

Analysis of the Operating Mechanism of Optoelectronic Synaptic Devices: From Materials to Device

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Abstract. Optoelectronic synaptic devices have garnered significant attention for their potential in neuromorphic computing, offering a pathway to overcome the limitations of von Neumann architectures by enabling parallel processing, low power consumption, and integrated sensing-memory-processing functionalities. These devices emulate biological synapses through mechanisms such as light-induced charge trapping/detrapping and light-driven ion migration, which support synaptic plasticity and non-volatile memory. However, performance limitations persist due to dependencies on device architecture and material properties. This article provides a comprehensive analysis of how different structural configurations—including two-terminal and three-terminal designs—along with various material systems, such as silicon-based semiconductors, two-dimensional materials, perovskites, organic polymers, and MXene-based composites, critically influence operational characteristics like responsivity, switching speed, energy efficiency, and environmental stability. By reviewing recent advances in heterojunction engineering and ion-gated transistors, this study underscores the importance of optimizing both material selection and device geometry to achieve high-performance, biomimetic optoelectronic synapses suitable for next-generation visual and cognitive computing applications.

Keywords: Optoelectronic synaptic; Materials; Mechanism.

1. Introduction

In the current era of rapid technological advancement, traditional Von Neumann computing architectures are constrained by limited processing speed and high energy consumption, thus proving inadequate to meet the growing computational demands of the future. Inspired by the innate information-processing mechanisms of the human brain, neuromorphic computing systems have emerged as a promising alternative. The neural network of the brain, a naturally evolved information-processing structure, exhibits remarkable energy efficiency and fault tolerance, along with capabilities such as parallel processing, reconfigurability, low power consumption, and the execution of complex functions including image recognition and self-learning [1]. Based on this principle, optoelectronic neuromorphic devices represent a new generation of computing applications aimed at advancing image recognition and real-time processing. Their core objective is to shift processing control from centralized data centers to edge devices, enabling direct information preprocessing and storage at the hardware level to significantly reduce overall energy consumption. These devices can recognize complex images across various electromagnetic wavelengths and convert optical signals into biological signals (i.e., electrical signals) for subsequent processing. Therefore, optoelectronic neuromorphic devices have the potential to act as critical signal reception units in bionic processors and artificial synapses.

Opto-neural morphological devices are not merely simple components; they constitute integrated systems. The fundamental building block of such devices is the photoresistor memory cell, also termed the photonic synapse. Photonic synapses exhibit high bandwidth, low crosstalk, and low power consumption, whilst responding instantaneously to optical signals. Within the human brain, visual neurons release bioelectric signals to modulate synaptic weights, thereby enabling functions such as learning and visual information storage. Correspondingly, within photonic synapses—or

photonic neuromorphic devices—adjusting various parameters of the optical input signal modulates the electrical signals within the device. This simulates authentic biological current regulation, ultimately enabling visual signal perception, information processing, and data storage. Consequently, advancements in photonic synapse devices hold significant importance for the successful realization of photonic neuromorphic devices.

Su et al. conducted a visualization analysis of the keywords from literature on optoelectronic synapses since 2010, revealing that current research hotspots primarily focus on synaptic plasticity, device design, memory functionality, and neuro-inspired applications [2]. In optoelectronic synapses, the effectiveness of a synapse is typically evaluated and validated through the postsynaptic current (PSC). Under optical stimulation, as long as the device can generate a stable PSC, it indicates that the device is functional and can proceed to further testing. In the performance characterization of optoelectronic synapses, synaptic plasticity serves as the foundation for various complex learning, cognitive, and memory functions; thus, research on the modulation of plasticity in optoelectronic synapses is of great significance. Synaptic plasticity is divided into short-term plasticity (STP) and long-term plasticity (LTP). STP influences information filtering, encoding, and transmission in neural signaling, while memory and learning are achieved through LTP [3]. This paper subsequently describes the fundamental operating principles of optoelectronic devices and provides a brief introduction and comparison of multiple opto-synaptic variants and their respective performances.

2. Principles of Optoelectronic Synaptic Device

2.1. Fundamental Principles of Optoelectronic Devices

The photoelectric effect forms the theoretical basis for photonic synapses: the photoelectric effect refers to the phenomenon whereby electrons are emitted from a material's surface when exposed to sufficiently high-frequency electromagnetic radiation [4]. This occurs because high-frequency electromagnetic radiation possesses substantial energy; upon reaching the material's surface, this energy is absorbed by surface electrons. When the absorbed energy exceeds the material's work function, it is divided into two components: one part overcomes the work function, enabling the electron to escape its original atomic confinement; the other part is converted into kinetic energy, propelling the electron away from its initial position. When light strikes a material's surface, the photons themselves carry energy. Thus, if the conditions for electron emission are met—namely, the photon's energy surpasses the material's work function—electrons will be emitted. Under sustained illumination, a continuous current is generated at the material's surface. This constitutes the fundamental principle whereby photonic synapses produce electrical signals in response to light. However, the conventional photoelectric effect relies entirely on light input; once the light stimulus is removed, the photonic information vanishes, precluding computational and memory functions between synapses. Consequently, photonic synapses themselves employ additional operational mechanisms.

