Gate-Tunable Synaptic Organic–Inorganic Hybrid Phototransistors Enabling Optoelectronic Memory and Neuromorphic Functionality

Ahasan Ullah[a], Roshell Lamug[b], Xueqiao Zhang[a], Oksana Ostroverkhova[b], Li-Jing Cheng*[a]

[a] School of Electrical Engineering and Computer Science, Oregon State University, 1148 Kelley Engineering Center, Corvallis, OR, USA; [b] Dept. of Physics, Oregon State University, 103 SW Memorial Pl., Corvallis, OR, USA 97331

ABSTRACT

We present an organic–inorganic hybrid phototransistor that emulates tunable synaptic behaviors through optically induced, gate-controlled memory retention. The device integrates a tetracene-based photoactive polymer with an IGZO thin-film transistor to form a heterojunction. Upon illumination, photogenerated electrons transfer into the IGZO channel while holes become trapped in the organic layer, inducing a persistent photogating effect that modulates channel conductance, mimicking synaptic weight adaptation. The applied gate voltage regulates the spatial distribution and release of trapped charges in the organic layer, enabling dynamic synaptic responses under subthreshold biases and stable memory states at negative gate voltages. This mechanism yields high photosensitivity (<5 μW/cm^2) and high linearity under repeated optical stimulation. Demonstrated applications include ultralow-light imaging down to 0.5 μW/cm^2, long-term memory retention (> 1000 s), optical trajectory mapping, and synaptic weight modulation with over 90% accuracy in image recognition tasks. This device demonstrates a promising building block for next-generation neuromorphic optoelectronic systems.

Keywords: Neuromorphic phototransistor, organic-inorganic heterojunction, photo-memory

1. INTRODUCTION

Neuromorphic computing aims to emulate biological synapses by integrating sensing, memory, and adaptive signal processing within individual devices, thereby reducing data-transfer overhead and energy consumption [1]. Optoelectronic synaptic devices are particularly attractive because optical stimuli provide contactless, low-noise programming, while electrical terminals enable deterministic control of retention and erasure. Organic–inorganic hybrid phototransistors offer a promising materials platform by combining strong optical absorption and charge-trapping behavior in organic semiconductors with the high mobility and stability of metal-oxide thin-film transistors (TFTs).

Here, we report an organic–inorganic hybrid phototransistor that emulates synaptic behavior through optically triggered, gate-tunable memory retention. The device integrates a photoactive tetracene-based polymer layer with an indium gallium zinc oxide (IGZO) TFT to form a type-II heterojunction. Under illumination, photogenerated electrons transfer into the IGZO channel, while holes are captured in deep trap states within the organic layer. These long-lived trapped holes induce a persistent photogating effect that modulates channel conductance even after the illumination is removed, analogous to synaptic weight adaptation in biological systems. In related hybrid heterojunction phototransistors using other organic materials, similar photogating arises but decays rapidly due to the absence of deep, long-lived trap states, yielding negligible memory behavior [2].

Comprehensive modeling and experiments reveal a deep-trap-dominated mechanism governing charge trapping, spatial redistribution, and release. The device supports multiple operational modes: under subthreshold gate bias, it functions as a dynamic synapse with history-dependent conductance modulation, while negative pulsed gate bias enables long-term, programmable retention. In contrast, positive gate bias accelerates charge release and redistribution, inducing rapid forgetting. Acting as an artificial neuromodulator [3], the gate bias polarity therefore controls potentiation, retention, and erasure by regulating the photogating efficiency of trapped charges (Figure 1a).

