

The Photoelectric Properties of Graphene Materials and Applications in Photodetectors

Junzhi Liu

*Department of Materials, The University of Manchester, Manchester, United Kingdom
junzhi.liu-2@student.manchester.ac.uk*

Abstract. Graphene is a kind of carbon nanomaterial with ultra-broadband optical absorption, ultra-high carrier mobility, and ultra-fast response speed, which has great potential in high-speed and broadband optoelectronic communications. Accordingly, this paper analyses the fundamental structure, electrical properties, and optical properties of graphene, along with production methods and characterization techniques. This paper focuses on the analysis of some important indicators of photodetectors, including key performance indicators such as photo responsivity, detector response time, noise equivalent power, and signal-to-noise ratio. These properties provide a systematic framework for evaluating the optical sensing capability of devices. Subsequently, the study examines various photocurrent generation mechanisms observed in graphene photodetectors, including the photovoltaic effect, photoconductive effect, photogating effect, and photothermoelectric effect, to enhance the understanding of their operating principles. Next, graphene, as a photodetector material, is compared with other two-dimensional materials to analyze their respective advantages and disadvantages, and the specific applications of graphene-based photodetectors are discussed. Finally, the potential development directions and prospects are analyzed.

Keywords: photodetection, graphene, two-dimensional materials, photoelectric properties

1. Introduction

Photodetectors serve as the fundamental sensory units in diverse optoelectronic systems, enabling the transformation of incoming light into detectable electrical outputs. Beyond their widespread applications in daily technologies, they also play an essential role in various industrial processes. With continuous progress in material design, device engineering, and signal processing, the deployment and optimization of conventional photodetectors have steadily advanced. As detection demands become more intricate, there is a rising need for devices capable of delivering fast response, enhanced sensitivity, and broad spectral detection. Modern photodetectors are therefore expected to move past simple light-intensity measurements, extending toward multifunctional integration. This includes functions such as wearable and flexible operation, multidimensional data acquisition, and even on-chip biomimetic visual processing. Through these developments, photodetectors are positioned to provide functionalities that extend well beyond their traditional roles. Within this context, graphene has emerged as a particularly promising two-dimensional

candidate, owing to its distinctive optoelectronic properties and capacity to address the outlined challenges [1].

Firstly, Graphene, owing to its zero-bandgap electronic structure, supports broadband photodetection that covers ultraviolet, visible, and atmospheric transmission windows, and further extends into the infrared and terahertz regions [2,3]. The photo-generated carriers in graphene exhibit recombination times of only several tens of picoseconds, which makes graphene highly suitable for ultrafast photodetectors [4]. By adjusting the gate voltage, photovoltaic bias, and local electric field, the intensity and polarity of graphene photocurrent can be accurately controlled, so that the device has programmable response, intelligent operation, and multi-functional integration ability [5-8]. Studies have shown that the intrinsic light absorption of single-layer graphene is only ~ 2.3% [9], and this low light capture efficiency directly restricts the responsivity performance of graphene-based photodetectors [9]. To overcome this drawback, graphene has been coupled with semiconductor materials that possess stronger light absorption capability, thereby enhancing overall detection performance [10,11]. In such hybrid architectures, graphene can act both as an electrode that collects photogenerated carriers and as a channel that enables charge transport, making it a central focus in the research of graphene-based photodetectors [1]. Furthermore, pristine graphene is inherently characterized by a low intrinsic responsivity, which significantly restricts its ability to convert incident photons into electrical signals. To overcome this limitation, researchers have developed and implemented various structural designs and material engineering approaches to enhance device responsivity.

This paper first introduces the structural, electrical, and optical characteristics of graphene, together with commonly employed production methods and characterization techniques. It then provides a systematic evaluation of the key performance parameters of photodetectors—including photo responsivity, specific detectivity, and detector response time—offering an assessment framework for the optical detection capabilities of graphene-based devices. Building upon this foundation, the mechanism of photocurrent generation in graphene photodetectors is further studied, and their working principles are discussed in detail. Following this, the comparative advantages and disadvantages of graphene relative to other two-dimensional materials in photodetection are examined, alongside their specific application scenarios. Finally, the paper highlights potential development pathways and future prospects.

