Two-Dimensional Materials for Optoelectronics Applications

Subjects: Nanoscience & Nanotechnology

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The past one and a half decades have witnessed the tremendous progress of two-dimensional (2D) crystals, including graphene, transition-metal dichalcogenides, black phosphorus, MXenes, hexagonal boron nitride, etc., in a variety of fields. The key to their success is their unique structural, electrical, mechanical and optical properties. Two-dimensional materials are layered crystalline solids that have strong bonding in the crystal plane, while the forces between the adjacent atomic layers are weak van-der-Waals forces. The special structure of 2D materials endows them with many remarkable abilities.

Keywords: two-dimensional materials ; graphene ; transition-metal dichalcogenides

1. Introduction

Graphene, as a representative two-dimensional (2D) material, has attracted considerable attention since it was mechanically exfoliated from bulk graphite in 2004 [1]. Its special two-dimensional honeycomb lattice endows it with numerous excellent properties such as high carrier mobility, high mechanical strength, excellent optical transparency, and a wide absorption spectrum [2][3], which makes it exhibit great application potential in many areas [4]. The discovery and development of graphene has further stimulated research interests in other 2D materials.

Two-dimensional materials are layered crystalline solids that have strong bonding in the crystal plane, while the forces between the adjacent atomic layers are weak van-der-Waals forces [5][6][7]. The special structure of 2D materials endows them with many remarkable abilities. First, quantum confinement in the direction perpendicular to the 2D plane introduces some novel optical and electronic performances to 2D materials, which are distinct from their bulk parent materials [8]. Second, the surfaces of these materials are naturally passivated and they have no dangling bond, which facilitates the integration of 2D materials with photonic structures [8][9]. In addition, using diverse 2D materials can build vertical heterostructures, in which the different layers are bonded by van der Waals forces, averting the issue of lattice mismatch. Third, a host of 2D materials can interact strongly with light [10]. For instance, monolayer MoS_2 can absorb nearly 10% of perpendicular incident light at excitonic resonances [11]. Finally, 2D materials can cover a broad range of electromagnetic spectra due to their different electronic properties [12]. Due to their special properties, 2D materials show great application potential in various fields, especially in optoelectronics applications [13][14][15]. For example, graphene has become a potential candidate in the applications of light modulation, detection and manipulation because it can interact with light in a wide range of spectra. Some transition metal dichalcogenides (TMDCs) such as MoS_2 and WS_2 have sizable bandgaps and possess illustrious light-emitting performances, ensuring their applications in photodetectors, transistors, and other optoelectronics devices [8][16].

2. Transition Metal Dichalcogenides

2.1. Basic Structure and Property

TMDCs are a class of materials with the formula of MX_2, where M is the transition metal element from group IV (Ti, Zr, Hf, and so on), group V (for instance V, Nb, and Ta) or group VI (Mo, W and so on), and X is a chalcogen (S, Se or Te) [17].

MX_2 are indirect bandgap semiconductors [18][19], whereas their monolayers have direct bandgaps, which are favorable for optoelectronic applications [20]. Native bandgap provides an excellent current on/off ratio in field-effect transistors (FETs) [21]. Their bandgap can be tuned based on the layer thickness, greatly expanding their range of applications in photonic devices.

TMDCs have excellent optical properties and a wide range of application prospects in the fields of light detection and photoluminescence. MoS_2 is a commonly used MX_2 nanomaterial. Although the photoluminescence of bulk MoS_2 is not obvious, the monolayer MoS_2 has strong photoluminescence [22], so the monolayer MoS_2 can be used in solar panels, photodetectors, and photovoltaic emitters.

The photoluminescence of TMDCs is closely related to the layer thickness. The photoluminescence of MoS_2 increases as the number of layers decreases, and the strongest photoluminescence is observed for a single layer [22]. Photoluminescence and Raman characterizations show that the direct bandgap can be blue-shifted for ~300 meV per 1% strain, which can effectively modulate its energy band structure [23]. In addition, the doping treatment can also significantly modulate the photoluminescence peak intensity of MoS_2 [24].

2.2. Production Methods

The preparation of large-area, high-quality 2D TMDCs is a prerequisite for electronic device applications, and there are two main types of preparation methods: top-down and bottom-up methods [25]. The top-down method is a method to obtain 2D TMDCs by chemical or mechanical exfoliation from the bulk material, while the bottom-up method is a method to prepare 2D TMDCs by CVD or thermal decomposition. Exfoliation procedures can produce 2D materials with the best accessible quality, and thus the method is widely used to prepare samples for fundamental physics and device studies [26]. However, this method is time-consuming and cannot be scaled up, which will provide significant challenges for large-scale implementation in the future. Physical and chemical processes provide another way to manufacture nanosheet materials, with the intention of achieving controllable, high-quality, and large-scale nanosheets. Among the numerous chemical synthesis methods including CVD, the hydrothermal method, laser-induced synthesis, and molecular beam epitaxy (MBE), CVD has the most potential for realizing controllable, high-quality, wafer-scale 2D TMDCs [27]. PVD is also a viable option for producing high-quality TMDCs on a large scale. PVD has been proven on TMDCs films for several decades with homogeneity across wide areas for various materials, and it is created at low processing temperatures. The most often utilized PVD-based technologies investigated for depositing TMDCs materials include sputtering and pulsed laser deposition (PLD) [26][28][29]. PLD is an alternate method for synthesizing TMDCs thin films with a wide area and homogeneity at low growing temperatures. Except for Si substrate, PLD is also suitable for various substrates such as Al_2O_3, GaN, and SiC-6H [30], on which MoS_2 shows a high degree of crystallinity and out-of-plane texture. Anti-position defects are usually observed in the samples that are prepared via the PVD method, while the vacancy defects that are usually found in the TMDCs films are prepared by the CVD method [31]. PVD approaches can obtain large-scale and uniform TMDC films for devices and circuits. However, they perform at a lower quality than chemical methods and exfoliation approaches because of small domains and numerous defects [32].

2.3. Optical Applications

Single-layer TMDCs are atomically thin and processable. They have primarily direct bandgaps; hence, they have great potential for applications in flexible and transparent optoelectronics.

2.3.1. Light-Emitting Diodes

A light-emitting diode (LED) is an optical source in which photons are generated by the electroluminescence (EL) effect [33][34]. Electrons and holes are permitted to recombine in a p-n junction so that the recombination energy can be released as photons in response to injected electrical bias currents. This is because of the availability of a large variety of direct bandgap TMDC monolayers with excellent photoluminescence quantum yield at sub-nanometer thicknesses [35][36][37]. TMDC materials have recently been investigated for their usage in LED fabrication. Due to several thermally aided processes resulting from impact ionization across a Schottky junction or a p-n junction [38][39][40], the EL is observed in various MoS_2 monolayer based devices [40]. However, because of the low optical quality of MoS_2 and the inadequate electrode connections, poor EL efficiency and considerable linewidth widening are found [41]. Due to the decreased contact resistance, increased current density, and the effective current injection, 2D TMDC-based heterostructure LEDs exhibit a high EL efficiency [41].

