Recent Advancements in Graphene Heterojunction Optoelectronic Devices, from Photodetection to Neuromorphic Computing

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Abstract. Graphene heterojunctions are new heterostructures with high transmittance, high carrier mobility, and effective separation of photogenerated carriers. This review is devoted to the mechanisms of interfacial charge transfer, trapping, and release, with a particular focus on their effect on photodetection and optoelectronic computing. To do this, these devices use photovoltaic, internal photoemission, and tunneling effects to get responsivity (R) and detectivity (D*) significantly higher than conventional detectors can provide. Graphene heterojunctions create memristive states in optoelectronic computing through nanostructuring. The mechanism behind it depends on the fact that carbon sp2 -sp3 hybridization is reversibly modulated by an applied external electric field, which works at small bias voltages (< 1 V). Such a low-voltage reversible hybrid control does not just provide the device with low-power computing features, but also allows the creation of biocompatible information systems. Graphene heterojunctions make possible the construction of artificial neural systems and have extensive future applications in various spheres of application, including consumer electronics.

Keywords: Graphene heterojunction; photoelectric detection; optical storage; optoelectronic computing; artificial neural vision system.

1. Introduction

Optoelectronic devices, such as organic phototransistors, photodetectors, and OLEDs, are widely used in daily life. As key components for photoelectric conversion, they are essential for detection and display applications [1]. Yet, as the bar for stability and efficiency is raised ever higher, traditional materials face limitations. Graphene has demonstrated remarkable advantages in related applications with its excellent electronic and mechanical properties. The integration of graphene into heterojunctions is not merely an incremental upgrade; it allows researchers to simultaneously tailor macroscopic performance while tackling microscopic efficiency bottlenecks that plague traditional designs.

In spite of such a promise, there is still a fragmented landscape in the existing review literature. There are very few works that treat both photodetection and brain-inspired computing as isolated silos, with an emphasis on a single functionality, rather than a holistic approach to the two functionalities, starting with the material basis through to the device. This review fills this gap by looking at the material basis of graphene heterojunctions as well as their use in photodetection, optical storage, and optoelectronic computing. It provides a complete view of how structural engineering evolves into device application and system integration and summarizes key developments in graphene-based optoelectronics.

2. Graphene Heterojunction Structure

Graphene has attracted significant attention in the field of optoelectronic devices because it has ultra-high carrier mobility, wide spectral absorption, high thermal conductivity, and good mechanical strength. However, Yao et al. pointed out that zero bandgap of graphene will cause low switching ratio, and its high transmittance (with a light absorption rate of only 2.3%), results in low light

photoresponsivity under normal illumination, which limits its practical applications [2]. To address this issue, the construction of graphene heterojunctions in combination with other photosensitive materials (such as transition metal dichalcogenides (TMDs), black phosphorus, quantum dots, etc.) can effectively solve these problems [2].

The graphene heterojunction, a structure formed by stacking graphene with other two-dimensional materials. By constructing a heterojunction photosensitive layer, the light absorption rate can be increased to absorb more photons and generate more excitons. Attributed to the high mobility of graphene, the force of the built-in electric field at the interface, and the special band alignment, it facilitates rapid exciton separation. Conversely, although interface defects are generally considered harmful to optoelectronic devices, Fu et al. pointed out through research, if it can make rational use of charge capture on the interface, defects can also have the ability to prolong carrier lifetime [3].

The charge transfer, capture, and release mechanisms at the interface directly determine the responsivity and response speed in photoelectric detection. This also determines the retention characteristics of optical storage, and the synaptic plasticity of neuromorphic devices, serving as the physical foundation connecting light perception and computing.

3. Photodetectors at the Sensing Level

A photodetector is a device that converts optical signals into electrical signals. Because graphene has a band gap-free band structure, its spectral response range is wider than that of traditional optoelectronic materials, covering a wide frequency band from visible light to mid- and far-infrared light. However, monolayer graphene has a low light absorption rate. High-performance detection cannot be achieved by relying solely on graphene itself; its photoelectric properties need to be modulated through structural design. To solve this problem, graphene is usually combined with other photosensitive semiconductors as a photogenerated carrier collection electrode or charge transport channel to form a heterojunction. The core mechanism for achieving high performance of graphene-semiconductor hybrid photodetectors lies in the photovoltaic effect, internal photoelectron emission effect, tunneling effect, photoconductive effect and optical gating effect, which enables the device to achieve responsivity (R) and detectivity (D*) far exceeding those of traditional detectors [4].

