TOPICAL REVIEW

Recent progress and challenges based on two-dimensional material photodetectors

Kaixuan Zhang , Libo Zhang , Li Han , Lin Wang , Zhiqingzi Chen , Huaizhong Xing and Xiaoshuang Chen

1 Department of Optoelectronic Science and Engineering, Donghua University, Shanghai 201620, People’s Republic of China
2 State Key Laboratory of Infrared Physics, Shanghai Institute of Technical Physics, Chinese Academy of Sciences, Shanghai 200083, People’s Republic of China
* Authors to whom any correspondence should be addressed.
E-mail: wanglin@mail.sitp.ac.cn, xinghz@dhu.edu.cn and xschen@mail.sitp.ac.cn

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Abstract

Two-dimensional (2D) materials have excellent electronic and optoelectronic properties, such as ultrafast charge transport and tunable photon absorption. These 2D materials include topological semimetal graphene, semiconductor material black phosphorus, transition-metal dichalcogenides, etc. Studying the ultra-high optical response speed and sensitivity, broadband spectrum and other excellent performance photodetectors are the goals of continuous pursuit and challenge. 2D material photodetectors have become a research hotspot due to the special properties of 2D materials including flexible tuning, no dangling bonds, high mobility, and many more. Herein, the electronic and optoelectronic properties of 2D materials and the quality factors of the photodetector are introduced. Then, the 2D material-based photodetectors with a detection wavelength from visible light to the terahertz band are summarized systematically. Finally, the prospects and challenges of 2D material-based photodetectors are discussed briefly.

1. Introduction

Since graphene was discovered in 2004 [1], two-dimensional (2D) materials have attracted extensive attention owing to their rich electrical, optical, and thermal properties, as well as their broad application prospect in the field of optoelectronic devices, photocatalysis, energy, and so on [2–4]. And 2D materials are constantly discovered or synthesized. The atoms in the same plane of the 2D materials are connected by covalent bonds, and the layers are connected by weak van der Waals (vdW) interaction. Micromechanical exfoliation makes it easy to peel 2D materials into thin slices with atomic thickness. The quantum confinement effect in the out-of-plane direction of 2D materials brings many excellent electronic and optoelectronic properties. Graphene has high mobility [5, 6], and good in-plane thermal conductivity [7]. Transition metal dichalcogenides (TMDCs) exhibit strong interaction with light [8, 9]. The direct bandgap and anisotropy of black phosphorus (BP) has important applications in wide-band detection [10, 11]. In addition, topological semimetals and topological insulators have also been used in photodetectors, demonstrating high responsivity. Based on this, 2D materials are considered to be the mainstream direction of next-generation optoelectronic information materials.

The research and application of photodetectors promote the progress and development of society. And photodetectors play an important role in medical imaging, optical communication and security inspection and so on [12, 13]. Although the traditional silicon-based photoelectric detection technology has been relatively mature, it has fallen into a bottleneck period in terms of operating wavelength as well as responsivity and speed. The manufacturing technology of silicon-based semiconductors has approached the limit of Moore’s Law. Other traditional materials, including HgCdTe, InGaAs, InSb, and type-II superlattices, covering the detection of the infrared spectral range. However, these types of photodetectors can only obtain highly sensitive detection under low-temperature working condition, and are faced with complicated manufacturing technology. Easy

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preparation and integration of 2D materials simplify the process of device preparation. In addition, its high mobility and strong interaction of light–matter can improve the sensitivity and speed of photodetector. The researchers improved the response speed of the photodetector through the design and control of various structures. Konstantatos et al achieved high-performance optical detection by coating PbS quantum dots on a thin layer of graphene [14]. As a light-absorbing layer, quantum dots improved the external quantum efficiency of the photodetector, and achieved an optical gain of 10^6 electrons/photons. Yan et al used the plasmon resonance effect to enhance the local electric field and increase the efficiency of generating graphene photogenerated carriers. The detection wavelength of the photodetector reached mid-infrared [15]. After more than ten years of rapid development, a series of research results have been achieved based on 2D materials electronic optoelectronic devices.

In this paper, we first briefly introduced the characteristics of different types of 2D materials and the mainstream preparation methods, and then discussed the performance parameters of photodetectors and the generation mechanism of photocurrent. It mainly summarized the application of photodetectors based on 2D materials and heterojunctions in different wavelength bands. The response band of the photodetector includes multiple bands from visible light to terahertz. Finally, the development and future challenges of 2D materials were briefly summarized and prospected.

2. Synthesis and properties of 2D materials

2.1. Synthesis of 2D materials

The preparation of high-quality 2D materials plays a crucial role in the performance of device. At present, a variety of methods for synthesizing 2D materials have been developed, mainly including micromechanical exfoliation, liquid-phase exfoliation, chemical vapor deposition, epitaxial growth and so on.

Micromechanical exfoliation method is a physical method to obtain high-quality 2D materials. Since single-layer graphene is obtained by micromechanical exfoliation [16], MoS2 [17], WS2 [18] single layer or multi-layer were also obtained in the same way. Figure 1(a) shows a schematic view of the micromechanical exfoliation. Although it is more convenient to obtain single-layer or multi-layer 2D materials by micromechanical exfoliation, the size of the sample is small, and the thickness of the sample cannot be guaranteed. This way will be greatly restricted in the future industrial development.

Liquid-phase exfoliation is a method that can easily operate and obtain a large number of samples. It can disperse bulk materials into specific solvents or surfactants, and the single-layer or multi-layer 2D materials are directly peeled from the bulk materials surface by the energy of ultrasonic waves, maintaining the complete appearance and performance of the 2D materials. Figure 1(b) shows a schematic view of the liquid exfoliation [20]. Coleman et al first used the organic solvent N-methyl pyrrolidone (NMP) to peel off the 2D materials directly with the help of ultrasonic waves [22]. Due to the high boiling point of the solvent, it is difficult to remove the solvent remaining in the layer, which will affect the device performance. In 2016, Pan et al successfully peeled WS2 [23] in water by ultrasonic waves method, but the nano sheet was unstable in water and the peeling efficiency was not high. It is the best way to prepare 2D materials on a large scale by finding more suitable stripping solution and process.