2.3.2. Solar Cells

As clean and renewable energy sources are widely studied, the photovoltaics (PV) effect has attracted the attention of many because it shows great application potential in energy harvesting. Due to the enormous surface area, lack of dangling chemical bonds on surfaces, and their potential as sunlight absorbers, 2D TMDC materials are regarded as promising prospects for solar applications. Two-dimensional TMDCs are applied in solar cells by forming a Schottky or p-n junction that works as an interface for the separation of charge carriers. TMDCs (MoS_2, $MoSe_2$, and WS_2) can absorb up to 5–10% incident sunlight in a monolayer (thickness less than 1 nm). The absorption of sunlight is one order of

magnitude more than that of typical semiconductors such as GaAs and Si. The efficiency of solar cells based on ultrathin TMDCs is limited by the loss of absorption under the thickness limitation [42]. Calculations suggest that a monolayer TMDC could absorb as much sunlight as 50 nm of Si and generate electrical currents as high as 4.5 mA cm^{-2} [43]. There are three ways to improve the performances of TMDC solar devices [44]: (1) careful control over the doping levels of TMDCs and Si, which would reduce the series resistance of the device; (2) utilization of large-area grown or deposited materials; (3) incorporating additional 2D semiconducting layers such as WSe_2 with complementary absorption spectra. In recent years, ultrathin solar cells have drawn much attention due to the possible reduction in cost and semiconductor material consumption, as well as their suitability for flexible and ultralight photovoltaics. A 120 nm thick MoS_2 p-n junction is presented [45]. Researchers have developed a straightforward method to fabricate ohmic contacts to both n and p MoS_2 and added an h-BN layer on top of the semiconductor to minimize the reflectance of the front surface. The homojunction device exhibits (3.8 ± 0.2)% efficiency and a 57% fill factor under AM1.5G illumination, which contributes to the maturity of the emerging technology of TMDC-based ultrathin solar cells. The incorporation of WS_2 as a photovoltaic material was presented [46]. With this optimized deposition parameter, WS_2 thin film was successfully fabricated for the very first time as a window layer in CdTe solar cells. The new device (ITO/WS_2/CdTe/CuC/Ag) exhibited V_{oc} = 0.39 V, J_{sc} = 10.45 mA cm^{-2}, fill factor = 29.42%, and efficiency = 1.2%. Shin et al. fabricated an organic solar cell (TFSA-GR/MoS_2/P3HT:PCBM/Al) by using MoS_2 as a hole transport layer, bis(trifluoromethanesulfonyl)-amide-doped graphene (TFSA-GR) as a transparent conductive electrode, and a GR quantum dots (GQDs)-added active layer [47]. They investigated the effect of the number of layers (L_n) of MoS_2 on the power conversion efficiency of organic solar cells. When L_n = 2, the fabricated solar cell shows a maximum power conversion efficiency of 4.23%. When L_n = 1, the power conversion efficiency is small because of the low absorption in the visible region. While L_n > 2, the power conversion efficiency is also lowered due to the lower amount of sunlight reaching the active layer. As a result, the selection of a suitable L_n of MoS_2 plays an important role in the performance of solar cells.

2.3.3. Photodetectors

Photodetectors have been the most extensively researched optoelectronic device for TMDCs, with research ranging from novel device topologies to utilizing unique physical features to strategies to improve performance [48][49][50][51]. ReS_2 has been shown to have an anisotropic band structure resulting in two major excitons with unequal binding energy [52][53][54]. This allows control over polarized light absorption, and the consecutive polarization of a sensitive photodetector. The appropriate calibration of such photodetectors permits the detection of both light intensity and polarization, allowing for the detection of polarization-encoded messages.

Mixed dimensional heterostructures and plasmonic-, organic material- or quantum dot-enhanced structures have been studied for performance enhancement [55][56][57]. According to preliminary research, photodetectors based on MoS_2 monolayers have better photoresponsivity than graphene-based devices [58][59]. MoS_2/$SnSe_2$ heterostructure-based photodetectors exhibit a high responsivity of up to 9.1 × 10^3 A W^{-1}, which is significantly greater than MoS_2 only film-based photodetectors [60]. The photoexcited electron-hole pairs of GaTe-MoS_2 p-n heterojunction phototransistors are separated by large built-in potential, formed at the GaTe-MoS_2 interface efficiently to generate a self-driven photocurrent within <10 ms [61]. Two-dimensional TMDCs heterostructures can also be explored for possible THz detection at room temperature [62].

3. Other 2D Materials

3.1. Black Phosphorus

3.1.1. Morphology and Structure

Black phosphorus (BP) is a stable layered structure similar to 2D structures such as graphene and TMDCs [63]. Like bulk graphite, BP has a layered substance in which individual atomic layers are stacked together by van der Waals interactions and can be similarly isolated from black phosphorus by the mechanical exfoliation method. BP is not planer but puckered due to the sp^3 hybridization. Each phosphorus atom is covalently bound with three adjacent phosphorus atoms inside a single layer to form a puckered honeycomb structure [64].

3.1.2. Optical Properties

The direct bandgap (≈0.3 eV) of BP thin film (eight layers, or thickness > 4 nm) can link the energy gap between the zero bandgap of graphene and the comparatively large bandgaps of numerous TMDCs (1.5–2.5 eV) [16][65][66][67]. Unlike graphene and TMDCs, the bandgap of few-layer BP can be tuned by interlayer interactions and is strongly dependent on the number of layers.

Due to the “puckered” crystal lattice, BP shows strong band dispersion anisotropy [68]. The anisotropic absorption was identified with a maximum absorption value of 28% in the mid-infrared region when the incident light was polarized along the armchair direction of BP [69]. Thin-film BP has also been widely applied for mid-infrared ultrafast photonics as saturable absorbers due to the decent optical absorption. BP exhibits broadband absorption from the visible to the mid-infrared spectral region, which is also manifested by the broadband nonlinear optical response. Multilayer BP flakes of 3–20 nm thickness dispersed in liquid exhibit strong saturable absorption at both 400 nm and 800 nm.

The robust optical conductivity of BP thin film in the wavelength range from 1 to 5 μm suggests BP as an attractive contender for near- and mid-infrared optoelectronics applications such as modulators, photodetectors, ultrafast optical switches, and, possibly, light-generation devices such as LEDs and ultrashort pulsed lasers [70].

3.1.3. Optical Applications

Numerous studies have also been performed on the applications of BP in photodetectors [71][72][73], polarization-sensitive detectors [74][75], saturable absorbers [76][77] and emitters [78], and photovoltaics devices [79][80].

Because of the direct bandgap and high carrier mobility, BP is promising in building broadband phototransistors for imaging and photodetection, especially in the near-infrared and mid-infrared wavelengths [81]. The response wavelength range of BP-based photodetectors can be increased by an external vertical electric field because the optical bandgap of few-layer BP is highly adjustable by the quantum-confined Stark effect [82][83][84]. Different portions of a single BP flake can be adjusted into opposing doping regimes to create an artificial PN junction that can generate a photocurrent via the photovoltaic effect. Because of the versatility and compatibility of 2D BP, it can be combined with other nanomaterials to improve the performances of photodetectors [85][86][87]. BP can be combined with other low-dimensional nanomaterials such as nanowires and quantum dot [88][89], allowing for the creation of unique heterostructures based on materials with different/multiple dimensions. BP is also an excellent midinfrared electro-optic material for modulation applications due to its solid electro-optical response and relatively small bandgap.

3.2. 2D Transition Metal Carbides MXenes

Transition metal carbides, carbonitrides, and nitrides were first discovered and termed MXenes (MX) by Barsoum et al. in 2011 [90]. The common formulation of MXs is $M_{n+1}X_nT_x$, where M embodies the transition metals (such as Ti, Ta, Mo, and Cr); X signifies nitrogen or carbon, n may differ from 1 to 4; and T_x denotes surface ends on the outer M layers (such as -O, -OH, -F, and -Cl) [91]. M^1 and M^2 are two different Ms. In case two different Ms have in-plane arranging and form rotating chains of M^1 and M^2 molecules inside the similar M layer, the ensuing MX configuration is known as i-MX with a general formula of (M14/3M22/3)

XT_x, where the percentage of every compound is mentioned as a decimal value. The M^1 and M^2 molecules positioned in distinct atomic planes holding an out-of-plane arrangement are known as o-MXs, in which M^2 molecules compose the internal layers and M^1 molecules are in the exterior surface. o-MXs are represented by two chemical formulations as (M12M2)X2TxTx and (M12M22)X3Tx
. MXs with V, Ti, Nb, Cr, Mo, Zr, Sc, Hf, Ta, Y, and W in the M spot were investigated. W, Sc, Y, and Cr have only been registered as elements of i-MXs, o-MXs, or in combination with the other metals listed above [92].