Unlike the photoelectric effect, which relies on active materials, photonic synapses exhibit the persistent photocurrent (PPC) phenomenon. Even after light exposure ceases, changes in resistance or potential persist, enabling the storage of various resistive states and thereby exhibiting distinct synaptic characteristics [5]. Different mechanisms operate in different material types, yet all simulate biological synaptic functional behaviour by modulating the internal resistance of the device through controlling the transport and recombination of photo-generated carriers. These will be introduced separately below.

The prevailing operating mechanism in phototransistors utilizing conventional semiconductors and two-dimensional materials is the photo-induced charge capture/decapture mechanism. During the operation and testing of synapses, a light pulse is first directed onto the device's channel or gate dielectric layer, generating electron-hole pairs. This is followed by the separation and capture of the photogenerated carriers (electrons or holes). Under the influence of an intrinsic electric field or

external bias, electrons and holes separate. One carrier type (typically electrons) is captured by defect states or trap states within the material or at interfaces. The trapped charge then acts as an additional gate electric field, continuously modulating the carrier concentration within the channel. This alters the source-drain current (i.e., the synaptic weight), constituting conductance modulation. Finally, the trapped charge requires a certain period to escape the trap via thermal excitation or recombination. The duration of charge retention corresponds to the persistence time of the synaptic weight, thereby enabling the simulation of transitions from short-term plasticity (STP) to long-term plasticity (LTP). This composite mechanism achieves the bionic effect of photonic synapses. At present, owing to the excellent compatibility of the photo-induced charge capture/de-capture mechanism with existing semiconductor processes, most research has been conducted on the basis of this mechanism for in-depth composite investigations.

Beyond the aforementioned mechanisms, the operational principle of photonic synapses within composite materials comprising ion gels/electrolytes and semiconductors involves light-driven ion migration. Similar to light-induced charge capture/de-capture mechanisms, the process commences with a light pulse generating electron-hole pairs within the semiconductor channel. Upon the generation of sufficient electron-hole pairs, a photogenerated electric field forms between the materials. At this point, the photo-induced electric field or thermal effects drive ions (e.g., H^+ , O^{2-} , Li^+) within the electrolyte (such as ion gels or solid-state electrolytes) to migrate towards the semiconductor channel interface. Ions migrating to the channel surface electrochemically dope the channel material, significantly and non-volatily altering its conductivity. This process resembles the opening and closing of ion channels in biological synapses. Finally, once migration is complete, ions remain in their new positions without reverse stimulation (e.g., counter-light pulses or electric fields) due to the high energy barrier of ion migration, thereby achieving non-volatile long-term memory (LTP). Furthermore, reversible doping and undoping can be achieved by controlling light pulses, enabling device reuse. Compared to light-induced charge capture/decapture mechanisms, the light-driven ion migration mechanism more closely mimics the ionic dynamics of biological synapses. It directly achieves non-volatile storage without requiring the transition from STP to LTP, exhibiting a higher degree of biomimetic fidelity. This represents a current research frontier for realizing high-performance neuromorphic computing and integrated sensory functions.

Both light-induced charge trapping/detrapping mechanisms and light-driven ion migration mechanisms are commonly studied in photonic synapses. Their commonality lies in their capacity to store light signals, akin to 'memory' in bionics. However, due to variations in selected materials or device structures, different photonic synapses exhibit distinct characteristics in terms of carrier mobility, light response range, and environmental sensitivity. The following sections will introduce the functions and structures of various photonic synapses.

2.2. Determining Factors of Optoelectronic Synaptic Performance

2.2.1. Influence of Device Structure on the Performance of Optoelectronic Synapses

Generally speaking, the design of synaptic devices is based on existing device architectures, encompassing both dual-terminal and triple-terminal configurations. Specifically, dual-terminal devices are categorised into planar and vertical structures according to the relative positioning of the source and drain terminals: planar structures feature the source and drain on the same plane, while vertical structures position them at the top and bottom of the device, respectively. Ye et al. [6] developed a fully optically modulated direct artificial synapse device utilising tin selenide thin films. Under illumination with 430 nm and 255 nm light, this device can achieve various forms of synaptic plasticity and realise reversible conductance modulation. Bipolar devices feature simple structures, compact unit dimensions, and high energy efficiency, making them suitable for large-scale integration. However, their functionality is relatively limited, making it challenging to independently realise excitatory postsynaptic currents (EPSCs) and inhibitory postsynaptic currents (IPSC) within the same device. Although circuit design can circumvent this limitation, it inherently lacks the natural flexibility of three-terminal devices. The structure of a three-terminal device is based on a field-effect