Chemical vapor deposition (CVD) can be used to prepare 2D materials with large area, good quality and uniform samples. Figure 1(c) shows a schematic view of CVD method to synthesize ReSe2 films [21]. Hua Xu et al demonstrated the CVD method for the controlled and scalable synthesis of large-area, high-quality ReSe2 film. Compared with the above two methods, CVD technology has the advantages of high repeatability and convenient operation. In addition, the growth of large-area, high-quality single crystal materials have important scientific significance and technical value for the preparation of 2D single crystal materials. Jiang Bei et al demonstrated batch synthesis of transfer-free graphene on quartz accomplishing wafer-scale uniformity [24]. The batch preparation technique is also suitable for the direct growth of graphene on other non-metallic substrate, such as SiO2/Si, sapphire, Si3N4, etc.

2.2. Graphene

Graphene is a 2D allotrope of carbon, which is formed by sp² hybridization of carbon atoms. The hexagonal honeycomb lattice of graphene, with two carbon atoms per unit cell and 3D band structure of graphene are shown in figure 2(a). Each atom strong covalently bonds to adjacent three ones through the σ bond with distance a = 1.42 Å from each C atom to its three neighbors [25]. The conduction band and the valence band of the graphene energy band overlap at the Fermi plane, making the conduction band and the valence band have good symmetry, and there is a linear dispersion relationship near the energy band along the high symmetry point [26]. The monoatomic thickness and stable crystal structure of graphene exhibit many unique properties, such
as high carrier mobility \cite{27} and broad response spectrum \cite{28}, and can interact with light from ultraviolet to far infrared and even to terahertz region. Graphene also exhibits strong light-material interaction \cite{29}. The optical absorption coefficient of monolayer graphene is 2.3\% in the visible and to near-infrared range under vertically incident light \cite{30}. The selective absorption of optical wavelength can also be realized by adjusting the Fermi level position of graphene. These unique advantages of graphene make it have great application value in photodetectors, especially in the far infrared and terahertz regions.

Figure 1. (a) Schematic description of micromechanical exfoliation, reprinted with permission \cite{19} Copyright (2015) American Chemical Society, (b) Schematic description of liquid exfoliation and optical images of phosphorene, reproduced with permission \cite{20}, (c) Illustration of the synthesis process for the CVD growth of ReSe$_2$ and optical images, reproduced with permission \cite{21}. 

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2.3. Transition-metal dichalcogenides

Transition metal dichalcogenides (TMDCs) are very important semiconductor materials. It is a layered structure composed of single or few layers of atoms in the hexagonal system. The generalized molecular formula is MX$_2$ (M = Mo, W, Re; X = S, Se, Te), for example MoS$_2$, WS$_2$, and MoSe$_2$, different TMDCs have similar crystal structures. Figure 2(b) shows the three structural phases are characterized by trigonal prismatic (2H), distorted octahedral (1T), and dimerized (1T’ phases) [31]. In particular, some of them are monolayer honeycomb-like structures and are further sub-divided into different types. 2H-structure with D$_{6h}$ point group symmetry and 1T-structure with D$_{3h}$ point group symmetry, namely, honeycomb (2H) and centered honeycomb (1T) structures [31, 33, 34]. There are approximately 40 different types of TMDCs materials through various combinations of chalcogenide elements and transition metals, which give TMDCs a variety of properties, such as charge density wave [34], semimetal [35], superconductivity [36] and so on. For example, the monolayer
MoS2 of direct bandgap (1.8 eV) could turns into its bulk semiconductor (1.2 eV) of indirect bandgap when relevant layers increase [37]. The phenomena of CDW phase exist in the group V layered dichalcogenides, TaS2 and TaSe2, and NbSe2, resulting from materials layers, the gate bias, different substrate or current excitation etc. Topological semimetals (e.g. PtSe2, PdTe2 and PtTe2) have remarkable chiral correlation transport characteristics, nonlinear optical phenomena and other strange physical properties [38, 39]. In addition, due to its symmetrically protected electronic state, topological semimetals have unique carrier properties and perform well in broadband photo-detection.

Based on the afore mentioned characteristic, TMDCs have far-ranging prospect in development and utilization of optoelectronics, tunable excitonic devices and spin-valley lasers etc [40, 41].

2.4. Group-V elemental 2D materials

Compared to zero bandgap of graphene and indirect bandgap and low mobility of TMDCs [42, 43], BP and other group V elemental layered materials are considered as 2D materials with development potential and broad electronic application prospect due to their unique high mobility and adjustable band gap [44–46]. The crystal lattice of BP is shown in figure 2(c). The band gap of BP varies with the number of atomic layers. It has always maintained a direct band gap and can be directly coupled with light [47]. It’s extraordinarily favorable that BP, due to its strong optical conductivity in the corresponding wavelength range, become a promising candidate from visible to mid-infrared optoelectronics as optoelectronic applications, such as photodetectors, lasers and sensors etc [44]. However, the instability of BP in the environment is a major challenge that limits further development [48].

2D layered elemental arsenic also has a high mobility [49] and an adjustable band gap [46, 50] for optoelectronic device applications. External electric field modulation can also affect the electrical transport properties of 2D layered elemental arsenic. Black arsenic has a single-layer puckered structure similar to black phosphorus, which makes black arsenic also have rich anisotropy [31], and the in-plane anisotropy is more obvious than BP. Black arsenic is more stable than 2D layered elemental phosphorus, and has the opportunity to realize the preparation and application of large-area ultra-thin layer samples. The bulk antimony exhibits the electrical transport characteristics of metals. 2D layered elemental antimony is an indirect band gap semiconductor [46], which may be limited in the development of optoelectronic devices. However, its high carrier concentration and mobility still make it have a large research value. At present, the research on arsenic and antimony needs to be developed. According to the existing research results, as new 2D layered semiconductor materials, arsenic and antimony have attracted more and more attention in the fields of transistor manufacturing, optoelectronic devices, quantum spin devices and so on.

2.5. MXenes

In recent years, MXenes has attracted researchers’ attention as a new type of 2D material. MXenes refers to a type of material system composed of M_{2n+1}X_nTx elements, where M represents an early transition metal element, X represents C or N, and T refers to a group or modification on the surface of the 2D materials, and n usually takes a value, the range is 1–3. Figure 3 shows the three different formulas: M_{x}X, M_{x}X_{2}, and M_{x}X_{3}. MXenes has the advantages of broadband optical transmittance, fast charge transfer, tunable band gap, high level of active sites, easy modification and low cost [52]. Currently, most MXenes materials have metal-like properties and band gaps are not open or small. By reducing the size of MXenes, direct band gaps can be formed to allow radiative electron transition [53]. Both MXenes quantum dots and nanosheets show good photoluminescence properties. In addition, the metallic nature of the 2D layered MXenes provides a good platform for the photon–electron coupling on its surface. It is widely used in biological, chemical and optical sensors, surface enhanced Raman spectroscopy (SERS) and other fields [54–56].