3.2.1. Morphology and Structure

MXenes consist of a transition metal-made (M) hexagonal close-packed crystal symmetry, and the X molecules occupy an octahedral spot between the adjacent M layers [91]. MXenes can be classified as ordered mono-M, ordered double-M and solid-solution M elements based on their atomic lattices and composition [93].

3.2.2. Optical Properties

MXenes have unique optical properties and a wide range of tunability, making them ideal materials for a variety of optical applications. Because of their large density of states at the Fermi level, MXenes have intriguing transport features, while TMDCs have low carrier mobility. MXene films have been found to exhibit a broadband optical transmittance of more than 90% [94][95], with a transmission valley of around 750–800 nm [96], which has been attributed to the surface plasmon resonance (around 780 nm) and inherent out-plane interband transitions (around 800 nm). When compared with the pristine MXene, the oxidized sample has a higher absorption in the visible region, while fluorinated and hydroxylated MXenes have a lower absorption. In the ultraviolet optical region, all functional groups lead to an enhancement of both the absorption and reflectivity of MXenes [97]. $M_{n+1}X_n$ with a smaller n is expected to be more transparent than MXenes with a larger n due to the lower density of states [97][98].

Both MXenes quantum dots and nanosheets exhibit strong photoluminescence due to the direct bandgap, which allows for radiative electronic transitions [99][100]. MXene quantum dots typically have three absorption peaks at 260 nm, 310 nm, and 350 nm, depending on the particle size and composition. The excitation wavelengths have a big impact on the photoluminescence spectral band. For example, the photoluminescence spectra of Ti_3C_2 quantum dots range from 400 to 600 nm when the excitation wavelengths vary from 340 to 440 nm [99].

3.2.3. Optical Applications

The MXenes such as $Ti_3C_2T_x$ slim layers are well-suited for optoelectronic applications which require adaptive translucent conductive electrodes due to their high transparency and low layer resistance [101]. Translucent conductive electrodes based on MXenes have been used to provide appropriate volumetric capacitance in translucent solid-state supercapacitors [94]. Except translucent conductive electrodes, MXenes also show great potential applications in other optical applications. For example, $Ti_3C_2T_x$ nanostructures have been widely used to realize ultrafast pulses in different lasers. In 2017, Jhon et al. reported MXene-based SA-activated ultrafast pulses, which achieved mode-locking at 1.5 m-band and q-switching pulses at 2 m-band, respectively [102]. MXenes exhibit excellent broadband saturable absorption capability in the near-mid-infrared region [103]. In 2019, Yi et al. reported the broadband nonlinear properties of MXenes in the three-wavelength band, in which mode-locked pulses operating at 1051 and 1565 nm and q-switched pulses operating at 2798 nm were realized using the same Ti_2CT_x-based SA [104]. A total of 1.2 nm of spin-coated Ti_3C_2T MXene film on glass, quartz and polyetherimide substrates achieves an ultra-low optical attenuation of 3% in the visible region [105]. It is noteworthy that the prepared Ti_3C_2T MXene films have a transmittance of up to 98% and can be used for flexible and conductive high-capacity capacitors [94][106]. In addition, $Ti_3C_2T_x$ nanosheets can be easily oxidized to TiO_2 during the delamination process. If stored in an oxygen-rich atmosphere, $Ti_3C_2T_x$-TiO_2 nanocomposites can be obtained in situ, further expanding their applications in electrochemical and optoelectronic devices. In 2008, Mochalin et al. prepared $Ti_3C_2T_x$-TiO_2 nanocomposites by the in situ oxidization of $Ti_3C_2T_x$ for UV photodetection [107]. $Ti_3C_2T_x$ MXenes can also serve as electron and hole collection layers in solar cells [108], accelerating charge extraction and improving photovoltaic efficiency. Meanwhile, doping $Ti_3C_2T_x$ MXenes into the electron transport layer, hole transport layer or activation layer can change the energy level and improve the electrical conductivity and carrier mobility. For example, Agresti et al. used $Ti_3C_2T_x$ with different termination groups (T_x) to tune the work function of the perovskite absorber and the TiO_2 electron transport layer, as well as to engineer the perovskite/electron transport layer interface [109]. The combined effect of work function tuning and interface engineering can significantly improve the performance of MXene-modified perovskite solar cells. Compared with the reference cell without MXene, the power conversion efficiency was improved by 26% and the hysteresis was reduced.

3.3. Hexagonal Boron Nitride

3.3.1. Morphology and Structure

hBN is one of the key 2D materials composed of alternating B and N atoms bonded by sp^2 covalent bonds in its hexagonal lattices. hBN crystal contains alternating B and N atoms in a base plane and, thus, has great variations in growth kinetics due to its different edge terminations. As a result, the morphologies of h-BN domains are varied with its B or N terminations [110].

3.3.2. Optical Properties

Despite the fact that hBN is an indirect bandgap semiconductor (with an energy gap of about 6 eV) [111], it has a very high internal quantum efficiency for deep UV emission (up to 40%). The frequency of the normal lattice vibrational modes (optic phonons) is similarly very anisotropic due to the highly anisotropic crystal structure of hBN, with two different optic phonon branches. When monolayer hBN was placed on different substrates and under THz irradiation, the carrier density could be enhanced considerably, especially on SiO_2/Si substrate, which suggested that the SiO_2/Si substrate was more appropriate for the construction of monolayer hBN-based electronic and optoelectronic devices when compared with quartz, PET, and sapphire [112]. The wavelength responses of S-doped hBN monolayer films on molten Au substrates are extended to 280 nm, and the photocurrent and responsivity for light irradiation with a wavelength of 280 nm are ~50 times higher than that of pristine hBN [113].

3.3.3. Optical Applications

h-BN can be used as a wide bandgap semiconductor for deep-UV emitters and detectors because of its large bandgap. To further improve the response rate and detection rate, it is necessary to modulate the optical and electrical properties of hBN. Tan et al. successfully prepared S-doped hBN monolayers on molten Au substrates by atmospheric CVD, and they systematically studied their optical and electrical properties [113]. The band gap is reduced from 5.83 eV to 5.69 eV, and

the conductivity is reduced by 140 meV. Moreover, the response range of the photodetector is extended to a 280-nm wavelength; the power density of the light source is 16.1 μW mm^{-2} (280 nm); and the responsiveness of the device with single, double and three-layer hBN is 3.63, 3.54 and 0.24 A W^{-1}, respectively. In addition, numerous studies have shown that hBN is also an excellent insulator that can be used as a substrate material for graphene-based devices [114][115]. Wu et al. demonstrated a deep ultraviolet photodetector based on a graphene/hBN/n-AlGaN heterostructure. The device not only exhibits high responsivity under UV illumination, but also exhibits a high UV/Vis rejection ratio. Several nanolayered graphene-hBN heterostructures are used to enhance the performance of photodetectors, successfully solving the strain problem between graphene and traditional bulk insulators [116]. Two-dimensional hBN film can provide almost ideal passivation due to its wide bandgap, no dangling bond and high dielectric constant. Raj et al. reported the passivation properties of monolayer hBN that was grown by metal-organic CVD [117]. Using an ITO/I-INP/P-INP solar cell structure with a small amount of hBN monolayer as the passivation layer, the solar cell performance is significantly improved. The maximum efficiency of five-monolayer (ML) hBN is 17.2%, V_{oc} is 0.78 V, J_{sc} is 29.4 mA cm^{-2}, and FF is 75.2%. The INP solar cell with 7 ML hBN has a measured efficiency of 15.7%, V_{oc}, J_{sc} and FF are 0.8 V, 27.1 mA cm^{-2} and 72.1%, respectively [117].