2. Fundamental properties and characterization of graphene

2.1. Basic properties of graphene

2.1.1. Graphene's crystalline lattice structure

In graphene's crystalline lattice, each carbon atom adopts sp^2 hybridization, wherein the linear combination of one 2s atomic orbital and two 2p orbitals generates three degenerate sp^2 hybrid orbitals. These hybrid orbitals exhibit a trigonal planar configuration with mutual bond angles of approximately 120° within the same plane and form three σ bonds with the sp^2 orbitals of three neighboring carbon atoms as illustrated in Figure 1b, ultimately forming the hexagonal layered structure of graphene (Figure 1a). Each carbon atom still has an unhybridized p orbital whose orientation is perpendicular to the plane of the σ bond. These p orbitals overlap laterally with those of adjacent atoms to form delocalized π bonds as illustrated in Figure 1b. The combination of strong in-plane σ bonds and delocalized π bonds results in a stable two-dimensional hexagonal honeycomb lattice. The C-C bond length in graphene is approximately 1.42 Å. When multiple layers of graphene

stack via van der Waals forces, these layers form graphite with interlayer spacings of more than 300 pm. This unique structure endows graphene with exceptional mechanical strength and structural stability [12].

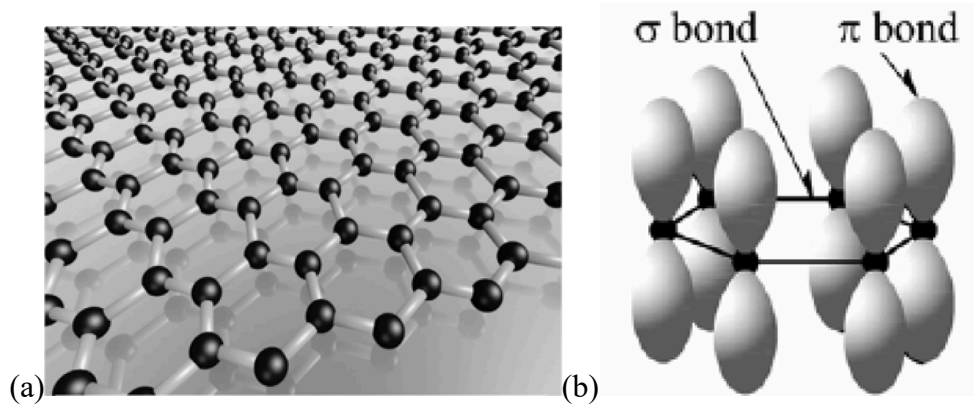


Figure 1. (a) Illustration of the hexagonal lattice structure of graphene [12], (b) Illustration of orbitals oriented perpendicular to the plane and σ bonds confined within the plane in graphene [12]

2.1.2. Electrical properties

Each carbon atom in graphene possesses one electron in a p_z orbital, and the overlap of these orbitals gives rise to a filled band as the valence band and an empty * band as the conduction band. Electrons propagate along the “zigzag” direction (Blue line) of the graphene lattice as shown in Figure 2a, resulting in a band structure with a corner shape, known as the Dirac cone, where the valence and conduction bands meet at the K point in Figure 2b. At this point, the density of states is zero, yet no bandgap exists. This unique band structure, combined with the defect-free honeycomb lattice of graphene, leads to its exceptionally high electrical conductivity of up to $10^6 \text{ S} \cdot \text{cm}^{-1}$ and outstanding electron mobility of up to $250,000 \text{ cm}^2 \cdot \text{V}^{-1} \cdot \text{S}^{-1}$. Additionally, electrons moving along the “armchair” direction (Red line) in Figure 2a exhibit semiconductor-like behavior at the M point as illustrated in Figure 2b [13].