3. Performance index of photodetector

The performance of photodetector with different sizes and working conditions can be analyzed by calculating the quality factor of the photodetectors.

3.1. Responsivity

The responsivity is called spectral responsivity or radiation sensitivity. The responsivity of photodetector generally refers to the ratio of photocurrent to incident light power, expressed as: $R(A W^{-1}) = \frac{l_P}{P}$ where P is the incident light power and $l_P$ is the difference between the total current with illumination $I_T$ and dark current $I_D$. For the photovoltaic device, responsivity is also defined as the ratio of the photogenerated voltage to the incident light power, expressed as: $R(V W^{-1}) = \frac{V}{P}$. Therefore, it is generally characterized by a spectral response curve. The wavelength ranges from $\lambda_{\text{min}}$ to $\lambda_{\text{max}}$ when the responsivity drops by half is the spectral response range of the photodetector.
3.2. Noise-equivalent power (NEP)
The noise equivalent power, called minimum measurable power, is given as signal light power illuminating on the photodetector with a signal-to-noise ratio of 1 at 1 Hz bandwidth. It characterizes the ability of photodetectors to detect weak optical signals, expressed as:
\[
\text{NEP} = \frac{I_N}{\sqrt{f}} \text{ W Hz}^{-1/2},
\]
where \(I_N\) is the noise current measured at 1 Hz bandwidth.

3.3. Quantum efficiency (QE)
If the photodetectors are to achieve high detection performance, their quantum efficiency (QE) must be high. Quantum efficiency (QE) is one of the main performance indicators of photodetectors, which is further subdivided into external quantum efficiency (EQE) and the internal quantum efficiency (IQE). When a photon is incident on the surface of the photosensitive device, part of the photons will excite the photosensitive material to generate electron-hole pairs, forming an electric current. The ratio of the collected electrons (through internal electron-hole recombination, etc) to the number of all photons illuminating the device is called external quantum efficiency (EQE), expressed as:
\[
\text{EQE} = \frac{N_c}{N_{ph}} = \frac{h c \lambda}{N_e} R \text{ A cm}^{-2} \text{ Hz}^{-1},
\]
where \(h\) is the Planck constant, \(c\) is the speed of light, \(e\) is the electron charge, \(\lambda\) is the wavelength of the incidence light and \(R\) is the responsivity of the photodetectors.

3.4. Response time (\(\tau\))
The response time (\(\tau\)) of the photodetector is a quantitative description of the response speed of the device. When the incident light is absorbed by the photodetector, the response time of the photodetector is the stable electrical signal generated by the photoelectric conversion of the device or the time required for the signal to decay to a certain value after the end of the illumination. Response time can be divided into rise time (\(\tau_r\)) and fall time (\(\tau_f\)) according to the beginning and end of light. The rise time of the detector is generally defined as the time required for the electrical signal to rise from 10% of the stable value to 90%, and the fall time is defined as the time required for the electrical signal to fall from 90% of the stable value to 10%.

3.5. Specific detectivity (D*)
The detectivity D is the reciprocal of noise equivalent power (NEP), expressed by \(D = \frac{1}{\text{NEP}}\). Specific detectivity (D*), termed as normalized detectivity, is described the detectivity of the device per unit device area and 1 Hz measurement bandwidth, represented as:
\[
D^* = \left( \frac{cm \cdot \text{W}^{-1/2}}{\text{W} \text{Hz}^{-1}} \right) = \frac{\sqrt{A_d \cdot B}}{\text{NEP}},
\]
where \(A_d\) is the area of device, \(B\) is the bandwidth and NEP is as defined above. It’s characterized that the greater the detectivity (D*), the stronger the photodetector’s ability to detect weak signals.

Figure 3. Three different formulas of MXenes: M\(_2\)X, M\(_3\)X\(_2\) and M\(_4\)X\(_3\), where M is an early transition metal and X is carbon or nitrogen, reproduced with permission [52].
3.6. Photoconductive gain (G)

The photoconductive gain (G) is defined as the ratio of photogenerated carrier lifetime (τ) to the drift transit time (τ_d) expressed as: \( G = \frac{\tau_d}{\tau} \). The photogenerated electron or hole can circulate many times in the channel and cause the photoconductive gain (G). The drift transit time (τ_d) is given as: \( \tau_d = \frac{L^2}{\mu \cdot V_{bias}} \) dependent on the carrier mobility (\( \mu \)), bias voltage (\( V_{bias} \)), and the length of the device channel (L). The photoconductive gain is also expressed as: \( G = \frac{I_p h}{P_{abs} q} \), where \( h \) is photo energy and \( P_{abs} \) is absorbed power.

4. Photocurrent generation mechanism

The dominant principle on which photodetection is the conversion of absorbed photons into a current or voltage signal and further carry out the next step. There are two types of photocurrent generation mechanisms on photodetectors. One is that photogenerated carrier as a result of absorbing photons cause the changes of semiconductor materials’ conductance, including the photoconductive effect and photogating effect etc. Another is that a Schottky barrier, formed by a semiconductor P-N junction or a semiconductor-to-metal contact under optical radiation, generates a potential owing to heating, including photo-thermoelectric, photovoltaic effect and bolometric effect etc.

4.1. Photo-thermoelectric effect

The Photo-thermoelectric effect is indirect effect rather than directly being converted into electrical signal by illumination (figures 4(a), (b)). By global illumination or local illumination, the absorption of light in different regions of the material is greatly different, which results in a temperature gradient in the channel of devices because
energy from absorbing incident light can convert into thermal motion energy of a lattice or electron. The thermal motion energy could cause temperature of detector element rise and finally change the electrical properties of the detector element. The Seebeck effect refers to the thermoelectric effect of a potential difference in the direction of the temperature gradient due to a temperature gradient is added to the conductor. According to it, temperature gradient will change into Potential difference, given as

\[ V_{PTE} = (S_2 - S_1) \Delta T, \]

where \( S_1 \) and \( S_2 \) are the thermoelectric coefficient of material (Seebeck coefficients) in units of V/K. Due to materials’ thermoelectric coefficient relating to its conductance, it can be expressed by Mott formula:

\[ S = \frac{dV}{dT} = \frac{-\pi^2 k_B T}{4e \sigma} \]

where \( k_B \) is Boltzmann Constant, \( e \) is the energy based on the Fermi energy and \( \sigma \) is conductance. The device operates at no bias voltage based on photo-thermoelectric effect.