3.4. 2D Metal Oxide

3.4.1. Basic Structure and Optical Properties

Two-dimensional metal oxides, formed by the O element and the metallic element, are gradually attracting more attention [118][119]. This is because they are not only rich in material species, but also contain a variety of structures including a nonlayered structure, a layered structure such as MoS_2, and inorganic molecular crystal. The special structure of 2D metal oxides endow these materials with numerous outstanding properties. Compared with typical 2D materials such as graphene and BP, 2D metal oxides possess many special characteristics. For example, they have excellent air stability due to the involvement of O and the relatively stable valence state of the elements that are contained in 2D metal oxides [120]. Second, 2D metal oxides generally have low requirements for a synthetic environment. Some 2D metal materials can even be obtained in an atmospheric environment. Third, most reported 2D metal oxides have wide bandgaps and exhibit excellent ultraviolet detection performances. As a result, they show great application potential in optoelectronics.

3.4.2. Optical Applications

Recently, Yu et al. fabricated a photodetector based on ZnO nanosheets [121]. At a visible-blind wavelength of 254 nm, this photodetector exhibits a high responsivity up to 2.0×10^4 A W^{-1} and high detectivity (6.83×10^{14} Jones). Messalea et al. reported an ultra violet photodetector based on ultrathin bismuth oxide (Bi_2O_3) nanosheets that were synthesized by a liquid metal facilitated approach [122]. The photodetector shows a high responsivity of about 400 A W^{-1} and a fast response time of ~70 μs at the wavelength of 365 nm. In addition to the application of photodetection in ultraviolet, 2D metal oxides can also be used in the long-wave-length infrared (LWIR) detecting devices. Yin et al. synthesized air-stable nonlayered ultrathin Fe_3O_4 nanosheets by a space-confined CVD approach [123]. The prepared Fe_3O_4 nanosheets can be used to fabricate high-performance ultrabroadband photodetectors with a detection range from ultraviolet to LWIR. Due to the synergistic mechanisms of the photoconductive effect and bolometric effect, the photodetectors exhibit an ultrahigh photoresponsivity of 562.1 A W^{-1}, a detectivity of 7.42×10^8 Jones, and an external quantum efficiency of 6.6×10^3% at the laser wavelength of 10.6 μm. Some 2D materials have a low symmetric crystal structure, leading to in-plane optical anisotropy [120]. Zhong et al. synthesized large-size 2D α-MoO_3 single crystals with structural in-plane anisotropy, which showed a remarkable ultraviolet photoresponse and electron transport anisotropies [124]. The photodetectors based on α-MoO_3 demonstrate a photoresponsivity of 67.9 A W^{-1} and an external quantum efficiency of 3.3×10^4% under solar-blind ultraviolet light (254 nm). Importantly, the photodetectors exhibit strong in-plane anisotropy in the optoelectronic response and transport properties. Although some photodetectors based on 2D metal oxides show excellent performances, there is still a long way to go for them to achieve practical applications. Exploring methods to produce high-quality 2D metal oxides is one of the effective ways to drive the further development of high-performance photodetectors.

References

1. Avouris, P.; Dimitrakopoulos, C. Graphene: Synthesis and applications. Mater. Today 2012, 15, 86–97.
2. Shim, J.; Park, H.Y.; Kang, D.H.; Kim, J.O.; Jo, S.H.; Park, Y.; Park, J.H. Electronic and Optoelectronic Devices based on Two-Dimensional Materials: From Fabrication to Application. Adv. Electron. Mater. 2017, 3, 1600364.
3. Vu, Q.A.; Yu, W.J. Electronics and Optoelectronics Based on Two-Dimensional Materials. J. Korean Phys. Soc. 2018, 73, 1–15.

4. Xu, M.; Liang, T.; Shi, M.; Chen, H. Graphene-like Two-Dimensional Materials. Chem. Rev. 2013, 113, 3766–3798.
5. Wang, Q.H.; Kalantar-Zadeh, K.; Kis, A.; Coleman, J.N.; Strano, M.S. Electronics and optoelectronics of two-dimensional transition metal dichalcogenides. Nat. Nanotechnol. 2012, 7, 699–712.
6. Mannix, A.J.; Kiraly, B.; Hersam, M.C.; Guisinger, N.P. Synthesis and chemistry of elemental 2D materials. Nat. Rev. Chem. 2017, 1, 0014.
7. Khan, M.F.; Ahmed, F.; Rehman, S.; Akhtar, I.; Rehman, M.A.; Shinde, P.A.; Khan, K.; Kim, D.K.; Eom, J.; Lipsanen, H.; et al. High performance complementary WS2devices with hybrid Gr/Ni contacts. Nanoscale 2020, 12, 21280–21290.
8. Xia, F.; Wang, H.; Xiao, D.; Dubey, M.; Ramasubramaniam, A. Two-dimensional material nanophotonics. Nat. Photonics 2014, 8, 899–907.
9. Liu, M.; Yin, X.; Ulin-Avila, E.; Geng, B.; Zentgraf, T.; Ju, L.; Wang, F.; Zhang, X. A graphene-based broadband optical modulator. Nature 2011, 474, 64–67.
10. Razaq, A.; Bibi, F.; Zheng, X.; Papadakis, R.; Jafri, S.H.M.; Li, H. Review on Graphene-, Graphene Oxide-, Reduced Graphene Oxide-Based Flexible Composites: From Fabrication to Applications. Materials 2022, 15, 1012.
11. Eda, G.; Maier, S.A. Two-dimensional crystals: Managing light for optoelectronics. ACS Nano 2013, 7, 5660–5665.
12. Liu, L.; Wu, L.; Wang, A.; Liu, H.; Ma, R.; Wu, K.; Chen, J.; Zhou, Z.; Tian, Y.; Yang, H.; et al. Ferroelectric-Gated InSe Photodetectors with High On/Off Ratios and Photoresponsivity. Nano Lett. 2020, 20, 6666–6673.
13. Li, H.; Zhang, J.; Gholizadeh, A.B.; Brownless, J.; Fu, Y.; Cai, W.; Han, Y.; Duan, T.; Wang, Y.; Ling, H.; et al. Photoluminescent Semiconducting Graphene Nanoribbons via Longitudinally Unzipping Single-Walled Carbon Nanotubes. ACS Appl. Mater. Interfaces 2021, 13, 52892–52900.
14. Khan, M.F.; Rehman, S.; Akhtar, I.; Aftab, S.; Ajmal, H.M.S.; Khan, W.; Kim, D.K.; Eom, J. High mobility ReSe2 field effect transistors: Schottky-barrier-height-dependent photoresponsivity and broadband light detection with Co decoration. 2D Mater. 2020, 7, 015010.
15. Li, Y.; Fu, J.; Mao, X.; Chen, C.; Liu, H.; Gong, M.; Zeng, H. Enhanced bulk photovoltaic effect in two-dimensional ferroelectric CuInP2S6. Nat. Commun. 2021, 12, 5896.
16. Mak, K.F.; Lee, C.; Hone, J.; Shan, J.; Heinz, T.F. Atomically thin MoS2: A new direct-gap semiconductor. Phys. Rev. Lett. 2010, 105, 136805.
17. Elahi, E.; Khan, M.F.; Rehman, S.; Khalil, H.M.W.; Rehman, M.A.; Kim, D.K.; Kim, H.; Khan, K.; Shahzad, M.; Iqbal, M.W.; et al. Enhanced electrical and broad spectral (UV-Vis-NIR) photodetection in a Gr/ReSe2/Gr heterojunction. Dalt. Trans. 2020, 49, 10017–10027.
18. Ding, Y.; Wang, Y.; Ni, J.; Shi, L.; Shi, S.; Tang, W. First principles study of structural, vibrational and electronic properties of graphene-like MX2 (M=Mo, Nb, W, Ta; X=S, Se, Te) monolayers. Phys. B Condens. Matter 2011, 406, 2254–2260.
19. Yun, W.S.; Han, S.W.; Hong, S.C.; Kim, I.G.; Lee, J.D. Thickness and strain effects on electronic structures of transition metal dichalcogenides: 2H-MX2 semiconductors (M = Mo, W; X = S, Se, Te). Phys. Rev. B-Condens. Matter Mater. Phys. 2012, 85, 033305.
20. Xia, C.; Li, J. Recent advances in optoelectronic properties and applications of two-dimensional metal chalcogenides. J. Semicond. 2016, 37, 051001.
21. Liu, L.; Wang, H.; Wu, Q.; Wu, K.; Tian, Y.; Yang, H.; Shen, C.M.; Bao, L.; Qin, Z.; Gao, H.J. Ferroelectric-gated ReS2 field-effect transistors for nonvolatile memory. Nano Res. 2022, 15, 5443–5449.
22. Eda, G.; Yamaguchi, H.; Voiry, D.; Fujita, T.; Chen, M.; Chhowalla, M. Photoluminescence from chemically exfoliated MoS2. Nano Lett. 2011, 11, 5111–5116.
23. Hui, Y.Y.; Liu, X.; Jie, W.; Chan, N.Y.; Hao, J.; Hsu, Y.T.; Li, L.J.; Guo, W.; Lau, S.P. Exceptional tunability of band energy in a compressively strained trilayer MoS2 sheet. ACS Nano 2013, 7, 7126–7131.
24. Mouri, S.; Miyauchi, Y.; Matsuda, K. Tunable photoluminescence of monolayer MoS2 via chemical doping. Nano Lett. 2013, 13, 5944–5948.
25. Brent, J.R.; Savjani, N.; O'Brien, P. Synthetic approaches to two-dimensional transition metal dichalcogenide nanosheets. Prog. Mater. Sci. 2017, 89, 411–478.
26. Yao, J.D.; Zheng, Z.Q.; Yang, G.W. Production of large-area 2D materials for high-performance photodetectors by pulsed-laser deposition. Prog. Mater. Sci. 2019, 106, 100573.
27. Zhou, J.; Lin, J.; Huang, X.; Zhou, Y.; Chen, Y.; Xia, J.; Wang, H.; Xie, Y.; Yu, H.; Lei, J.; et al. A library of atomically thin metal chalcogenides. Nature 2018, 556, 355–359.