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* chengli@oregonstate.edu

Quantum Sensing and Nano Electronics and Photonics XXII, edited by Manijeh Razeghi, Giti A. Khodaparast,
Miriam S. Vitiello, Proc. of SPIE Vol. 13908, 1390808 · 2026 Published by SPIE
0277-786X · doi: 10.1117/12.3084068

The phototransistor operates under ultralow optical power densities (<5 μW cm^{-2}) and exhibits highly linear conductance updates under repeated optical stimulation, making it well-suited for energy-efficient neuromorphic computing. Its intrinsic wavelength-dependent response enables tunable potentiation step sizes. Leveraging these properties, we demonstrate high-contrast ultralow-light detection, memory retention exceeding 1000 s, spatiotemporal encoding via light trajectory tracking, and analog synaptic weight modulation, achieving over 90% accuracy in pattern-recognition tasks. Together, these results establish the hybrid phototransistor as a compact and versatile building block for neuromorphic optoelectronic and in-memory computing systems.

2. RESULTS AND DISCUSSIONS

Heterojunction Phototransistor Operating Principle

The synaptic phototransistor consists of a bottom-gate IGZO thin-film transistor overlaid with a blended TIPS-Tc:PMMA photoactive layer. The incorporation of PMMA improves film uniformity and mechanical stability while preserving the optical and trapping characteristics of TIPS-Tc. A type-II band alignment at the organic–inorganic interface promotes efficient exciton dissociation: photogenerated electrons are energetically favored to transfer into the IGZO channel, whereas holes remain confined within the TIPS-Tc layer and are captured by localized trap states.

Under weak green illumination (535 nm, <10 μW cm^{-2}), this charge separation induces a negative shift in the threshold voltage and an increase in drain current through a photogating mechanism. The trapped holes act as a quasi-static positive gate bias, electrostatically enhancing electron accumulation in the IGZO channel. Notably, after the light is turned off, a substantial fraction of these holes remains trapped, sustaining an elevated channel conductance for extended periods (Figure 1b). This persistent photogating forms the physical basis of synaptic memory in the device.

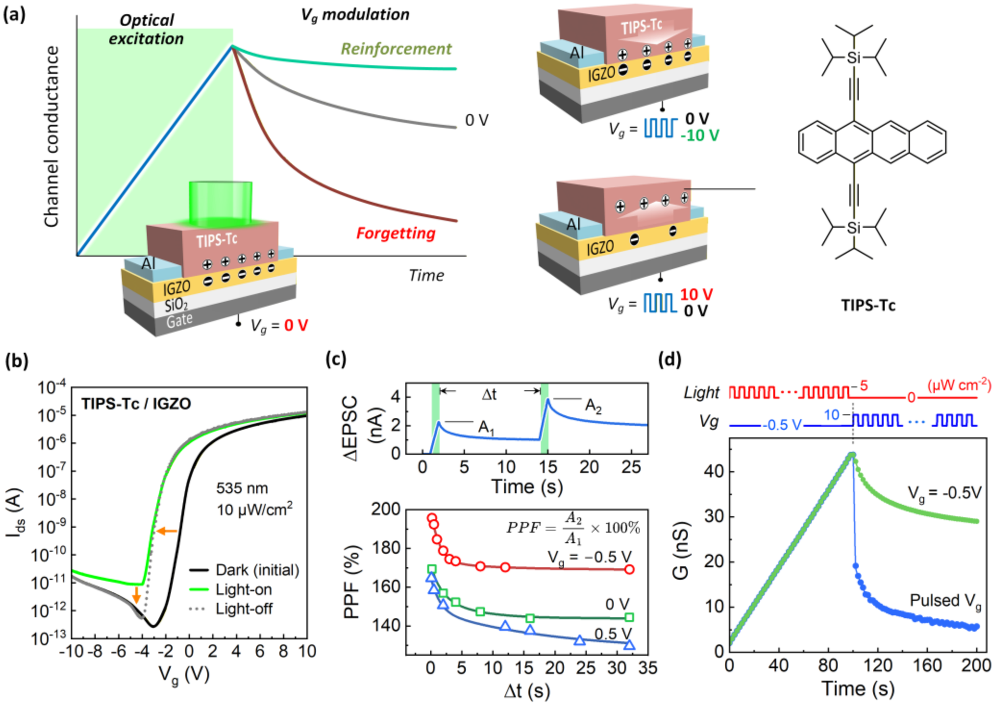


Figure 1 (a) Neuromodulatory analogy in the TIPS-Tc/IGZO phototransistor: optical pulses generate trapped holes that photogate the channel (potentiation), negative gate pulses stabilize the trapped charge (memory reinforcement), and positive gate pulses promote detrapping (reset/forgetting). (b) Transfer characteristics in dark and under illumination. (c) Paired 1-s optical pulses with inter-pulse interval Δt at Vg = –0.5 V and Vds = 1 V, with PPF index versus Δt showing gate-bias-dependent short-term plasticity. (d) Synaptic plasticity via optical LTP and electrical LTD under pulsed or constant gate biases.