In terms of device performance, Stefan et al. proposed that graphene photodetectors have an electro-optic bandwidth of over 500 GHz, a spectral width range of over 200 nm, and can be adapted to a variety of center wavelengths from <1400 nm to >4200 nm [5]. The realization of a stacked metamaterial perfect absorber device allows achieving the resonance increase. The method will not only raise the intensity of the local optical field but also form efficient electrical contacts and produce pn doping that is useful in the swift extraction and isolation of charge carriers.

Nowadays, the detectors with graphene/quantum dot heterojunctions have experienced an important breakthrough in terms of their performance. Their responsivity is as high as 10 9 A/W and their detectivity as high as 10^{13} Jones, which is a combination of the advantages of wide-band spectral response and high sensitivity [6].

Based on this groundwork, research guidelines are slowly changing as they are now no longer directed at improving performance but are expanding their functionality. At present, graphene heterojunction detectors are not only trying to achieve greater sensitivity but also working hard to increase the dimensions in which the detectors can be applied. It is being done in two ways introducing anisotropic materials such as black phosphorus or creating chiral structure.

Such a possibility enables the synchronized detection of various degrees of freedom, such as the wavelength of light and its polarization state, which drives the devices into multidimensional sensing. In addition, the long-lived photoconductivity effect, which has carriers, is a phenomenon that generally needs to be eliminated in standard detection. However, by manipulating the interfaces or the bandgap, this effect can even be used as a method to store optical signals.

4. Optical Storage Devices Enabling the Transition from Perception to Computing

4.1. Role of Graphene in Optical Storage Devices

In the present age of information, the survival of human civilization is essentially contingent upon storing digital data in long term [7]. One of the most important steps towards the development of multifunctional brain-like devices in the context of neuromorphic optoelectronic systems built on the basis of graphene van der Waals heterostructures is to find the way to switch the transient light sensing to the steady information storage. Compared to other storage technologies, optical storage devices have significant advantages such as large capacity, fast response speed, long lifespan, and low power consumption. However, a simple photoelectric response usually only produces a transient signal. However, brain-like systems can use spiking neural networks to combine transient photosensing with storage mechanisms.

Early ideas about computation and neural information processing laid the theoretical foundation for brain-like computing. In 1950, Alan Turing proposed related ideas; in 1958, John von Neumann further proposed theories about neurons, nerve impulses, neural networks and information processing mechanisms in the human brain [8]. Optical computing based on optical storage platforms (which uses photons instead of electrons for computation) promises to enable ultra-high-speed parallel data processing. Therefore, optical storage is widely regarded as the most promising next-generation advanced storage technology [7].

4.2. Optical Storage Mechanism in Graphene Heterostructures

Two-dimensional materials, due to their unique physicochemical properties, are showing increasingly important application value in optoelectronic and storage devices. For example, the confinement effect of electrons in a plane with atomic-level thickness can significantly change its band structure and transport behavior, while a higher surface area to volume ratio is beneficial to enhancing the material's response sensitivity to external stimuli (such as light, electric fields, etc.).Meanwhile, the interlayer coupling mode dominated by van der Waals interaction makes the construction of heterostructures more flexible and provides rich means for interface engineering and carrier control[9]. Based on this, as a carbon-based material with good chemical tunability, reduced graphene oxide can adjust its conductivity and defect state distribution through controllable oxidation/reduction reactions, thereby realizing multi-level information writing and storage functions. Zhang et al. further discovered that by selecting a stable oxidation state and introducing nanocomposite materials into the recording medium, random fluctuations during the writing process can be effectively suppressed, significantly improving the writing stability and reliability of the device [10].Thus, the specific benefits of two-dimensional materials in interface control and charge transfer, along with the controllable chemical conditions and multi-level storage stability properties of reduced graphene oxide, are an essential material basis and direction of development in achieving high-performance and high-stability optoelectronic storage devices.

5. Computational Memristors and Photoelectronic Synapses

5.1. Multimode Weighting of Graphene Photomemristors

Opto-memristors are fundamental building blocks of opto-optical fusion computing, which have been found to play an important role in the new generation of neuromorphic computation systems. Stable memristor states may be achieved using different types of nanostructure including graphene or graphene oxide combined with either diamondene or bilayer graphene structures.

The physical mechanism behind this phenomenon is the reversible change of the structure of carbon atoms, sp^3-sp^2 hybrid, in response to an external electric field. Such a structural change allows efficient manipulation of the conductive channels and charge transport properties of materials, and

consequently, enables the dynamic modification of electrical conductivity properties of a device. In addition, it is usually possible to do this procedure with a low bias i.e. below 1 V which is not only power saving but also improves the safety and stability of device operation. The reversible hybrid control controlled with low voltage has major energy saving benefits to the device as well as indicating possible future applications within biocompatible heterogeneous information processing networks [11].