28. Sahu, R. Two-Dimensional MoS2 and Heterostructure Growth by Pulsed Laser Deposition. Mod. Concept. Mater. Sci. 2019, 2, 000534.
29. Loh, T.A.J.; Chua, D.H.C.; Wee, A.T.S. One-step Synthesis of Few-layer WS2 by Pulsed Laser Deposition. Sci. Rep. 2015, 5, 18116.
30. Serrao, C.R.; Diamond, A.M.; Hsu, S.L.; You, L.; Gadgil, S.; Clarkson, J.; Carraro, C.; Maboudian, R.; Hu, C.; Salahuddin, S. Highly crystalline MoS2 thin films grown by pulsed laser deposition. Appl. Phys. Lett. 2015, 106, 052101.
31. Chen, X.; Shehzad, K.; Gao, L.; Long, M.; Guo, H.; Qin, S.; Wang, X.; Wang, F.; Shi, Y.; Hu, W.; et al. Graphene Hybrid Structures for Integrated and Flexible Optoelectronics. Adv. Mater. 2020, 32, 1902039.
32. Wu, M.; Xiao, Y.; Zeng, Y.; Zhou, Y.; Zeng, X.; Zhang, L.; Liao, W. Synthesis of two-dimensional transition metal dichalcogenides for electronics and optoelectronics. InfoMat 2021, 3, 362–396.
33. Lien, D.-H.; Kang, J.S.; Amani, M.; Chen, K.; Tosun, M.; Wang, H.-P.; Roy, T.; Eggleston, M.; Wu, M.C.; Dubey, M.; et al. Engineering Light Outcoupling in 2D Materials. Nano Lett. 2015, 15, 1356–1361.
34. Lien, D.H.; Amani, M.; Desai, S.B.; Ahn, G.H.; Han, K.; He, J.H.; Ager, J.W.; Wu, M.C.; Javey, A. Large-area and bright pulsed electroluminescence in monolayer semiconductors. Nat. Commun. 2018, 9, 1229.
35. Withers, F.; Del Pozo-Zamudio, O.; Mishchenko, A.; Rooney, A.P.; Gholinia, A.; Watanabe, K.; Taniguchi, T.; Haigh, S.J.; Geim, A.K.; Tartakovskii, A.I.; et al. Light-emitting diodes by band-structure engineering in van der Waals heterostructures. Nat. Mater. 2015, 14, 301–306.
36. Kim, H.C.; Kim, H.; Lee, J.U.; Lee, H.B.; Choi, D.H.; Lee, J.H.; Lee, W.H.; Jhang, S.H.; Park, B.H.; Cheong, H.; et al. Engineering Optical and Electronic Properties of WS2 by Varying the Number of Layers. ACS Nano 2015, 9, 6854–6860.
37. Cheng, R.; Li, D.; Zhou, H.; Wang, C.; Yin, A.; Jiang, S.; Liu, Y.; Chen, Y.; Huang, Y.; Duan, X. Electroluminescence and photocurrent generation from atomically sharp WSe2/MoS2 heterojunction p-n diodes. Nano Lett. 2014, 14, 5590–5597.
38. Baugher, B.W.H.; Churchill, H.O.H.; Yang, Y.; Jarillo-Herrero, P. Optoelectronic devices based on electrically tunable p-n diodes in a monolayer dichalcogenide. Nat. Nanotechnol. 2014, 9, 262–267.
39. Ross, J.S.; Klement, P.; Jones, A.M.; Ghimire, N.J.; Yan, J.; Mandrus, D.G.; Taniguchi, T.; Watanabe, K.; Kitamura, K.; Yao, W.; et al. Electrically tunable excitonic light-emitting diodes based on monolayer WSe2 p-n junctions. Nat. Nanotechnol. 2014, 9, 268–272.
40. Pospischil, A.; Furchi, M.M.; Mueller, T. Solar-energy conversion and light emission in an atomic monolayer p-n diode. Nat. Nanotechnol. 2014, 9, 257–261.
41. Sundaram, R.S.; Engel, M.; Lombardo, A.; Krupke, R.; Ferrari, A.C.; Avouris, P.; Steiner, M. Electroluminescence in single layer MoS2. Nano Lett. 2013, 13, 1416–1421.
42. Bernardi, M.; Palummo, M.; Grossman, J.C. Extraordinary sunlight absorption and one nanometer thick photovoltaics using two-dimensional monolayer materials. Nano Lett. 2013, 13, 3664–3670.
43. Polman, A.; Atwater, H.A. Photonic design principles for ultrahigh-efficiency photovoltaics. Nat. Mater. 2012, 11, 174–177.
44. Ponraj, J.S.; Xu, Z.Q.; Dhanabalan, S.C.; Mu, H.; Wang, Y.; Yuan, J.; Li, P.; Thakur, S.; Ashrafi, M.; McCoubrey, K.; et al. Photonics and optoelectronics of two-dimensional materials beyond graphene. Nanotechnology 2016, 27, 462001.
45. Antolín, E.; Svatek, S.A.; Bueno-Blanco, C.; Martí, A.; Lin, D.-Y.; Rodríguez-Peña, M.; Luna, M. MoS2 solar cell with 120 nm-absorber and 3.8% AM1.5G efficiency. In Proceedings of the 49th IEEE Photovoltaic Specialists Conference, Philadelphia, PA, USA, 5–10 June 2022.
46. Bin Rafiq, M.K.S.; Amin, N.; Alharbi, H.F.; Luqman, M.; Ayob, A.; Alharthi, Y.S.; Alharthi, N.H.; Bais, B.; Akhtaruzzaman, M. WS2: A New Window Layer Material for Solar Cell Application. Sci. Rep. 2020, 10, 771.
47. Shin, D.H.; Jang, C.W.; Ko, J.S.; Choi, S.H. Enhancement of efficiency and stability in organic solar cells by employing MoS2 transport layer, graphene electrode, and graphene quantum dots-added active layer. Appl. Surf. Sci. 2021, 538, 148155.
48. Flöry, N.; Ma, P.; Salamin, Y.; Emboras, A.; Taniguchi, T.; Watanabe, K.; Leuthold, J.; Novotny, L. Waveguide-integrated van der Waals heterostructure photodetector at telecom wavelengths with high speed and high responsivity. Nat. Nanotechnol. 2020, 15, 118–124.
49. Varghese, A.; Saha, D.; Thakar, K.; Jindal, V.; Ghosh, S.; Medhekar, N.V.; Ghosh, S.; Lodha, S. Near-Direct Bandgap WSe2/ReS2 Type-II pn Heterojunction for Enhanced Ultrafast Photodetection and High-Performance Photovoltaics.