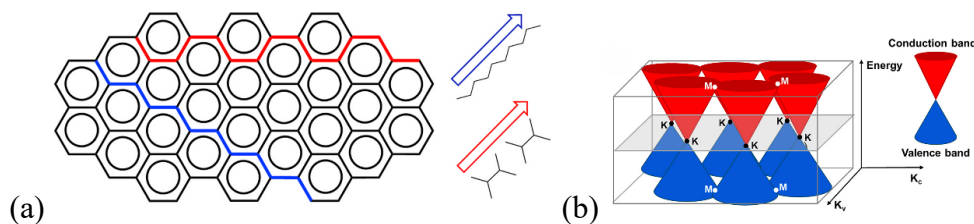


Figure 2. (a) Electronic transmission line, (b) Electronic band structure of graphene materials [13]

2.1.3. Optical properties

The multilayer structure of graphene enables absorption of radiation over a range of frequencies. Graphene exhibits a distinctive layer-dependent optical absorption behavior that follows a linearly scaling relationship, where monolayer graphene absorbs approximately 2.3% of incident light, while bilayer graphene reaches up to 4.6%. For the individual layer, the absorption relationship can be expressed by the fine-structure constant α using the relation $A = 1 - T = \pi\alpha$, where $\alpha \approx 1/37$. Due to its atomic-level thickness, the absorption of graphene is independent of the incident light frequency, distinguishing it from conventional optical materials. These optical properties originate from the

delocalized π -electron system, the conical band structure, and the presence of holes at the Dirac fermion points [14].

2.2. Preparation methods of graphene

Graphene synthesis approaches are generally divided into top-down and bottom-up categories. Top-down methods include mechanical exfoliation, chemical exfoliation, and reduction of graphene oxide. [15]. Mechanical exfoliation method separates monolayer graphene from graphite by applying a lateral force to overcome weak van der Waals interactions between layers [14]. This preparation method yields large-sized, unmodified sheets but suffers from very low production yield. The chemical exfoliation method involves forming graphite intercalation compounds to reduce the interlayer van der Waals forces and increase the interlayer spacing, followed by rapid thermal or ultrasonic exfoliation. This preparation method produces unmodified graphene at low cost but suffers from low yield and separation challenges. Reduction of graphene oxide is achieved by oxidizing graphite to graphite oxide, exfoliating it into single- or few-layer nanosheets via sonication, and then removing oxygen groups via chemical, thermal, or electrochemical reduction. This preparation method enables scalable, low-cost production but typically leaves residual oxygen-containing functional groups [15].

Bottom-up methods include pyrolysis and chemical vapor deposition (CVD). In pyrolysis, sodium and ethanol are used as precursors to form a sodium ethoxide intermediate, which is then subjected to thermal decomposition and ultrasonic exfoliation, yielding graphene sheets up to 10 μm in size. The pyrolysis method is low-cost and can produce high-purity, functionalized graphene at relatively low temperatures, but the resulting material often contains numerous defects. CVD decomposes hydrocarbon gases such as methane or acetylene at high temperatures on metal substrates like Ni or Cu, where carbon atoms diffuse and rearrange into graphene films. CVD produces large-area, high-quality graphene but is limited by a small production scale [15].

2.3. Characterization of graphene

Graphene characterization is essential for assessing structural quality, layer number, morphology, and defects. [12]. Raman spectroscopy, as shown in Figure 3a, reveals three characteristic peaks: the D peak at 1350 cm^{-1} , associated with disorder in sp^2 hybridization; the G peak at 1580 cm^{-1} , representing lattice vibrations; and the 2D peak at 2700 cm^{-1} , a second-order scattering feature near the Dirac point. Increased disorder elevates the I_D/I_G ratio due to elastic scattering from defects, while amorphization reduces this ratio [12]. Transmission electron microscopy (TEM) in Figure 3b provides direct visualization of layer count and structural quality. In dimethyl sulfoxide, TEM images display 3–6 dark fringes corresponding to graphene layers, aligned parallel to the electron beam [12].