Short-term synaptic plasticity naturally arises from the distribution of trap depths within the TIPS-Tc layer. The post-illumination drain current, measured at a constant gate voltage and interpreted as an excitatory post-synaptic current (ΔEPSC), exhibits a bi-exponential decay profile. The fast component is attributed to rapid release from shallow tail states, while the slow component originates from relaxation of holes stored in deeper mid-gap traps, consistent with prior reports on organic–inorganic hybrid photogating systems [4] (Figure 1c).

When two optical pulses are applied in close succession, residual trapped holes from the first pulse enhance the photogating field during the second, leading to an amplified ΔEPSC response. This paired-pulse facilitation behavior closely parallels biological synapses, where residual calcium ions modulate neurotransmitter release. The paired-pulse facilitation (PPF) index decreases monotonically with increasing interpulse interval as trapped charge gradually decays, directly linking the device response to its optical stimulation history.

Gate-Tunable Synaptic Behaviors

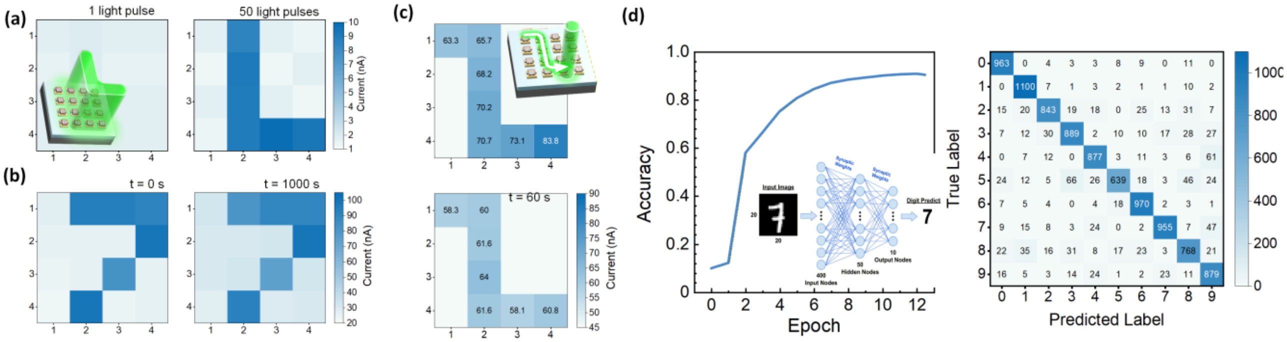
Beyond optical excitation, the gate bias plays a central role in regulating synaptic retention and erasure. Negative gate voltage stabilizes the photogated state and significantly prolongs memory retention, whereas positive gate voltage accelerates conductance decay and induces rapid forgetting (Figure 1d). This polarity-dependent behavior originates from the gate-controlled redistribution of trapped holes within the TIPS-Tc layer.

Under negative gate bias, holes are electrostatically drawn toward the TIPS-Tc/IGZO interface, where trap density is highest and capacitive coupling to the channel is strongest. This configuration increases trap occupancy and maximizes the photogating field acting on the IGZO channel, thereby reinforcing synaptic potentiation. In contrast, positive gate bias pushes holes away from the interface and deeper into the organic bulk, where active trap density is reduced and field-assisted emission mechanisms, such as Poole–Frenkel detrapping, become more prominent. As a result, retrapping is suppressed, and the photogating effect rapidly weakens.