4.2. Bolometric effect
The bolometric effect is associated with increase of temperature owing to material absorbing photon, then variation of materials’ conductance and is widely used in the wavelength range of submillimeter (THz), where they are among the most sensitive detectors. Unlike the photo-thermoelectric effect, the bolometric effect doesn’t work without applying an external bias and must operate at a uniform temperature without temperature difference at both ends of the junction. The change of materials’ conductance, such as increase of metal resistance or decrease of semiconductor resistance, can be measured by four-probe method (figures 4(c), (d)).

4.3. Photovoltaic effect
Due to the separation of photogenerated electron-hole pairs by built-in electric field at a p-n junction or a Schottky junction, photocurrent generates when absorbing incident photon energy is greater than material bandgap energy. In the open circuit case, separated electron-hole pairs would be accumulated at the opposite junction, resulting in an open circuit voltage (Voc) whose direction is contrary to built-in electric field. The same seems to be happening without illumination when the source–drain applies a bias voltage (Vbias) in order to create an external electric field (figures 5(a), (b)). In addition, the built-in electric field can be introduced in different ways: by taking advantage of the work function difference between semiconductor and a contacting metal, by local chemical doping [12] or electrostatically using gates.

4.4. Photoconductive effect
The photoconductive effect is that semiconductor material which absorbed photon energy, could cause the increase of free carrier concentration and excite electron-hole pair, and subsequently the conductivity of the semiconductor material is changed (figure 6(a), (b)). If absorbing photon energy is greater than bandgap of semiconductor material, it will generate electron–hole pairs whose direction of propagation is different from electric field driven by the applied bias, forming the photocurrent. It can be inferred that the photocurrent generated under the light radiation is:

\[ I = \frac{qN}{L} \left( \tau_e \mu_n + \tau_p \mu_p \right), \]

where \( qN \) is the internal current formed by photoelectrons, \( V \) is a applied bias, \( L \) is the length of channel, \( \mu_n, \mu_p \) is mobility of electron and hole and \( \tau_e, \tau_p \) is the lifetime of N electron-hole pairs generated per unit time under irradiation. Extremely, unlike the photovoltaic effect producing photocurrent with no need for an applied bias, the photoconductive effect is impossibly achieved under the same condition.
4.5. Photogating effect
The photogating effect, which is commonly found in 2D material photodetector due to existing the local state such as surface state or defect, is an exceptional case of photoconductive effect. If the electrons or holes generated from illumination excitation are trapped in trap states of 2D material, the charged trap states carrying a similar function of gate voltage can serve as a localized gate effectively modulating the carrier density ($D_n$) of channel and further affecting the conductance ($s_D$) of 2D material. Its conductance could be expressed by $s_D = mDn\mu$, where $\mu$ is the mobility. The essential difference to the bolometric effect, which is based on the change in $\mu$ owing to heat, is that the photogating effect is dependent on a light-excited change in $n$. The process of detrapping is slow, which can greatly prolong the lifetime of photogenerated carriers and achieve high gain, then further a high photo-responsivity of photodetector can be obtained (figure 6(c)).

4.6. Dyakonov-Shur (Plasma-wave-assisted mechanism)
Dyakonov and Shur [60] have shown that a steady DC current flow in a ballistic field effect transistor (FET) may be unstable, and a relatively low drain current should induce plasma oscillation in the terahertz frequency range. It's shown that under an appropriate bias conditions, the plasma wave in the channel will amplify, called the Dyakonov and Shur effect or plasma-wave-assisted mechanism since a FET carrying a 2D electron gas can serve as a plasma waves cavity (collective density oscillations).

5. Photodetectors based on two-dimensional materials with different wavelengths
2D materials have the diversity of electronic structures, the optical response can be allowed from ultraviolet (UV) to terahertz. Herein, we highlight the photodetector of 2D materials on visible to terahertz.

5.1. Photodetectors in visible, near infrared, and short-wave infrared range
The wavelength range of visible light is 400 to 750 nm, while near infrared (NIR) range is usually in the range from 750 nm to 1.1 $\mu$m. The wavelength range of short-wave infrared (SWIR) is 1 to 3 $\mu$m. Photodetectors have many important applications in visible light, near infrared, and shortwave infrared, especially in biomedical imaging, communications, and night vision thermal imaging and so on [61–63]. Performance of photodetectors based on 2D materials in visible light, near infrared and shortwave infrared are summarized in table 1.

In order to enhance the responsivity of the photodetector, Thomas Mueller et al studied graphene photodetectors [65]. The photodetector adopted a crossed metal-graphene-metal structure and used the photovoltaic effect to effectively separate photogenerated carriers for photodetection. The mirror symmetry of the internal electric field profile of the traditional device was broken, and the maximum responsivity of 6.1 mA W$^{-1}$ was achieved at a wavelength of 1.55 $\mu$m. By using metal fingers with different metal materials, dark currents can be reduced, effective light detection area can be increased, and electric field can be enhanced. In order to enhance the photodetection capability, Marco Furch demonstrated that by monolithically integrating graphene with a Fabry-Pérot microcavity. Graphene microcavity photodetector is shown schematically in figure 7(a). The light absorption rate of graphene was increased by the enhancement of the light field in the resonance cavity, graphene-based microcavity photodetector with a responsivity of 21 mA W$^{-1}$ [64].
Gate was used to improve the MoS2 mobility of phototransistors. Figure 7 appeals for optoelectronic device applications.

Topological insulator (TI) materials have unique physical properties such as strong spin–orbit interaction and bulk band inversion [93, 94]. Bismuth telluride (Bi2Te3) is a new topological insulator material with a band gap of 0.21 eV, which has important application value in infrared detection [35]. Zhang Hongbin et al demonstrated that the Bi2Te3-based photodetector had stable optical response and high sensitivity to visible light and NIR (figure S(a)) [96]. Juan et al demonstrated a silicon-based single crystal Bi2Te3 photodetector, which had obvious sensitivity to 1064 nm and 1550 nm lasers at room temperature, but the responsivity was low (figure 8(b)) [97].