Scanning electron microscopy (SEM) in Figure 3c examines morphology, detecting impurities, folds, and discontinuities. Encapsulation with polyethylene terephthalate (PET) increases nanosheet thickness from 1.57 nm to 50 nm and enlarges surface area, enhancing interface properties [12]. X-ray diffraction (XRD) as illustrated in Figure 3d distinguishes phases of graphite, graphite oxide, and graphene. Graphite exhibits a sharp peak at 26.6° , shifting to 13.3° in graphite oxide due to oxygen incorporation. Absence of these peaks after fabrication confirms graphene formation [12]. UV to visible spectroscopy differentiates graphene oxide, with an absorption peak at $\sim 230\text{ nm}$ ($\pi-\pi^*$ transition), from pristine graphene, with peaks between 250–270 nm. Transmittance also indicates layer number and thickness [12]. Atomic force microscopy (AFM) measures thickness and surface

structure by scanning a nanoscale cantilever over the sample, detecting deflection-induced laser signal changes to reconstruct topography [12].

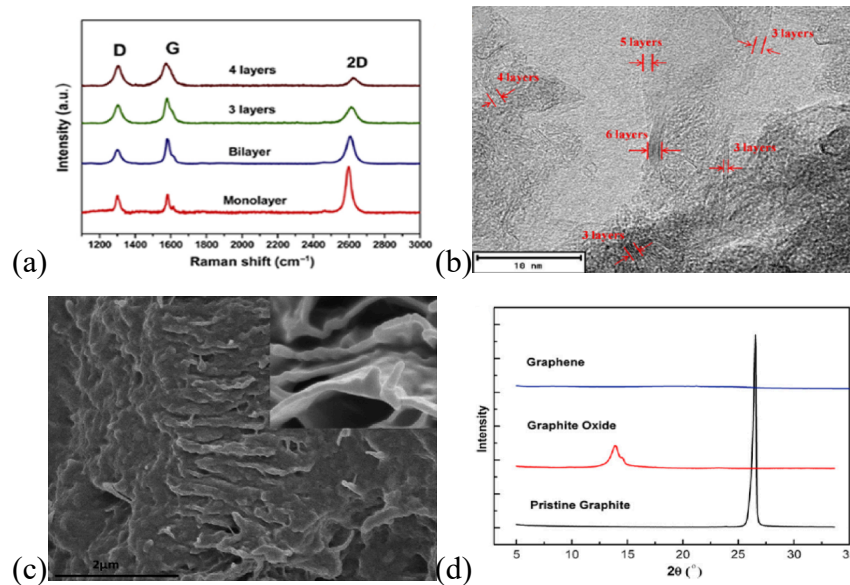


Figure 3. (a) Raman spectrum of graphene grown on an alumina substrate using a Ni electrode [12]. (b) High-resolution TEM visualization of graphene in dimethyl sulfoxide [12]. (c) SEM micrographs of a graphene sheet configuration enclosed in PET [12]. (d) XRD patterns of graphene, graphite oxide, and pristine graphite [12]

3. Principles and comparative analysis of graphene-based photodetection systems

3.1. Mechanisms of graphene-based photodetectors

3.1.1. Photovoltaic effect

In field-effect transistors based on two-dimensional materials such as graphene, the photovoltaic effect is a representative mechanism for photocurrent generation. When differently doped regions or p-n junctions are formed, incident light excites electron-hole pairs, which are then spatially separated by the built-in electric field, resulting in the generation of photocurrent. The separation efficiency can be further enhanced by applying an external bias. In cases where the built-in electric field is weak, the photoexcited carriers tend to recombine rapidly, leading to no contribution to the external photocurrent. To improve this performance, surface chemical modification of the two-dimensional material can be applied to tune its bandgap, and asymmetric structures at the metal contact regions can be introduced to enhance the built-in electric field, thereby promoting more effective carrier separation [16].

