequential characteristics dependent on the sequence of successive external field application, with no initialization performed during this process (logical state definition: "0": no optical stimuli, $V_{ds} = 2\text{ V}$, $V_{gs} = 0\text{ V}$; "1": 5 mW, 532 nm optical stimuli, $V_{ds} = 10\text{ V}$, $V_{gs} = -5\text{ V}$).

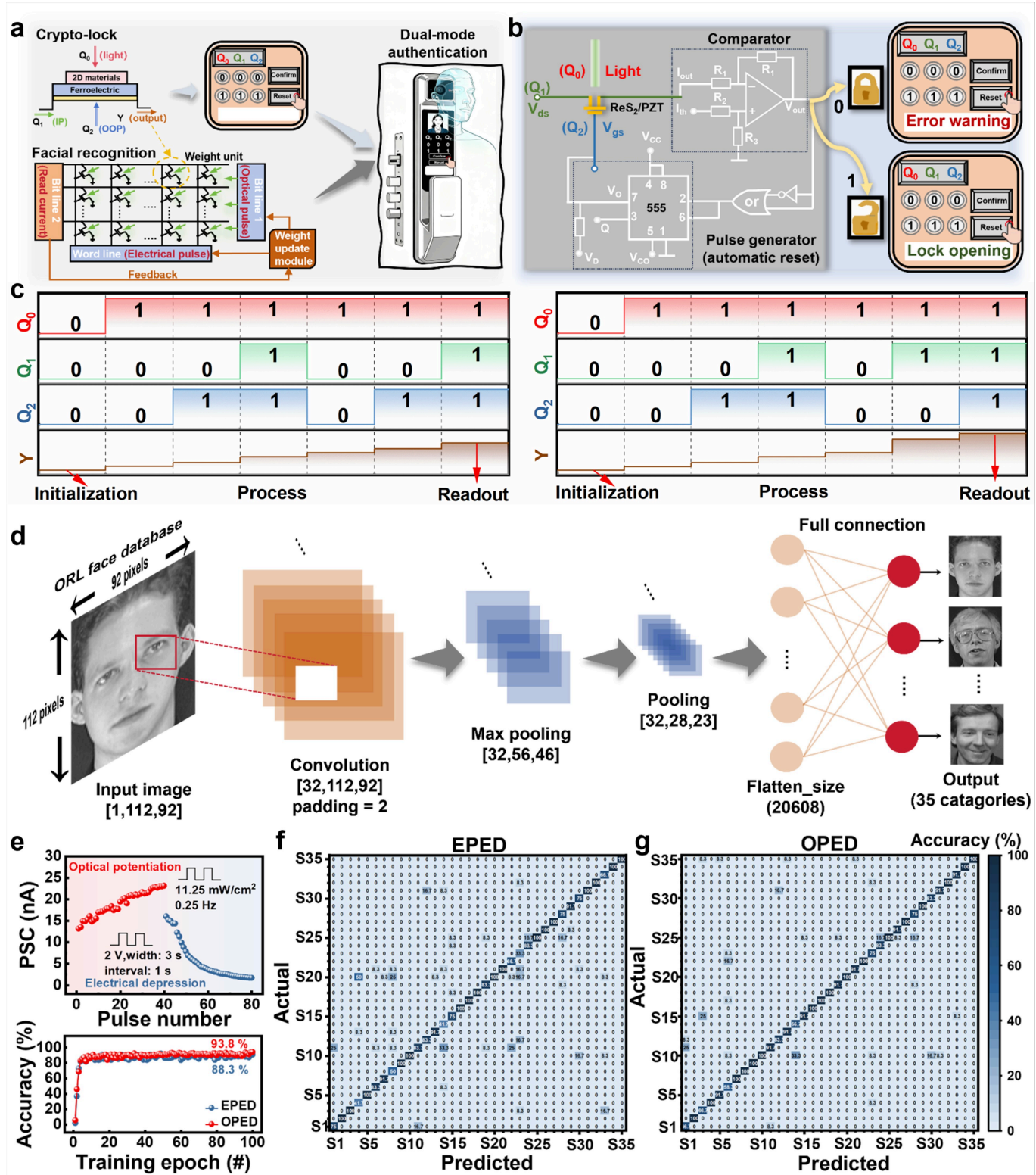


Figure 5

ReS₂/PZT-based intelligent authentication system integrating the crypto-lock and facial recognition functions. **a** Design concept of the intelligent authentication system. **b** Circuit diagram of the crypto-lock module. **c** Cases of preventing password cracking by complicating the input sequence. **d** The structure of a CNN used for facial recognition. **e** LTP/LTD characteristic curves of the synaptic device triggered by consecutive 40 potentiation pulses (532 nm, 11.25 mW/cm²) and depression pulses (V_{gs} of 2 V) (upper panel); recognition rate as a function of the epoch obtained from the electrical-electrical and optical-electrical training (lower panel). **f, g** Confusion matrix showing the comparison between actual and predicted images after electrical-electrical and optical-electrical training, respectively.

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