Nano Lett. 2020, 20, 1707–1717.

50. Wang, X.; Cui, Y.; Li, T.; Lei, M.; Li, J.; Wei, Z. Recent Advances in the Functional 2D Photonic and Optoelectronic Devices. Adv. Opt. Mater. 2019, 7, 1801274.
51. Wei, X.; Yan, F.; Lv, Q.; Shen, C.; Wang, K. Fast gate-tunable photodetection in the graphene sandwiched WSe2/GaSe heterojunctions. Nanoscale 2017, 9, 8388–8392.
52. Li, X.; Zuo, X.; Li, H.; Han, L.; Gao, Q.; Li, D.; Cui, B.; Liu, D.; Qu, F. Exotic magnetism in As-doped α/β-In2Se3 monolayers with tunable anisotropic carrier mobility. Phys. Chem. Chem. Phys. 2019, 21, 19234–19241.
53. Zhao, C.; Sekhar, M.C.; Lu, W.; Zhang, C.; Lai, J.; Jia, S.; Sun, D. Anisotropic visible photoluminescence from thermally annealed few-layer black phosphorus. Nanotechnology 2018, 29, 245202.
54. Sim, S.; Lee, D.; Trifonov, A.V.; Kim, T.; Cha, S.; Sung, J.H.; Cho, S.; Shim, W.; Jo, M.H.; Choi, H. Ultrafast quantum beats of anisotropic excitons in atomically thin ReS2. Nat. Commun. 2018, 9, 351.
55. Qin, J.K.; Ren, D.D.; Shao, W.Z.; Li, Y.; Miao, P.; Sun, Z.Y.; Hu, P.; Zhen, L.; Xu, C.Y. Photoresponse Enhancement in Monolayer ReS2 Phototransistor Decorated with CdSe-CdS-ZnS Quantum Dots. ACS Appl. Mater. Interfaces 2017, 9, 39456–39463.
56. Ni, Z.; Ma, L.; Du, S.; Xu, Y.; Yuan, M.; Fang, H.; Wang, Z.; Xu, M.; Li, D.; Yang, J.; et al. Plasmonic Silicon Quantum Dots Enabled High-Sensitivity Ultrabroadband Photodetection of Graphene-Based Hybrid Phototransistors. ACS Nano 2017, 11, 9854–9862.
57. Liu, X.; Luo, X.; Nan, H.; Guo, H.; Wang, P.; Zhang, L.; Zhou, M.; Yang, Z.; Shi, Y.; Hu, W.; et al. Epitaxial Ultrathin Organic Crystals on Graphene for High-Efficiency Phototransistors. Adv. Mater. 2016, 28, 5200–5205.
58. Zhang, Y.; Ye, J.; Matsuhashi, Y.; Iwasa, Y. Ambipolar MoS2 thin flake transistors. Nano Lett. 2012, 12, 1136–1140.
59. Yin, Z.; Li, H.; Li, H.; Jiang, L.; Shi, Y.; Sun, Y.; Lu, G.; Zhang, Q.; Chen, X.; Zhang, H. Single-layer MoS2 phototransistors. ACS Nano 2012, 6, 74–80.
60. Zhou, X.; Zhou, N.; Li, C.; Song, H.; Zhang, Q.; Hu, X.; Gan, L.; Li, H.; Lü, J.; Luo, J.; et al. Vertical heterostructures based on SnSe2/MoS2 for high performance photodetectors. 2D Mater. 2017, 4, 025048.
61. Yang, S.; Wang, C.; Ataca, C.; Li, Y.; Chen, H.; Cai, H.; Suslu, A.; Grossman, J.C.; Jiang, C.; Liu, Q.; et al. Self-Driven Photodetector and Ambipolar Transistor in Atomically Thin GaTe-MoS2 p-n vdW Heterostructure. ACS Appl. Mater. Interfaces 2016, 8, 2533–2539.
62. Yang, J.; Qin, H.; Zhang, K. Emerging terahertz photodetectors based on two-dimensional materials. Opt. Commun. 2018, 406, 36–43.
63. Castellanos-Gomez, A.; Vicarelli, L.; Prada, E.; Island, J.O.; Narasimha-Acharya, K.L.; Blanter, S.I.; Groenendijk, D.J.; Buscema, M.; Steele, G.A.; Alvarez, J.V.; et al. Isolation and characterization of few-layer black phosphorus. 2D Mater. 2014, 1, 025001.
64. Cartz, L.; Srinivasa, S.R.; Riedner, R.J.; Jorgensen, J.D.; Worlton, T.G. Effect of pressure on bonding in black phosphorus. J. Chem. Phys. 1979, 71, 1718–1721.
65. Jones, A.M.; Yu, H.; Ross, J.S.; Klement, P.; Ghimire, N.J.; Yan, J.; Mandrus, D.G.; Yao, W.; Xu, X. Spin-layer locking effects in optical orientation of exciton spin in bilayer WSe2. Nat. Phys. 2014, 10, 130–134.
66. Li, C.; Cao, Q.; Wang, F.; Xiao, Y.; Li, Y.; Delaunay, J.J.; Zhu, H. Engineering graphene and TMDs based van der Waals heterostructures for photovoltaic and photoelectrochemical solar energy conversion. Chem. Soc. Rev. 2018, 47, 4981–5037.
67. Splendiani, A.; Sun, L.; Zhang, Y.; Li, T.; Kim, J.; Chim, C.Y.; Galli, G.; Wang, F. Emerging photoluminescence in monolayer MoS2. Nano Lett. 2010, 10, 1271–1275.
68. Sofer, Z.; Sedmidubský, D.; Huber, Š.; Luxa, J.; Bouša, D.; Boothroyd, C.; Pumera, M. Layered Black Phosphorus: Strongly Anisotropic Magnetic, Electronic, and Electron-Transfer Properties. Angew. Chem. 2016, 128, 3443–3447.
69. Xia, F.; Wang, H.; Jia, Y. Rediscovering black phosphorus as an anisotropic layered material for optoelectronics and electronics. Nat. Commun. 2014, 5, 4458.
70. Debnath, P.C.; Park, K.; Song, Y.-W. Recent Advances in Black-Phosphorus-Based Photonics and Optoelectronics Devices. Small Methods 2018, 2, 1700315.
71. Xu, Y.; Liu, C.; Guo, C.; Yu, Q.; Guo, W.; Lu, W.; Chen, X.; Wang, L.; Zhang, K. High performance near infrared photodetector based on in-plane black phosphorus p-n homojunction. Nano Energy 2020, 70, 104518.
72. Ma, Y.; Dong, B.; Wei, J.; Chang, Y.; Huang, L.; Ang, K.W.; Lee, C. High-Responsivity Mid-Infrared Black Phosphorus Slow Light Waveguide Photodetector. Adv. Opt. Mater. 2020, 8, 2000337.