3.1.2. Photoconductive effect

In the photoconductive effect, photo-irradiation introduces additional charge carriers, which significantly increase the concentration of free carriers in the material and consequently reduce the resistance of the semiconductor. Under an applied bias voltage, these carriers are driven to generate a photocurrent. In the absence of light, the limited number of intrinsic carriers produces only a small dark current. Upon illumination, photons excite electron-hole pairs, which are then separated by the

external electric field, resulting in a photocurrent stronger than the dark current. Without an applied bias, the photoconductive mechanism cannot generate photocurrent, distinguishing it fundamentally from the photovoltaic effect [16].

3.1.3. Photogating effect

As a control form of photoconductive effect, the light gate effect is particularly significant in phototransistors and photoconductive detectors, and the efficient control of photogenerated carriers can be realized by regulating the gate voltage [16]. Its main feature is the modulation of conductivity through photo-induced equivalent gate potentials, rather than being governed only by trap states. Upon illumination of a two-dimensional material, electron-hole pairs are created. If charge carriers are captured within localized states, the resulting trapped charges behave like a floating gate, thereby altering the channel conductivity. For instance, photogenerated holes trapped in such states generate positive charges, which effectively dope the channel with electrons and cause a negative shift in the transfer curve.

3.1.4. Photothermoelectric effect

The photothermoelectric effect arises from a temperature gradient created by photoexcitation, which induces a thermoelectric voltage and plays a critical role in the photoresponse of two-dimensional optoelectronic devices. Upon illumination, photogenerated high-energy carriers progressively transfer their energy to the lattice of the two-dimensional material, leading to the establishment of a nonequilibrium hot fermion distribution. The resulting difference in hot-electron distribution produces a photovoltage expressed as $V_{PTE} = (S_1 - S_2)\Delta T$. Here S_1 and S_2 represent the Seebeck coefficients of two regions with distinct doping levels, while ΔT corresponds to the electron temperature difference between the illuminated domain and its surroundings. Mott relation reveals the quantum mechanical relation between S and electrical conductivity σ in thermoelectric materials [16]:

$$S = -\frac{2k_B^2 T_e}{3e} \frac{1}{\sigma} \frac{\partial \sigma}{\partial \epsilon} \quad (1)$$

3.2. Performance parameters in graphene-based photodetection

3.2.1. Responsivity (R)

Responsivity (R) quantifies the efficiency of photoelectric conversion in a photodetector and is defined as [17]:

$$R_v = \frac{V_{ph}}{P_{in} \bullet A} \text{ or } R_i = \frac{I_{ph}}{P_{in} \bullet A} \quad (2)$$

Where V_{ph} is the photovoltage (V), I_{ph} is the photocurrent (A), P_{in} is the light power (W), and A is the effective illuminated area of the device (m^2) [17]. Higher R values indicate stronger electrical response to incident light, especially at low intensities.

3.2.2. Signal to noise ratio (SNR) and response time (τ_{tes})

The SNR of the photodetector can be defined as [17]:

$$\text{SNR} = P_s/P_n \quad (3)$$

Where P_s is signal power, and p_n is noise power. A higher SNR indicates improved detection capability because it represents stronger signal clarity relative to the background noise.

Response time reflects the temporal speed at which a photodetector reacts to light switching on or off. The response time is characterized by two key parameters: the rise time τ_r (the time required for the photocurrent to rise from 10% to 90% of the steady-state value) and the decay time τ_d (the duration to fall from 90% to 10%). These two parameters jointly determine the tracking ability of the device for transient optical signals, where τ_r reflects the fast transport characteristics of carriers, and τ_d is closely related to the recombination process [17]. Shorter response times imply faster device operation and are crucial for high-speed photodetection applications.