InSb 980 nm 7870 A W−1 10, 10 [36]
SnS 660 nm 927 A W−1 10, 10 [37]
InSe 980 nm 7870 A W−1 10, 10 [38]
Sb2Se3 300–1000 nm 4320 mA W−1 10, 10 [39]
Bi2Se3 735 nm 10.1 mA W−1 10, 10 [40]
Bi2Te3 300–1000 nm 201 A W−1 10, 10 [41]
InSb 940 nm 311.5 A W−1 10, 10 [42]
Sb0.55Te0.45 1.55 μm 1.5 A W−1 10, 10 [43]
Tellurene 520 nm, 1.55 μm and 3.39 μm 383 A W−1, 19.2 and 18.9 mA W−1 10, 10 [44]

| Material | Wavelength | Responsivity | References |
|----------|-------------|--------------|------------|
| Graphene | 855 nm      | 21 mA W−1    | [64]       |
| Graphene | 1550 nm     | 6.1 × 10−3 A W−1 | [65]     |
| BP       | 400–900 nm  | 7 × 106 A W−1 | [66]       |
| BP       | 400–1700 nm | 4.5 × 10−4 A W−1 | [67]     |
| BP       | 2004 nm     | 2163 A W−1   | [68]       |
| ReS2     | 532 nm      | 8.8 × 104 A W−1 | [69]     |
| ReS2     | 633 nm      | 95 A W−1     | [70]       |
| PtS2     | 500 nm      | 1.56 × 107 A W−1 | [71]     |
| PdSe2    | 1064 nm     | 708 A W−1    | [72]       |
| PtSe2    | 765 nm      | 1.4 mA W−1   | [73]       |
| MoS2     | 532 nm      | 2200 A W−1   | [74]       |
| MoS2     | 400–680 nm  | 880 A W−1    | [75]       |
| MoS2     | 532 nm      | 59 A W−1     | [76]       |
| Mo2      | 500–1100 nm | 0.1 A W−1    | [77]       |
| MoTe2    | 0.6–1.75 μm | 0.03 A W−1   | [78]       |
| WS2      | Visible to NIR | 1050 A W−1 | [79]       |
| WSe2     | 520, 852 nm | 0.25, 2 A W−1 | [80]     |
| SnS      | 660 nm      | 927 A W−1    | [81]       |
| InSe     | 980 nm      | 7870 A W−1   | [82]       |
| Sb2Se3   | 300–1000 nm | 4320 mA W−1  | [83]       |
| Bi2Se3   | 735 nm      | 10.1 mA W−1  | [84]       |
| Bi2Te3   | 300–1000 nm | 201 A W−1    | [85]       |
| InSb     | 940 nm      | 311.5 A W−1  | [86]       |
| Sb0.55Te0.45 | 1.55 μm | 1.5 A W−1    | [87]       |
| Tellurene | 520 nm, 1.55 μm and 3.39 μm | 383 A W−1, 19.2 and 18.9 mA W−1 | [88] |

Table 1. Visible, near infrared, and short-wave infrared photodetectors based on 2D materials.

TMDCs exhibit strong light-material interaction in the visible to NIR wavelength range, which have certain appeal for optoelectronic device applications [91, 92]. Yin Zongyou et al first studied single-layer MoS2 phototransistors. Figure 7(b) shows an optical image of a single-layer MoS2 FET device. Compared with graphene-based devices, single-layer MoS2 phototransistors achieved a better optical response [89]. Hee Sung Lee made top-gate phototransistors based on single, double, and triple-layer MoS2 nanosheets (figure 7(c)). The thickness of the MoS2 nanosheet was used to modulate the optical gap, while the transparent and patterned top gate was used to improve the MoS2 mobility [90].

The zero-band gap of graphene and the low mobility of TMDCs have their limitations in the application of detectors. It is essential to find suitable 2D semiconductor materials to improve the stability of the device. Topological insulator (TI) materials have unique physical properties such as strong spin–orbit interaction and bulk band inversion [93, 94]. Bismuth telluride (Bi2Te3) is a new topological insulator material with a band gap of 0.21 eV, which has important application value in infrared detection [35]. Zhang Hongbin et al demonstrated that the Bi2Te3-based photodetector had stable optical response and high sensitivity to visible light and NIR (figure S(a)) [96]. Juan et al demonstrated a silicon-based single crystal Bi2Te3 photodetector, which had obvious sensitivity to 1064 nm and 1550 nm lasers at room temperature, but the responsivity was low (figure 8(b)) [97].
Although the responsivity of the above-mentioned Bi$_2$Te$_3$ photodetector was lower than other 2D materials, it provided an attractive material platform for exploring the performance and practical application of topological insulators. In 2019, J L Liu studied a NIR flexible photodetector based on vdW-grown Bi$_2$Te$_3$ nanoplates, reaching a high responsivity of 55.06 mA W$^{-1}$ (figure 8(c)) [98]. Bi$_2$Te$_3$-photodetector was far superior to other semiconductor nanostructured near-infrared detectors.

BP is a narrow bandgap semiconductor material covering a spectral range from visible light to near-infrared, which gives BP a good prospect in the application of broadband photodetectors. In 2014, Michael Engel et al. studied a photodetector made of multiple layers of black phosphorus, recording images of microscopic patterns in the visible and near-infrared spectral regime (figure 8(d)) [99]. In 2016, Huang Mingqiang et al. demonstrated a high-performance BP-based photodetector with a wavelength range of 400 to 900 nm, demonstrating a high responsivity (figure 8(e)) [66]. In 2017, Huang Li by utilizing the electrostatic gating effect, BP phototransistors achieved a responsivity of 8.5 A W$^{-1}$ and a low noise equivalent power (NEP) of less than 1 pW/Hz$^{1/2}$ at 2 $\mu$m by applying a small source-drain bias (figure 8(f)) [100]. The method is simple and effective, and the detection capability of BP photodetector can be constantly adjusted. At the same time, Tan et al. showed a tunable black phosphor carbide (b-PC) infrared phototransistor with a wavelength of 2004 nm. The responsivity was up to 2163 A W$^{-1}$, and the minimum carrier life was 0.7 nanoseconds through gate control [68].

5.2. Photodetectors in mid infrared range

Mid-infrared light (MIR) is usually in the range from 3 $\mu$m to 30 $\mu$m and is an area of interest in many scientific and technological applications. Photodetectors working at MIR have many important applications especially like biomedicine, free space communications, and environmental monitoring and so on [101–104]. Performance of photodetectors based on 2D materials in MIR are summarized in table 2.