transistor, comprising source/drain and gate electrodes, an insulating gate dielectric layer, and a semiconductor channel layer [7]. By applying a voltage to the gate, an electric field controls the current flow between source and drain. In three-terminal devices, the source and drain are typically coplanar. Within the transistor architecture of three-terminal devices, representative structures include bottom-gate transistors, floating-gate transistors, and ionic liquid-gated transistors [8]. Taking the ionic liquid-gated transistor as an example, the selection and preparation of the dielectric layer are critical. A liquid ionic electrolyte gate is progressively introduced into the device, wherein the electrolyte is deposited into the gap between the channel and gate electrodes. Jiang et al. employed drop-coated poly(vinyl alcohol) (PVA) electrolyte to modulate the MoS₂ channel. Whilst devices based on liquid ionic electrolyte gates can emulate a range of neuromorphic behaviours, the flowing electrolyte represents the most significant constraint for integrating such devices into circuits. Consequently, solid-state ionic electrolytes manufactured by immobilising ionic liquids within polymers have demonstrated potential in artificial synapse devices. Within solid-state ionic electrolytes, an electrolyte double layer (EDL) can form, exhibiting gate effects and low-voltage operation characteristics [9]. Sun et al. proposed a SnO₂ nanowire solar-blind photonic synapse transistor triggered by 275 nm laser. An ion gel comprising poly(vinylidene difluoride-co-hexafluoropropylene) [P(VDF-HFP)] and 1-ethyl-3-methylimidazolium bis(trifluoromethanesulfonyl)imide [(EMIM)(TFSI)] was employed as the planar gate. The combination of the EDL effect and charge trapping within the ionic gel enables diverse neural functions under both electrical and optical stimulation [10]. Thus, compared to two-terminal devices, three-terminal devices offer richer functionality and enhanced biomimetic properties. Furthermore, the inherent signal amplification within the transistor renders them more sensitive to weak optical signals. However, due to their inherent complexity, three-terminal structures require larger unit areas and are unsuitable for ultra-high integration scales.

2.2.2. Influence of Material Types on the Performance of Optoelectronic Synapses

Beyond the device structure, the choice of materials employed is also pivotal in determining device performance. Materials used for fabricating photonic synapses primarily comprise traditional inorganic semiconductors and emerging semiconductor materials. The photonic synapses fabricated from these two categories of materials will be introduced in turn.

First are traditional inorganic semiconductor materials. In photonic synapses, these primarily manifest as silicon-based materials and compound semiconductors (III–V group elements, metal oxides). Silicon-based materials are compatible with existing processes and readily integrated. However, silicon is an indirect bandgap semiconductor with relatively low light absorption efficiency, and its response wavelength is primarily confined to the visible spectrum, hence current research is comparatively limited. Materials with high electron mobility and direct bandgaps exhibit superior photoconductive efficiency and rapid response speeds. Lee et al. demonstrated an AlN artificial photonic synapse device, proving that the crystalline quality of wide bandgap synapses determines their synaptic properties. Their research indicates that photonic synapses with higher crystallinity exhibit superior optical neural plasticity. In high-crystallinity wide bandgap (WBG) synapses, the effective multi-level states, dynamic range, and linearity that facilitate artificial synaptic weight updating can enhance training, improve robustness, and reduce power consumption in artificial neural networks [11]. Nevertheless, the drawbacks of III–V group semiconductors lie in their prohibitively high fabrication costs and difficulties in integration with silicon processes.

Emerging semiconductor materials for photonic synapses include: two-dimensional materials and their stacked heterojunctions, perovskite materials (halide perovskites, oxide perovskites), organic semiconductors, and polymeric materials. Each material possesses distinct advantages and disadvantages. Among these, two-dimensional materials offer near-atomic thickness, exceptionally high photosensitivity, significant photocurrent on/off ratios, outstanding optical gain, extremely rapid response times, and minimal dark current. Graphene, for instance, exhibits high carrier mobility, superior thermal conductivity, exceptional optical transparency, and robust thermal stability. As graphene is a zero-bandgap material, intrinsic graphene exhibits semimetallic properties. Yu et al.