3.2.3. Noise equivalent power (NEP) and specific detectivity (D^*)

NEP represents the minimum detectable optical power of a photodetector, determining its detection limit. NEP is calculated as [17]:

$$\text{NEP} = \frac{I_n \text{ or } V_n}{R} \quad (4)$$

The mean-square noise voltage in the dark with a bandwidth of 1 Hz is denoted by V_n , and the mean square noise current is I_n [17]. A lower NEP value corresponds to a better detection limit, indicating the capability to detect weaker optical signals under the same noise level.

Specific Detectivity (D^*) is a normalized measure of photodetector sensitivity, defined as [17]:

$$D^* = \frac{(A \cdot \text{BW})^{1/2}}{\text{NEP}} \quad (5)$$

Where A is the effective photosensitive area of the photosensitive element (cm^2) and BW is the operating frequency bandwidth of the device (in Hz). These two parameters together determine the noise characteristics and frequency response of the detector. A larger D^* Value indicates superior performance, as it corresponds to the ability to detect weaker optical signals under the same noise conditions.

3.3. Comparison of graphene with other two-dimensional materials for photodetection

Graphene photodetectors exploit wideband absorption, rapid carrier transport, and compatibility with silicon photonics, enabling detection from ultraviolet to far-infrared. However, due to its gapless band structure, graphene exhibits a low intrinsic responsivity. In the mid-infrared region, illumination at $2.75 \mu\text{m}$ on a graphene/silicon heterojunction waveguide integrated with SOI produced a responsivity of 0.13 A/W when a 1.5 V bias was applied. On SOS waveguides incorporating CVD-grown graphene, the responsivity remained relatively low, reaching 0.9 mA/W at the telecom-relevant wavelength of $1.55 \mu\text{m}$ but increasing to 4.5 mA/W under $2.75 \mu\text{m}$ excitation. By contrast, when graphene was combined with chalcogenide glass waveguides, a markedly enhanced response was obtained, with the peak responsivity measured at 250 mA/W for incident light of $2.03 \mu\text{m}$. [18].

Monolayer TMDC materials, such as MoS_2 , WS_2 , etc., which are known for their tunable direct band gaps and pronounced excitonic absorption, making them attractive for photodetection. A stacked heterostructure formed by combining $2\text{H} - \text{MoS}_2$ with $1\text{T}@2\text{H} - \text{MoS}_2$ demonstrated an

increasing responsivity of 1917 A/W together with a detection sensitivity approaching 10^{11} Jones [18]. In another case, a lateral $\text{MoSe}_2/\text{WS}_2$ p–n junction integrated on a SiN waveguide exhibited a peak responsivity of around 0.9 A/W in the red-light region, while maintaining a very low dark current of about 50 pA, together with a bandwidth approaching 20 MHz and rapid signal transitions within 30 ns. Moreover, by employing self-assembled monolayer doping, the responsivity of WSe_2 was boosted from 517.2 A/W to 1.45×10^4 A/W, and that of MoS_2 increased from 219 A/W to 5.75×10^3 A/W [18].

The typical characteristics of black phosphorus (BP) materials are their large tunable band gap and high absorptivity. Asymmetric Schottky BP transistors demonstrated a detectivity of 2.47×10^{11}

Jones across the 400–2200 nm spectrum. BP/RGO Schottky junctions-maintained operation up to 400 K with near-infrared responsivity extending to 2200 nm, while BP/PtSe₂ Schottky devices showed ~25 A/W at 470 K, outperforming III–V photodetectors in the MWIR region at room temperature [18].

Two-dimensional MXenes, with their high conductivity and tunable work functions, show strong potential in photodetection. Schottky junctions of MXene/Ge delivered 665 mA/W responsivity and 1.24×10^{13} Jones detectivity at 1550 nm, indicating excellent near-infrared performance. MXene/ Bi_2S_3 composites enabled dual-band operation, giving 36.7 A/W in the UV and 26.2 A/W in the near-infrared, while MXene/AlGaN junctions reached 101.85 mA/W under deep-UV light. At 980 nm, MXene/ Bi_2S_3 heterostructures achieved 7.56 A/W, and Nb_2CT_x -based devices showed a polarization-sensitive broadband response with an extinction ratio of 7.6, together reflecting the material's broad applicability [18].