73. Huang, L.; Dong, B.; Guo, X.; Chang, Y.; Chen, N.; Huang, X.; Liao, W.; Zhu, C.; Wang, H.; Lee, C.; et al. Waveguide-Integrated Black Phosphorus Photodetector for Mid-Infrared Applications. ACS Nano 2019, 13, 913–921.

74. Jiao, H.; Wang, X.; Chen, Y.; Guo, S.; Wu, S.; Song, C.; Huang, S.; Huang, X.; Tai, X.; Lin, T.; et al. HgCdTe/black phosphorus van der Waals heterojunction for high-performance polarization-sensitive midwave infrared photodetector. Sci. Adv. 2022, 8, eabn1811.

75. Zhu, W.; Wei, X.; Yan, F.; Lv, Q.; Hu, C.; Wang, K. Broadband polarized photodetector based on p-BP/n-ReS2 heterojunction. J. Semicond. 2019, 40, 092001.

76. Zhang, M.; Wu, Q.; Zhang, F.; Chen, L.; Jin, X.; Hu, Y.; Zheng, Z.; Zhang, H. 2D Black Phosphorus Saturable Absorbers for Ultrafast Photonics. Adv. Opt. Mater. 2019, 7, 1800224.

77. Zhu, Y.; Tang, B.; Jiang, C. Tunable ultra-broadband anisotropic absorbers based on multi-layer black phosphorus ribbons. Appl. Phys. Express 2019, 12, 032009.

78. Matsuno, Y.; Nagumo, N.; Araki, M.; Yada, K.; Yamaga, K.; Sakurai, A. Non-equilibrium mid-infrared black phosphorus light emitter and absorber for thermophotonic applications. J. Quant. Spectrosc. Radiat. Transf. 2022, 288, 108271.

79. Gong, X.; Guan, L.; Li, Q.; Li, Y.; Zhang, T.; Pan, H.; Sun, Q.; Shen, Y.; Grätzel, C.; Zakeeruddin, S.M.; et al. Black phosphorus quantum dots in inorganic perovskite thin films for efficient photovoltaic application. Sci. Adv. 2020, 6, eaay5661.

80. Kim, D.K.; Hong, S.B.; Jeong, K.; Lee, C.; Kim, H.; Cho, M.H. P-N Junction Diode Using Plasma Boron-Doped Black Phosphorus for High-Performance Photovoltaic Devices. ACS Nano 2019, 13, 1683–1693.

81. Guo, Q.; Pospischil, A.; Bhuiyan, M.; Jiang, H.; Tian, H.; Farmer, D.; Deng, B.; Li, C.; Han, S.J.; Wang, H.; et al. Black phosphorus mid-infrared photodetectors with high gain. Nano Lett. 2016, 16, 4648–4655.

82. Xie, C.; Wang, Y.; Zhang, Z.X.; Wang, D.; Luo, L.B. Graphene/Semiconductor Hybrid Heterostructures for Optoelectronic Device Applications. Nano Today 2018, 19, 41–83.

83. Yan, F.; Wei, Z.; Wei, X.; Lv, Q.; Zhu, W.; Wang, K. Toward High-Performance Photodetectors Based on 2D Materials: Strategy on Methods. Small Methods 2018, 2, 1700349.

84. Zhang, L.; Wang, B.; Zhou, Y.; Wang, C.; Chen, X.; Zhang, H. Synthesis Techniques, Optoelectronic Properties, and Broadband Photodetection of Thin-Film Black Phosphorus. Adv. Opt. Mater. 2020, 8, 72–81.

85. Zhou, X.; Hu, X.; Yu, J.; Liu, S.; Shu, Z.; Zhang, Q.; Li, H.; Ma, Y.; Xu, H.; Zhai, T. 2D Layered Material-Based van der Waals Heterostructures for Optoelectronics. Adv. Funct. Mater. 2018, 28, 1706587.

86. Yang, Z.; Hao, J. Recent Progress in Black-Phosphorus-Based Heterostructures for Device Applications. Small Methods 2018, 2, 1700296.

87. Yuan, J.; Najmaei, S.; Zhang, Z.; Zhang, J.; Lei, S.; Ajayan, P.M.; Yakobson, B.I.; Lou, J. Photoluminescence quenching and charge transfer in artificial heterostacks of monolayer transition metal dichalcogenides and few-layer black phosphorus. ACS Nano 2015, 9, 555–563.

88. Huang, H.; Li, J.; Yi, Y.; Wang, J.; Kang, Y.; Chu, P.K.; Ong, H.C.; Yu, X.F. In situ growth of all-inorganic perovskite nanocrystals on black phosphorus nanosheets. Chem. Commun. 2018, 54, 2365–2368.

89. Qiao, H.; Li, Z.; Huang, Z.; Ren, X.; Kang, J.; Qiu, M.; Liu, Y.; Qi, X.; Zhong, J.; Zhang, H. Self-powered photodetectors based on 0D/2D mixed dimensional heterojunction with black phosphorus quantum dots as hole accepters. Appl. Mater. Today 2020, 20, 100765.

90. Naguib, M.; Kurtoglu, M.; Presser, V.; Lu, J.; Niu, J.; Heon, M.; Hultman, L.; Gogotsi, Y.; Barsoum, M.W. Two-dimensional nanocrystals produced by exfoliation of Ti3AlC2. Adv. Mater. 2011, 23, 4248–4253.

91. Naguib, M.; Mochalin, V.N.; Barsoum, M.W.; Gogotsi, Y. 25th anniversary article: MXenes: A new family of two-dimensional materials. Adv. Mater. 2014, 26, 992–1005.

92. Dhamodharan, D.; Dhinakaran, V.; Byun, H.S. MXenes: An emerging 2D material. Carbon N. Y. 2022, 192, 366–383.

93. Anasori, B.; Lukatskaya, M.R.; Gogotsi, Y. 2D metal carbides and nitrides (MXenes) for energy storage. Nat. Rev. Mater. 2017, 2, 16098.

94. Zhang, C.J.; Anasori, B.; Seral-Ascaso, A.; Park, S.H.; McEvoy, N.; Shmeliov, A.; Duesberg, G.S.; Coleman, J.N.; Gogotsi, Y.; Nicolosi, V. Transparent, Flexible, and Conductive 2D Titanium Carbide (MXene) Films with High Volumetric Capacitance. Adv. Mater. 2017, 29, 1702678.

95. Zhang, C.J.; Nicolosi, V. Graphene and MXene-based transparent conductive electrodes and supercapacitors. Energy Storage Mater. 2019, 16, 102–125.

96. Dong, Y.; Chertopalov, S.; Maleski, K.; Anasori, B.; Hu, L.; Bhattacharya, S.; Rao, A.M.; Gogotsi, Y.; Mochalin, V.N.; Podila, R. Saturable Absorption in 2D Ti3C2 MXene Thin Films for Passive Photonic Diodes. Adv. Mater. 2018, 30, 1705714.

97. Berdiyorov, G.R. Optical properties of functionalized Ti3C2T2 (T = F, O, OH) MXene: First-principles calculations. AIP Adv. 2016, 6, 055105.

98. Bai, Y.; Zhou, K.; Srikanth, N.; Pang, J.H.L.; He, X.; Wang, R. Dependence of elastic and optical properties on surface terminated groups in two-dimensional MXene monolayers: A first-principles study. RSC Adv. 2016, 6, 35731–35739.

99. Xu, Q.; Ding, L.; Wen, Y.; Yang, W.; Zhou, H.; Chen, X.; Street, J.; Zhou, A.; Ong, W.J.; Li, N. High photoluminescence quantum yield of 18.7% by using nitrogen-doped Ti3C2 MXene quantum dots. J. Mater. Chem. C 2018, 6, 6360–6369.