utilized a heterostructure composed of graphene and MoS₂ to fabricate a mechanical photonic artificial synapse, achieving long-term memory and continuous neural facilitation through the synergistic action of mechanical displacement and spatiotemporal light pulses [12]. Another two-dimensional material, TMD (transition metal dichalcogenide), possesses large and tunable bandgaps. Its photovoltaic tunability, flexibility, and atomically smooth surfaces render it suitable for high integration density and scalability, enabling rapid switching and reduced power consumption. Furthermore, its exceptional optical transparency and pliability make it ideal for fabricating flexible transparent devices. Chai et al. utilized large-area bilayer MoS₂ films to fabricate insect-like visual synapse arrays. These effectively respond to ultrafast optical stimuli through energy-level defects and interfacial carrier trapping [13]. To modulate the photoresponse of MoS₂ channels, various device architectures, bandgap modulation techniques, and insulating layers can be combined. Lin et al. fabricated dual-ended CeO₂/MoS₂ heterostructure optoelectronic channels, realizing a multifunctional artificial visual system integrating charge storage, light sensing, memory, and visual perception [14]. Perovskite materials are renowned for their exceptional performance in optoelectronic applications, characterized by efficient light absorption, prolonged carrier lifetime, extensive diffusion length, high charge carrier mobility, and relatively low exciton binding energy. In a study by Kim et al., Dion-Jacobson-type two-dimensional perovskites were utilized to achieve highly linear and symmetric conductance modulation. A fabricated 7×7 array showed excellent production yield and low device-to-device variation. Capitalizing on the environmental stability of 2D DJ-phase perovskites, the structure also demonstrated remarkable moisture resistance that persisted for over seven months [15]. Meanwhile, organic semiconductors and polymer-based systems have attracted significant interest due to their mechanical flexibility, adjustable electronic properties, and compatibility with solution-based processing techniques. For instance, Huang et al. developed a photonic synapse exhibiting nonlinear decay behavior using a photoactive polymer semiconductor (p-NDI), which is known for effective exciton dissociation and space-charge-limited transport [16]. This device allows integrated sensing, storage, and preprocessing of optical signals. Aside from these dominant material families, composite functional systems—such as quantum dot hybrids and MXenes—are also gaining attention. Huang and coworkers designed a retina-inspired photonic synaptic transistor with broadband response, incorporating a wide-spectrum photoactive charge-trapping layer and a heterojunction composed of PbS quantum dots (PbS QDs) and an organic semiconductor [17]. The resulting neuromorphic vision array successfully emulates combined image sensing, memory, and preprocessing operations. MXenes, an emerging class of two-dimensional inorganic compounds, have sparked widespread research interest owing to their high electrical conductivity, substantial specific surface area, and diverse surface chemistry. In particular, their layered morphology and abundant functional groups contribute to broad-wavelength light absorption and extended carrier lifetimes. Moreover, narrow bandgap properties further promote the efficient movement of photo-induced charge carriers. Chai's team employed MXene/VP van der Waals heterostructures to construct opto-synaptic devices for cross-modal visual-olfactory perception. This device achieved synaptic behaviour solely through optical pulses and responded to varying humidity and gas conditions, a phenomenon strongly correlated with MXenes hydrophilicity and abundant surface functional groups [18]. The heterojunction structure, previously mentioned in the preceding example, is engineered by meticulously arranging interface band structures to confine charge carriers within selected layers. This not only facilitates electron-hole pair separation but also suppresses their recombination. Xie et al. engineered van der Waals P3HT/GaAs nanowire PN junctions by precisely guiding organic molecular alignment, enabling multifaceted avian-inspired visual enhancement. This encompasses broadband non-volatile storage, low-light sensing, and near-zero-power operation in both single devices and 5 × 5 arrays on arbitrary substrates [19].

3. Conclusion

In summary, the advancement of photonic synapse devices represents a pivotal step forward in the field of neuromorphic computing, offering a promising pathway to overcome the limitations of traditional von Neumann architectures. These devices emulate biological synaptic functions through

mechanisms such as light-induced charge capture/release and light-driven ion migration, thereby enabling non-volatile storage, plasticity control, and low-power operation. The performance of photonic synapses is profoundly influenced by device architecture and material selection. Structurally, dual-terminal devices offer advantages in integration density and energy efficiency, whilst triple-terminal devices provide enhanced functionality and biomimetic fidelity. Regarding materials, traditional inorganic semiconductors (such as silicon and III-V compounds) offer process compatibility and high mobility, whereas emerging materials (including two-dimensional materials, perovskites, organic semiconductors, and MXenes) provide tunable optoelectronic properties, flexibility, and novel heterostructure functionality. Given the extensive range of materials available and the potential for combinatorial exploration across diverse materials, research into photonic synapses will continue to advance, aiming to achieve devices with superior performance.

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