The advantages of graphene such as high mobility [1] and tunable optical properties [2] are the first to be used as an ideal 2D material on the photodetectors [17]. However, the weaker light absorption and zero-band gap limitations of graphene-based photodetectors result in high dark current and noise. In order to overcome the existing obstacles, researchers have made a lot of efforts, Graphene-based MIR photodetectors of various structure types have developed rapidly.

In 2013, Zhang Yongzhe et al. introduced an electron trapping center and creating a bandgap in graphene through band structure engineering. Figures 9(a)–(c) shows graphene quantum dot-like (GQD) array FET structure and electrical characteristics of the samples. The photodetector achieved a broadband photoresponse.
with high responsivity from the visible to the MIR \cite{106}. In 2014, Liu Changhua et al studied a broadband photodetector based on two graphene layers sandwiching a thin tunnel barrier. Figures 9(d)–(f) shows the graphene double-layer device structure, (c), (f) gate dependence of photocurrent under different illumination powers with excitation wavelengths at 1.3 μm and 2.1 μm, reproduced with permission \cite{105}. In addition to graphene, BP has a moderate band gap and high carrier mobility, which can suppress dark current. In addition, BP is suitable for integration with traditional electronic materials such as silicon and can be placed on different substrates \cite{116}. In 2016, Ryan J Suess et al proposed a photodetector using BP photoconductive effect to detect mid infrared light at room temperature, which had nano scale response time and thermal noise limiting performance \cite{113}. At the same time, Xu Mei et al achieved an optical response in the mid-infrared range from 2.5 to 3.7 μm through photovoltaic and photogating effects \cite{110}. Guo Qiushi et al studied a BP broadband detector. The photoresponsivity was up to 82 A W\(^{-1}\) at 3.39 μm (figures 10(a), (b)). The advantage of this device is that it has low dark current and high light guide gain \cite{108}. Chen Xiaolong et al studied a mid-infrared photodetector based on hexagonal boron nitride (hBN)/BP/hBN-sandwiched heterostructure (figure 10(c)). By using hBN not only to prevent oxidation of BP but also to ensure ultra-clean interface. The response wavelength of the photodetector reached 7.7 μm \cite{107}. Skylar Deckoff-Jones et al first showed the waveguide-integrated BP mid-infrared photodetectors, which provided a new platform for the research of 2D materials.

Table 2. Mid infrared photodetectors based on 2D materials.

| Material   | Frequency | Responsivity | References |
|------------|-----------|--------------|------------|
| Graphene   | 3.2 μm    | 1.1 A W\(^{-1}\) | \cite{105} |
| Graphene   | 0.532–10 μm | 0.4 A W\(^{-1}\) | \cite{106} |
| BP         | 3.4,5,7,7 μm | 518,30,2.2 mA W\(^{-1}\) | \cite{107} |
| BP         | 3.39 μm   | 82 A W\(^{-1}\) | \cite{108} |
| b-As\(_{0.83}P_{0.17}\) | 3.4,5,7,7 μm | 190,16,1.2 mA W\(^{-1}\) | \cite{109} |
| BP         | 3.7 μm    | 21 mA W\(^{-1}\) | \cite{110} |
| BP         | 3.68,4 μm | 25.2 A W\(^{-1}\) | \cite{111} |
| BP         | 0.4–3.75 μm | — | \cite{112} |
| BP         | 1.56–3.75 μm | — | \cite{113} |
| b-PC       | 8 μm      | 2163 A W\(^{-1}\) | \cite{68} |
| PtTe\(_2\) | 10.6 μm   | 0.67 mA W\(^{-1}\) | \cite{114} |
| SnSe       | 10.6 μm   | 0.16 A W\(^{-1}\) | \cite{115} |

Figure 9. (a) Graphene quantum dot-like (GQD) array structure, (b), (c) The electrical characteristics as a function of the gate voltage (transfer curve); the inset shows the I–V curves under different gate voltages. The Dirac point occurs at \(V_{\text{G}} \approx 60\) V, reproduced with permission \cite{106}; (d) Graphene double-layer device structure, (e), (f) gate dependence of photocurrent under different illumination powers with excitation wavelengths at 1.3 μm and 2.1 μm, reproduced with permission \cite{105}.
material photodetectors [117]. Huang Li et al used silicon waveguide and grating structures to overcome the limitation of BP thickness on absorption length and enhanced the interaction between light and BP (Figure 10(d)). The BP photodetector achieved a responsivity of 23 A W⁻¹ at 3.68 μm and 2 A W⁻¹ at 4 μm and a NEP less than 1 nW/Hz¹/₂ at room temperature (Figure 10(e)) [111]. The integration of waveguide and photodetector enables the miniaturization of photosystem. Black arsenic phosphorus (b-AsP) is a material similar to BP. It is an alloy of BP and As atoms in the form of AsₓP₁₋ₓ, b-AsP as a new narrow bandgap semiconductor. The dark current and noise can be effectively reduced by using the good optical properties of b-AsP and the simple manufacturing method of vdW heterojunction. By changing the composition ratio of P, the band gap changes accordingly from 0.3 to 0.15 eV, indicating that b-AsP can detect wavelengths up to 8.5 μm [118]. In the same year, Matin Amani et al performed a systematic investigation gated-photoconductors based on b-Pas alloys as a function of thickness over the composition range of 0−91% As. The cut-off wavelength can be adjusted from 3.9 to 4.6 μm [119]. In 2018, Yuan Shaofan et al showed that b-As₀.₆₈P₀.₁₇ covers the wavelength range of 3.4 to 7.7 μm, significantly extending the operating wavelength range of photonic devices [109], and hBN packaging provided long-term air stability for the device.

5.3. Photodetectors in terahertz range

Terahertz (THz) light is typically defined as the light wavelength range from 30 μm ~ 3 mm. This frequency range lies in the transition area between photonics and electronics and has the unique advantage of photon radiation. However, due to the lack of a stable THz source and detector, this electromagnetic spectrum needs to be developed. Based on the excellent electronic and optoelectronic properties of 2D materials, the detection of weak THz signals can be achieved through various mechanisms. Performance of photodetectors based on 2D materials in THz are summarized in Table 3.