By simultaneously modulating both trapping and detrapping processes, enhanced capture near the interface versus accelerated release away from it, the gate electrode provides a physically grounded mechanism for synaptic potentiation and depression. Negative gate bias enables memory consolidation, while positive gate bias allows active, programmable forgetting, closely mirroring neuromodulatory control in biological neural circuits.

Applications of In-Sensor Memory and Neuromorphic Computing

The intrinsic integration of photodetection and charge storage in the TIPS-Tc/IGZO phototransistor enables in-sensor memory and computation without the need for external storage elements. In a reconstructed pixel array, illumination at an ultralow intensity of 0.5 μW cm^{-2} produces negligible contrast following a single optical pulse. However, repeated weak pulses progressively accumulate trapped charge, resulting in a high-contrast image that persists after illumination ceases (Figure 2a). This behavior highlights the ability of the device to integrate optical events over time.



True Label \ Predicted Label	0	1	2	3	4	5	6	7	8	9
0	963	0	4	3	3	8	9	0	11	0
1	0	1100	7	1	3	2	1	1	10	2
2	15	20	843	19	18	0	25	13	31	7
3	7	12	30	889	2	10	10	17	28	27
4	0	7	12	0	877	3	11	3	6	61
5	24	12	5	66	26	639	18	3	46	24
6	7	5	4	0	4	18	970	2	3	1
7	9	15	8	3	24	0	2	955	7	47
8	22	35	16	31	8	17	23	3	768	21
9	16	5	3	14	24	1	2	23	11	879

Figure 2. Functional demonstrations enabled by optically induced, gate-tunable memory in the hybrid phototransistor: (a) ultralow-light detection with in-sensor charge accumulation, (b) long-term conductance retention reinforced by negative gate bias, (c) beam-trajectory tracking through spatiotemporal conductance encoding, and (d) artificial neural network (ANN) inference using differential synaptic weights for MNIST classification.

Periodic application of negative gate pulses refreshes interfacial traps and stabilizes channel conductance, extending image retention beyond 1000 s (Figure 2b). The same temporal persistence enables trajectory tracking: as a scanning beam moves sequentially across the pixel array, each pixel encodes both the intensity and recency of illumination. The resulting spatial conductance gradient reveals the direction of motion even after the stimulus is removed, demonstrating spatiotemporal encoding within a single device layer (Figure 1c). Such functionality represents a compact hardware primitive for motion inference in event-based vision systems.

In addition to sensory processing, the device supports analog synaptic weight storage with high linearity and low nonlinearity over hundreds of optical programming pulses. Using differential-pair synapses, a hardware-realistic neural network was trained on the MNIST dataset, with conductance evolution described by a compact empirical update model. The dominance of deep traps suppresses premature saturation, enabling medium-resolution optical programming (535 nm, 0.25 s pulses) and achieving classification accuracy exceeding 90% (Figure 2d). After training, negative gate operation locks the device into a stable memory mode, allowing both learning and inference to be performed on the same optoelectronic platform.

3. CONCLUSION

We have demonstrated a neuromodulator-inspired hybrid optoelectronic synapse based on a TIPS-Tc/IGZO phototransistor, in which long-lived trapped holes generate persistent photogating under ultralow optical power. Gate bias provides dynamic control over retention and relaxation, enabling programmable potentiation and forgetting within a single device. The resulting platform supports weak-light imaging, trajectory tracking, and near-linear synaptic weight updates, underscoring its potential for compact, low-energy, in-sensor neuromorphic processors that unify sensing, memory, and computation.

ACKNOWLEDGEMENTS

The authors thank Prof. J. Anthony for the TIPS-Tc derivatives and Rick Presley and Chris Tasker for their assistance with the RF sputtering and thermal evaporation tools. This work was supported in part by the National Science Foundation (NSF) (CHE-1956431 to O.O). Part of this research was conducted at the Northwest Nanotechnology Infrastructure, a National Nanotechnology Coordinated Infrastructure (NNCI) site at Oregon State University, supported in part by NSF grant NNCI-2025489 and Oregon State University.

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