Photomemristors based on graphene have a great potential in low-power usage and multi-state control since they permit switching of carbon atoms hybridization reversibly. These devices will also be fundamental in facilitating efficient and scalable optoelectronic fusion computing.

5.2. Graphene Photoelectronic Synapses as the Core of Neuromorphic Computing

Building upon photoelectric memristors, graphene photoelectronic synapses further introduce the regulation of synaptic dynamics, enabling devices to not only store information but also process and learn in a manner similar to biological synapses.

In graphene heterostructures, various charge carriers exhibit characteristics such as the generation and transport of light-point charge carriers, charge transfer at the interface, and band and localization state (e.g., $sp^3 \leftrightarrow sp^2$) transitions regulated by applied bias voltage. Compared to purely electronic synapses, graphene photoelectronic synaptic arrays not only realize basic synaptic functions, but their linearly symmetrical conductivity update characteristics also enable them to be used for high-precision, high-fault-tolerant neuromorphic computing image recognition. In addition, the synapses integrate logic functions such as NAND and NOR gates and can be executed via optical path [12]. Therefore, graphene optoelectronic synapses are considered core hardware units in neuromorphic optoelectronic systems and have important application prospects in low-power edge computing, neuromorphic sensor processing, and other fields.

6. Artificial Neural Vision System

6.1. The Potential of Graphene Heterojunction in the Field of Neural Visual System

Guo et al. employed a graphene heterojunction structure to construct a basic artificial visual electronic system, simulating the hyperpolarization behavior of cone cells and rod cells, and achieving various synaptic behaviors possessed by organisms [13]. When rod cells and cone cells are stimulated with light in the biological retina, they generate hyperpolarized potential variations, and the potential of the cell membrane is made more negative. The heterojunction does well to mimic this behavior, as it suggests that it is capable of processing optical signals in the same manner as living organisms. The contribution helps to construct artificial vision systems based on bionics, which may be used to understand how biological synapses work.

Meftakhutdinov studied floating-gate transistors on graphene heterojunctions in the context of high-speed response and dynamic learning. In this case, ultrafast switching rates are obtained through charging through the Fowler-Nordheim mechanism. Moreover, the device can also show synaptic properties of pulse enhancement and plasticity when the memory window is adjusted using the voltage scanning range of the control electrode [14]. Using these fast charging and response time, the structure has the ability to obtain fast moving objects or fast changing optical signals and can be used in applications such as autonomous driving to provide real-time visual feedback. Last but not least, pulse enhancement and plasticity indicate that the visual sensor has the learning ability, allowing it to copy biological learning systems and change its behavior with different images.

6.2. The Application Prospects of Integrated Artificial Neural Vision Systems

The artificial neural visual system can be constructed by graphene heterostructure. This system is based on the theoretical technology of photogenerated carriers, combined with various device-level applications such as photodetectors, transistors, optical storage devices, optoelectronic memristors, and optoelectronic synapses. Such a system can not only detect the surrounding environment but also

store and process information, transmitting it to the required devices. It is not merely a single-function photodetector, but also an intelligent bionic system that integrates perception, storage, and computation. Exhibiting adaptive and learning capabilities, the system can realize human "intelligence" and holds significant potential in many technological fields.

7. Conclusions

Structures represented by graphene heterojunctions, utilizing the regulation of carriers, contribute to enhancing the stability and efficiency of optoelectronic devices.

There has been a breakthrough in the operation of graphene/quantum dot heterojunction detectors in the field of optoelectronic detection, and it is slowly shifting towards the development of new properties rather than improving existing ones. In optoelectronic storage, reduced graphene oxide can control its conductivity and defect state distribution by controllable oxidation/reduction reactions, with multilevel information writing and storage capabilities. In optoelectronic computing, stable memristive states may be built using nanostructures such as graphene/graphene oxide or bilayer graphene/diamondene. Such memristive states can effectively regulate the conductive channels and charge transport properties of materials, not only reduce energy consumption but also enhance the safety and stability of device operation. In artificial neural vision, graphene heterojunctions simulate the hyperpolarization behavior of cone and rod cells, regulating the memory window to exhibit biological synaptic characteristics, which mimic the processing of light signals by organisms. This paves the way for bionic artificial vision systems.

The above applications demonstrate that graphene heterojunctions contribute to the development of optoelectronic devices and have extremely high performance at work. In the future, it is expected that new two-dimensional materials can overcome physical bottlenecks nowadays. Plus, by using artificial intelligence to optimize algorithms, constructing a more intelligent visual system, such invention holds profound application potential in various fields such as mobile phone cameras and industrial detection.

Authors Contribution

All the authors contributed equally, and their names were listed in alphabetical order.

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