In 2012, L. Vicarelli et al studied a THz photodetector based on antenna-coupled graphene field effect transistors at 0.3 THz. This device can work efficiently at room temperature, realizing large-area and rapid imaging of samples [125]. In 2014, Audrey Zak et al proposed a THz photodetector based on a split bow-tie antenna integrated graphene field effect transistor. The photodetector was capable of room-temperature...
rectification of a 0.6 THz signal with a responsivity of 14 V W$^{-1}$ and a minimum noise equivalent power (NEP) was 515 pW/Hz$^{0.5}$ [126].

The photothermoelectric (PTE) effect is rooted in the Seebeck effect, semiconductor with a temperature difference at both ends. And carriers in a high-temperature region have more energy and faster speed than carriers in a low-temperature region. The THz photodetector based on the PTE effect can realize high responsivity, ultra-wideband and room temperature photodetection. Cai Xinghan et al. showed a graphene thermoelectric THz detector with asymmetric electrodes. At room temperature, the responsivity was up to 10 V W$^{-1}$ [127]. The gate voltage can adjust the Fermi level of graphene to achieve different optical response. Sebastian Castilla et al. optimized the PTE-THz photodetector with a narrow-gap dual-gated, dipole antenna structure, so that incident THz light was collected at the small photoactive area of the photodetector. This device resulted in a strong enhancement of THz absorption in graphene. Figure 11(a) shows a graphene antenna-integrated pn junction device. The device realized THz light detection in the picosecond range [137].

Table 3. THz photodetectors based on 2D materials.

| Material         | Frequency | Responsivity | NEP       | References |
|------------------|-----------|--------------|-----------|------------|
| Graphene         | 0.1 THz   | 1000 V W$^{-1}$ | —         | [120]      |
| Graphene         | 0.12 THz  | 280 V W$^{-1}$ | 100 pW/Hz$^{0.5}$ | [121] |
| Graphene         | 0.13 THz  | 20 V W$^{-1}$ | 0.6 nW/Hz$^{0.5}$ | [122] |
| Graphene         | 0.14 THz  | 6.0 kW W$^{-1}$ | 0.1 nW/Hz$^{0.5}$ | [123] |
| Graphene         | 0.15 THz  | 400 V W$^{-1}$ | 0.5 nW/Hz$^{0.5}$ | [124] |
| Graphene         | 0.3 THz   | 0.15 V W$^{-1}$ | 30 nW/Hz$^{0.5}$ | [125] |
| Graphene         | 0.6 THz   | 14 V W$^{-1}$ | 515 Pw/THz$^{-0.5}$ | [126] |
| Graphene         | 2.52 THz  | >10 V W$^{-1}$ | 1100 Pw/Hz$^{0.5}$ | [127] |
| BP               | 0.12 THz  | 297 V W$^{-1}$ | 58 Pw/Hz$^{0.5}$ | [128] |
| BP               | 0.15 THz  | 300 V W$^{-1}$ | 1 nW/Hz$^{0.5}$ | [129] |
| BP               | 0.3 THz   | 7.5 V W$^{-1}$ | 4 nW/Hz$^{0.5}$ | [130] |
| BP               | 0.3 THz   | 0.15 V W$^{-1}$ | 40 nW/Hz$^{0.5}$ | [131] |
| BP               | 0.3 THz   | 0.9 mV W$^{-1}$ | —         | [132] |
| Se-doped BP      | 3.4 THz   | 3 V W$^{-1}$ | 7 nW/Hz$^{0.5}$ | [133] |
| Bi$_2$Se$_3$     | 0.12 THz  | 75 A W$^{-1}$ | 36 pW/Hz$^{0.5}$ | [134] |
| PTTe$_2$         | 0.12 THz  | 102 V W$^{-1}$ | 10 pW/Hz$^{0.5}$ | [135] |
| PDTe$_2$         | 0.12 THz  | 10 A W$^{-1}$ | 2 pW/Hz$^{0.5}$ | [136] |

Figure 11. (a) Schematic diagram of the antenna-integrated pn junction device, (b) The photocurrent was amplified by a current preamplifier (Femto) and the data were acquired with a fast oscilloscope. The inset shows how the photocurrent $V_{\text{PTE}}$ follows the switching of the pulsed laser, reproduced with permission [137], (c) Schematic diagram of the PTE device, (d) The pulsed current response at various excitation frequencies, reproduced with permission, (e) The optical picture of a metallic key and THz image for the key enclosed in an envelope, reproduced with permission [128].
shortcomings of the photodetector in terms of sensitivity, speed, operating temperature and spectral range provide a solution. Guo Wanlong et al reported the THz detection of the PTE effect based on the BP ultra-short channel (figure 11(c)). The hot carrier flow was realized by asymmetric Cr/Au and Ti/Au through angular evaporation technology [128]. Figure 11(d)–(e) shows the pulsed current response at various excitation frequencies and THz image for the key. The photodetector exhibited excellent sensitivity of 297 V W$^{-1}$ and the NEP was less than 58 pW/Hz$^{0.5}$. It is better than other thermal effect detectors at room temperature. The surface of BP exposed to the environment is easily oxidized and degraded. Dopants can be used to make BP have better transmission performance and higher stability. Leonardo Viti et al designed antenna-coupled field-effect transistors to integrate selenium-doped BP sheets with different thicknesses into active channels. The asymmetric structure realized THz light detection, the response band reached 3.4 THz and the maximum responsivity at room temperature was up to 3 V W$^{-1}$ [133]. The doped BP flakes reduced the degree of oxidation to a certain extent, so that the device have a better stability.

Weak electrons in 2D materials interact with phonons, and hot carriers can be efficiently manipulated to enhance the photocurrent response [138]. The photoelectric conversion through carriers makes the THz photodetector has a large response speed and sensitivity. Liu Changlong et al studied a new type of high-gain photodetector based on hot carriers manipulation (figures 12(a), (b)). By designing a deep sub-wavelength structure, the graphene photodetector with a log-periodic antenna had a responsivity of 4 kV W$^{-1}$ in the THz band (figure 12(c)) [121]. Hot carriers assist the rapid generation or recombination of graphene carriers and electrons in metal electrodes. The electromagnetic field is analogous to the gate in a field-effect transistor to regulate the conductivity in the channel. Further, they concentrated the light field in a split gate structure, which can lead to high photoconductive gain (figure 12(d)). At room temperature, the responsivity was up to 6.6–6 kV W$^{-1}$, and the NEP was less than 0.1 nw/Hz$^{0.5}$ (figure 12(e)) [123]. The split-finger structure enhanced the focusing effect of the device channel on the THz, so that the device had a high photoconductance gain. Finally, the electrostatic control of the gate can realize the conversion of different working modes of the device.