Compared with BP, MXenes, and TMDs, graphene offers broader detection from UV to far-IR, faster carrier transport, and better environmental stability, particularly in MIR sensing. Compared with graphene, BP provides greater spectral tunability and stronger polarization sensitivity, but has poorer air stability. Compared with graphene, MXenes achieve higher responsivity and detectivity in certain spectral ranges, and offer mechanical flexibility for wearable devices. Compared with graphene, TMDs show stronger excitonic absorption but operate within narrower spectral ranges [18].

3.4. Application of graphene photodetectors

Graphene photodetectors have shown significant potential in various optoelectronic scenarios due to their exceptional carrier mobility, ultrafast photo response, and mechanical flexibility. In high-speed optical communication, graphene-based photodetectors can operate at bandwidths above 100 GHz, which positions them as promising candidates for future ultra-fast data communication technologies. Furthermore, the natural alignment of graphene with CMOS processes and silicon photonic devices enables straightforward integration into chip-level photonic circuits and high-speed optical links [18].

For flexible and wearable optoelectronic systems, graphene's remarkable structural flexibility and excellent optical transparency enable the realization of advanced devices such as emerging human–device platforms, flexible screens, and adaptive electronics seamlessly incorporated onto soft or curved substrates [18].

The combination of outstanding functionality, excellent integration potential, along with structural resilience, makes 2D photodetectors prominent candidates for the development of flexible and wearable optoelectronic systems [18].

4. Conclusion

Graphene's sp^2 -bonded honeycomb lattice and delocalized π -electron network provide exceptional electrical conductivity, ultrafast carrier transport, and broadband optical absorption that scales linearly with layer number. Monolayer graphene exhibits strong optical transparency, while its mechanical flexibility and fabrication compatibility further support its integration into advanced optoelectronic devices.

In photodetection, graphene operates through photovoltaic, photoconductive, photogating, and photothermoelectric effects, covering ultraviolet to far-infrared wavelengths. Waveguide-integrated devices exhibit strong performance across the near- to mid-infrared range.

Compared with other 2D materials, graphene offers a wider spectral range, faster carrier dynamics, and greater environmental stability. BP provides superior spectral tunability and polarization sensitivity, but is air-unstable. MXenes deliver higher responsivity and detectivity in certain bands and allow mechanical flexibility for wearable systems. TMDs exhibit strong excitonic absorption but operate over narrower ranges.

Future progress necessitates optimization of synthesis processes to achieve higher yields, lower defect densities, and uniform large-area film deposition. Device performance could be enhanced through optimized heterostructure engineering and waveguide integration to boost responsivity without sacrificing broadband coverage. In applications where polarization sensitivity or deep-UV response is critical, hybrid designs combining graphene with complementary 2D materials may overcome its current limitations. Improving long-term operational stability under varying environmental conditions will be essential for reliable deployment in flexible and integrated optoelectronic systems.