100. Huang, D.; Xie, Y.; Lu, D.; Wang, Z.; Wang, J.; Yu, H.; Zhang, H. Demonstration of a White Laser with V2C MXene-Based Quantum Dots. Adv. Mater. 2019, 31, 1901117.

101. Hantanasirisakul, K.; Zhao, M.Q.; Urbankowski, P.; Halim, J.; Anasori, B.; Kota, S.; Ren, C.E.; Barsoum, M.W.; Gogotsi, Y. Fabrication of Ti3C2Tx MXene Transparent Thin Films with Tunable Optoelectronic Properties. Adv. Electron. Mater. 2016, 2, 1600050.

102. Jhon, Y.I.; Koo, J.; Anasori, B.; Seo, M.; Lee, J.H.; Gogotsi, Y.; Jhon, Y.M. Metallic MXene Saturable Absorber for Femtosecond Mode-Locked Lasers. Adv. Mater. 2017, 29, 1702496.

103. Jiang, X.; Kuklin, A.V.; Baev, A.; Ge, Y.; Ågren, H.; Zhang, H.; Prasad, P.N. Two-dimensional MXenes: From morphological to optical, electric, and magnetic properties and applications. Phys. Rep. 2020, 848, 1–58.

104. Yi, J.; Du, L.; Li, J.; Yang, L.; Hu, L.; Huang, S.; Dong, Y.; Miao, L.; Wen, S.; Mochalin, V.N.; et al. Unleashing the potential of Ti2CTx MXene as a pulse modulator for mid-infrared fiber lasers. 2D Mater. 2019, 6, 045038.

105. Dillon, A.D.; Ghidiu, M.J.; Krick, A.L.; Griggs, J.; May, S.J.; Gogotsi, Y.; Barsoum, M.W.; Fafarman, A.T. Highly Conductive Optical Quality Solution-Processed Films of 2D Titanium Carbide. Adv. Funct. Mater. 2016, 26, 4162–4168.

106. Chen, J.; Chen, M.; Zhou, W.; Xu, X.; Liu, B.; Zhang, W.; Wong, C. Simplified Synthesis of Fluoride-Free Ti3C2Tx via Electrochemical Etching to Performance Electrochemical Capacitors. ACS Nano 2022, 16, 2461–2470.

107. Chertopalov, S.; Mochalin, V.N. Environment-Sensitive Photoresponse of Spontaneously Partially Oxidized Ti3C2 MXene Thin Films. ACS Nano 2018, 12, 6109–6116.

108. Yu, Z.; Feng, W.; Lu, W.; Li, B.; Yao, H.; Zeng, K.; Ouyang, J. MXenes with tunable work functions and their application as electron- and hole-transport materials in non-fullerene organic solar cells. J. Mater. Chem. A 2019, 7, 11160–11169.

109. Agresti, A.; Pazniak, A.; Pescetelli, S.; Di Vito, A.; Rossi, D.; Pecchia, A.; Auf der Maur, M.; Liedl, A.; Larciprete, R.; Kuznetsov, D.V.; et al. Titanium-carbide MXenes for work function and interface engineering in perovskite solar cells. Nat. Mater. 2019, 18, 1228–1234.

110. Zhang, J.; Tan, B.; Zhang, X.; Gao, F.; Hu, Y.; Wang, L.; Duan, X.; Yang, Z.; Hu, P.A. Atomically Thin Hexagonal Boron Nitride and Its Heterostructures. Adv. Mater. 2021, 33, 2000769.

111. Cassabois, G.; Valvin, P.; Gil, B. Hexagonal boron nitride is an indirect bandgap semiconductor. Nat. Photonics 2016, 10, 262–266.

112. Bilal, M.; Xu, W.; Wang, C.; Wen, H.; Zhao, X.; Song, D.; Ding, L. Optoelectronic properties of monolayer hexagonal boron nitride on different substrates measured by Terahertz time-domain spectroscopy. Nanomaterials 2020, 10, 762.

113. Tan, B.; Wu, Y.; Gao, F.; Yang, H.; Hu, Y.; Shang, H.; Zhang, X.; Zhang, J.; Li, Z.; Fu, Y.; et al. Engineering the Optoelectronic Properties of 2D Hexagonal Boron Nitride Monolayer Films by Sulfur Substitutional Doping. ACS Appl. Mater. Interfaces 2022, 14, 16453–16461.

114. Yamoah, M.A.; Yang, W.; Pop, E.; Goldhaber-Gordon, D. High-Velocity Saturation in Graphene Encapsulated by Hexagonal Boron Nitride. ACS Nano 2017, 11, 9914–9919.

115. Meng, J.H.; Liu, X.; Zhang, X.W.; Zhang, Y.; Wang, H.L.; Yin, Z.G.; Zhang, Y.Z.; Liu, H.; You, J.B.; Yan, H. Interface engineering for highly efficient graphene-on-silicon Schottky junction solar cells by introducing a hexagonal boron nitride interlayer. Nano Energy 2016, 28, 44–50.

116. Zhang, H.; Virally, S.; Bao, Q.; Kian Ping, L.; Massar, S.; Godbout, N.; Kockaert, P. Z-Scan measurement of the nonlinear refractive index of graphene. Opt. Lett. 2012, 37, 1856–1858.

117. Raj, V.; Chugh, D.; Black, L.E.; Shehata, M.M.; Li, L.; Kremer, F.; Macdonald, D.H.; Tan, H.H.; Jagadish, C. Passivation of InP solar cells using large area hexagonal-BN layers. NPJ 2D Mater. Appl. 2021, 5, 12.

118. Wang, Y.; Ren, B.; Qu, J.Z.; Xu, K.; Yang, C.; Li, Y.; Zhang, H. Engineering two-dimensional metal oxides and chalcogenides for enhanced electro- and photocatalysis. Sci. Bull. 2021, 66, 1228–1252.

119. Kumbhakar, P.; Chowde Gowda, C.; Mahapatra, P.L.; Mukherjee, M.; Malviya, K.D.; Chaker, M.; Chandra, A.; Lahiri, B.; Ajayan, P.M.; Jariwala, D.; et al. Emerging 2D metal oxides and their applications. Mater. Today 2021, 45, 142–168.
120. Hu, X.; Liu, K.; Cai, Y.; Zang, S.-Q.; Zhai, T. 2D Oxides for Electronics and Optoelectronics. Small Sci. 2022; early view.
121. Yu, H.; Liao, Q.; Kang, Z.; Wang, Z.; Liu, B.; Zhang, X.; Du, J.; Ou, Y.; Hong, M.; Xiao, J.; et al. Atomic-Thin ZnO Sheet for Visible-Blind Ultraviolet Photodetection. Small 2020, 16, 2005520.
122. Messalea, K.A.; Carey, B.J.; Jannat, A.; Syed, N.; Mohiuddin, M.; Zhang, B.Y.; Zavabeti, A.; Ahmed, T.; Mahmood, N.; Della Gaspera, E.; et al. Bi2O3 monolayers from elemental liquid bismuth. Nanoscale 2018, 10, 15615–15623.
123. Yin, C.; Gong, C.; Chu, J.; Wang, X.; Yan, C.; Qian, S.; Wang, Y.; Rao, G.; Wang, H.; Liu, Y.; et al. Ultrabroadband Photodetectors up to 10.6 μm Based on 2D Fe3O4 Nanosheets. Adv. Mater. 2020, 32, 4–11.
124. Zhong, M.; Zhou, K.; Wei, Z.; Li, Y.; Li, T.; Dong, H.; Jiang, L.; Li, J.; Hu, W. Highly anisotropic solar-blind UV photodetector based on large-size two-dimensional α-MoO3 atomic crystals. 2D Mater. 2018, 5, 035033.