In addition to graphene, BP and other 2D materials, Tang Weii et al proposed a direct detection of THz photons based on sub-wavelength metal-topological insulator-metal (MTM) structure. Topological insulator Bi$_2$Se$_3$ as the activity material of photodetector. Figure 13(a) shows device structure of Bi$_2$Se$_3$-based MTM photodetector. Figure 13(b) shows the responsivity dependence on bias voltage under irradiation with 0.12 THz radiation and response time. For self-powered and bias-mode devices operating at room temperature, 0.3 THz photon responsivity exceed 75 and 475 A W$^{-1}$ [134]. Xu Huang et al used a 2D thin sheet of PtTe$_2$ material to contact a bow-tie antenna electrode with a sub-wavelength gap to the material to form a channel to enhance the absorption of terahertz millimeter waves by the detector (figure 13(c)). Under zero bias voltage, the responsivity
of the detector at 0.12 THz reached more than 1.6 A W$^{-1}$ [135], which was much higher than that of graphene-based THz photodetectors (figure 13(d)).

5.4. Photodetectors based on 2D heterostructures

2D materials can be easily prepared with different combinations of 2D material heterojunctions by mechanical transfer and stacking. Due to the combination of van der Waals forces between layers, there will be no lattice mismatch problem. And it has more rich energy band structure. Therefore, photodetectors based on 2D material heterojunctions have broad application prospects. Graphene and TMDCs form a heterojunction, so that the zero-bandgap graphene and wide-bandgap TMDCs photodetectors have a broad response spectrum. In 2016, Gao Anyuan et al studied graphene/WSe$_2$ heterojunctions photodetector (figure 14(a)), demonstrating excellent light detection performance [139]. In 2017, Bao and co-workers reported on MoTe$_2$/graphene heterojunction near-infrared photodetector (figure 14(b)). The responsivity of the photodetector at 1064 nm wavelength reached 970.82 A W$^{-1}$ and wide-band optical detection is achieved [140]. Due to the ultra-high carrier mobility of graphene, the photocurrent of the device is greatly enhanced. Therefore, the device achieved a high responsivity. Black phosphorus has a moderate band gap and anisotropy. Liu Yan et al reported high-responsivity near-infrared detection of graphene/BP heterojunction photodetector (figure 14(c)) [141].

Graphene is a high-efficiency carrier transport layer and reduces the Schottky barrier between BP and metal. The responsivity of the device at 1550 nm reached $3.3 \times 10^3$ A W$^{-1}$. Leonardo Viti et al studied THz detection based on hBN-BP-hBN heterojunction photodetector [142], Yuan Shaofan et al studied a mid-infrared photodetector based on hBN/black arsenic phosphorus/hBN heterojunction (figure 14(d)) [143]. hBN has a wide band gap and strong chemical stability. As a protective layer of BP and black arsenic phosphorus, hBN improved the stability of the device in the air.

Silicon is the most widely used semiconductor material. We discussed the photoelectric performance of heterojunction detectors based on 2D materials and silicon. In 2015, Wang Liu et al studied MoS$_2$/Si heterojunction photodetector. The detectivity of device was up to $10^{15}$ Jones, the response time was about 3 $\mu$s, and the device exhibited stability in air [149]. In 2016, Mao Jie et al reported a high-performance Graphene/MoS$_2$/Si heterojunction photodetector. The vertical structure of MoS$_2$ had stronger light absorption capacity and broadened the spectral range of the photodetector, enabling the device to absorb ultraviolet light to near-infrared light (figure 14(h)) [147]. In the same year, Zhang Hongbin et al reported Bi$_2$Se$_3$/Si heterostructure photodetector. The photodetector exhibited excellent sensitivity of 297 V W$^{-1}$, a high detectivity of $4.39 \times 10^{13}$ Jones and fast response speed [150]. In 2018, Peng Xiao reported, for the first time, the reduced graphene oxide (RGO)-MoS$_2$ composite film/pyramid Si heterojunction. The photodetector had ultra-
wideband detection capability from ultraviolet (UV) to mid-infrared (figure 14) [146]. In 2020, Lu Zhijian demonstrated, for the first time, the fabrication of few-layer (FL)-MoTe$_2$/Si heterojunction for high-speed and broadband photodiodes by pulsed laser deposition technique. The photodetector exhibited a high responsivity of $0.19 \, \text{A W}^{-1}$ and a large detectivity of $6.8 \times 10^{13} \text{Jones}$ (figure 14(e)) [144]. Palladium selenide (PdSe$_2$) was also an emerging high mobility 2D TMDs. Wu Di demonstrated a highly polarization-sensitive, broadband, self-powered photodetector based on graphene/PdSe$_2$/germanium heterojunction (figure 14(f)) [145]. Zeng Longhui developed a fast, self-powered, highly polarization-sensitive, and broadband photodetector by integrating PdSe$_2$ with Cs-doped FAPbI$_3$ (figure 14(i)). The responsivity was up to $313 \, \text{mA W}^{-1}$ and specific detectivity ($\approx 10^{13} \text{Jones}$) [148].

6. Summary and outlook

In this paper, we first introduced the synthesis and properties of 2D materials. Secondly, we introduced the performance indicators of photodetectors and the generation mechanism of photocurrent. And finally, we summarized the application of 2D materials and heterojunction photodetectors in various wave bands.

Since the discovery of graphene, variety of 2D materials have emerged, and their excellent characteristics have been applied to photodetectors. At present, 2D material photodetectors still face many challenges. First of all, most high-quality 2D materials are obtained by micromechanical exfoliation, but they cannot be produced in large areas and cannot be applied to actual production. Furthermore, the contact barrier between the 2D materials and the electrode is relatively high, and the stability of the device is poor. More importantly, many new photodetection mechanisms need to be further explored. For high-performance and excellent photodetectors, the following methods can be adopted: to improve the preparation method of 2D materials, to be able to prepare high-quality 2D materials, and to design and optimize the antenna structure to match the detected wavelength and improve the sensitivity of the photodetector.
In general, with the in-depth study of 2D materials in the future, there will be more high-performance 2D materials, and photodetectors based on 2D materials in the future will have good development and application prospects.

**ORCID iDs**

Kai Xu Zhang  
Li Han  
Lin Wang

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