References

- [1] Fu, J., Nie, C., Sun, F., Li, G. and Wei, X. (2023) Photodetectors based on graphene–semiconductor hybrid structures: Recent progress and future outlook. *Advanced Devices & Instrumentation*, 4, 0031.
- [2] Cakmakyapan, S., Lu, P.K., Navabi, A. and Jarrahi, M. (2018) Gold-patched graphene nano-strips for high-responsivity and ultrafast photodetection from the visible to infrared regime. *Light: Science & Applications*, 7(1), 20.
- [3] Vicarelli, L., Vitiello, M.S., Coquillat, D., Lombardo, A., Ferrari, A.C., Knap, W., Polini, M., Pellegrini, V. and Tredicucci, A. (2012) Graphene field-effect transistors as room-temperature terahertz detectors. *Nature Materials*, 11(10), 865–871.
- [4] Chen, X., Shehzad, K., Gao, L., Long, M., Guo, H., Qin, S., Wang, X., Wang, F., Shi, Y., Hu, W., Xu, Y. and Wang, X. (2019) Graphene hybrid structures for integrated and flexible optoelectronics. *Advanced Materials*, 32(27), 1902039.
- [5] Freitag, M., Low, T., Xia, F. and Avouris, P. (2012) Photoconductivity of biased graphene. *Nature Photonics*, 7(1), 53–59.
- [6] Buscema, M., Island, J. O., Groenendijk, D. J., Blanter, S. I., Steele, G. A., van der Zant, H. S. and Castellanos-Gomez, A. (2015) Photocurrent generation with two-dimensional van der waals semiconductors. *Chemical Society Reviews*, 44(11), 3691–3718.
- [7] Wei, J., Xu, C., Dong, B., Qiu, C.-W. and Lee, C. (2021) Mid-infrared semimetal polarization detectors with configurable polarity transition. *Nature Photonics*, 15(8), 614–621.
- [8] Han, J., Wang, J., Yang, M., Kong, X., Chen, X., Huang, Z., Guo, H., Gou, J., Tao, S., Liu, Z., Wu, Z., Jiang, Y. and Wang, X. (2018) Graphene/organic semiconductor heterojunction phototransistors with broadband and bi-directional photoresponse. *Advanced Materials*, 30(49), 1804020.
- [9] Nair, R. R., Blake, P., Grigorenko, A. N., Novoselov, K. S., Booth, T. J., Stauber, T., Peres, N. M. and Geim, A. K. (2008) Fine structure constant defines visual transparency of graphene. *Science*, 320(5881), 1308–1308.
- [10] Xie, C., Wang, Y., Zhang, Z.-X., Wang, D. and Luo, L.-B. (2018) Graphene/semiconductor hybrid heterostructures for optoelectronic device applications. *Nano Today*, 19, 41–83.

- [11] Lin, S., Lu, Y., Xu, J., Feng, S. and Li, J. (2017) High performance graphene/semiconductor van der waals heterostructure optoelectronic devices. *Nano Energy*, 40, 122–148.
- [12] Mbayachi, V. B., Ndayiragije, E., Sammani, T., Taj, S., Mbuta, E. R. and khan, A. ullah. (2021) Graphene synthesis, characterization and its applications: A Review. *Results in Chemistry*, 3, 100163.
- [13] Lalire, T., Longuet, C. and Taguet, A. (2024) Electrical properties of graphene/multiphase polymer nanocomposites: A Review. *Carbon*, 225, 119055.
- [14] Sagadevan, S., Shahid, M. M., Yiqiang, Z., Oh, W.-C., Soga, T., Anita Lett, J., Alshahateet, S. F., Fatimah, I., Waqar, A., Paiman, S. and Johan, M. R. (2021) Functionalized graphene-based nanocomposites for smart optoelectronic applications. *Nanotechnology Reviews*, 10(1), 605–635.
- [15] Bhuyan, Md. S., Uddin, Md. N., Islam, Md. M., Bipasha, F. A. and Hossain, S. S. (2016) Synthesis of graphene. *International Nano Letters*, 6(2), 65–83.
- [16] Yang, C., Wang, G., Liu, M., Yao, F. and Li, H. (2021) Mechanism, material, design, and implementation principle of two-dimensional material photodetectors. *Nanomaterials*, 11(10), 2688.
- [17] Jiang, J., Wen, Y., Wang, H., Yin, L., Cheng, R., Liu, C., Feng, L. and He, J. (2021) Recent advances in 2D materials for photodetectors. *Advanced Electronic Materials*, 7(7), 2001125.
- [18] Odebowale, A. A., Berhe, A. M., Somaweera, D., Wang, H., Lei, W., Miroshnichenko, A. E. and Hattori, H. T. (2025) Advances in 2D photodetectors: Materials, mechanisms, and applications. *Micromachines*, 16(7), 776.