Optoelectronic and photonic devices based on transition metal dichalcogenides

Kartikey Thakar and Saurabh Lodha
Department of Electrical Engineering, Indian Institute of Technology Bombay, Mumbai—400076, India
E-mail: kmtmicro@ee.iitb.ac.in and slodha@ee.iitb.ac.in

Keywords: optoelectronics, photonics, 2D materials, transition metal dichalcogenides, photodetectors, photovoltaics, light emitting devices

Abstract
Transition metal dichalcogenides (TMDCs) are a family of two-dimensional layered materials (2DLMs) with extraordinary optical properties. They present an attractive option for future multifunctional and high-performance optoelectronics. However, much remains to be done to realize a mature technology for commercial applications. In this review article, we describe the progress and scope of TMDC devices in optical and photonic applications. Various response mechanisms observed in such devices and a brief discussion on measurement and analysis methods are described. Three main types of optoelectronic devices, namely photodetectors, photovoltaics and light-emitting devices are discussed in detail with a focus on device architecture and operation. Examples showing experimental integration of 2DLM-based devices with silicon photonics are also discussed briefly. A wide range of data for key performance metrics is analysed with insights into future directions for device design, processing and characterization that can help overcome present gaps and challenges.

Introduction
Two-dimensional layered materials (2DLMs)
A large number of scientists and researchers has been attracted towards research on electronic devices based on two-dimensional layered materials (2DLMs) in the last decade. Owing to some of their unique physical properties and virtually endless possibilities to form heterostructures, 2DLMs can open the doors to a plethora of novel devices and applications that are not easily executable with conventional 3D semiconductors like Si, Ge or III-V materials. Flexible and transparent electronics are two such examples. While the field is still in its infancy and requires significant efforts toward standardizing various approaches towards a mature technology, it has already shown promising results in broader aspects of compatibility, integration and performance for future electronics. Sensors are increasingly becoming an integrated part of the global electronic eco-system with the rise of data-driven technologies. There is a growing need for networks of cost-effective, robust and reliable sensors and their integration with present technologies. Optoelectronic and photonic devices are of importance for both sensing as well as high-speed optical communication applications. 2DLMs demonstrate significant light–matter interaction that is tunable with external physical and electronic parameters such as pressure, strain, electric and magnetic field [1–6]. Moreover, 2DLMs show strong dependence of their band structure on thickness with a transition to direct bandgap in monolayers in most of the known 2DLMs [7–9]. Graphene has been the most studied material since its discovery in 2004 [10–12]. Apart from graphene, there are nearly 1500 possible 2DLMs with a wide range of material properties as predicted by first principle simulations [13]. Transition metal dichalcogenides (TMDCs) are a family of 2DLMs in the form of MX2 compounds, where M is a transition metal (Mo, W, Re) and X is a chalcogen (S, Se, Te). TMDCs are promising for electronic applications due to their semiconducting behaviour as opposed to semi-metallic graphene, and better thermal stability than materials such as black phosphorus and silicene [14–19].
Optoelectronic devices based on TMDCs

TMDCs have been the most studied 2DLMs, apart from graphene and black phosphorus, for electronic and optoelectronic device applications \[20, 21\]. They have a sizeable bandgap in the visible and near infrared (NIR) range (\(\sim 1–2\) eV) that is optimal for optoelectronic sensors and light-emitting sources for short-range optical communication \[22, 23\]. Moreover, alloying of the transition metals and chalcogens provides an additional knob for tuning electrical and optical properties \[24, 25\]. Literature on optoelectronics based on TMDCs is growing rapidly every year with reports on single material and heterostructure devices. Enhanced light–matter interaction even at monolayer thickness along with a direct bandgap and mechanical flexibility gives a clear advantage over silicon (Si) technology \[6, 26\]. Optoelectronic devices such as photodetectors, photovoltaics, light-emitting devices and optical modulators have been demonstrated using TMDCs across a wide range of device architectures and measurement methodologies \[4, 27, 28\]. Figure 1 gives a picture of published reports on TMDCs in the field of optoelectronics and photonics. The data has been collected through keyword search on the Web of Science (www.webofknowledge.com) in April, 2019. It should be noted that the numbers are prone to slight error due to the limitations of keyword search. Figure 1(a) shows the total number of articles published on graphene and other 2DLMs across various fields. (b) Pie charts showing material-wise number of research articles published in the field of optoelectronics and photonics. (c) Year-wise number of articles published for select set of materials. Different materials are color-coded. BP = black phosphorus, HS = heterostructure. (d) Number of articles plotted for different materials for the same data as in (c).

This review

It is crucial to study the fundamental mechanical, electrical and optical properties of TMDCs and several recent articles have presented focused discussions on their synthesis and material-related properties which can have significant impact on device performance \[29–33\]. In this article, however, we start with a basic introduction to the physical mechanisms/phenomena in TMDC-based optoelectronic devices, followed by a brief discussion on optoelectronic device characterization, analysis and performance evaluation. This is intended for a novice reader.
in the field. The field of optoelectronics is vast and literature on TMDCs is rich with studies on exciton physics, substrate effects, and various material-level effects such as charge transfer \([34–36]\). While most studies on optoelectronic devices mainly focus on performance improvement, they also employ a diverse range of device architectures and physical mechanisms. This has resulted in a wide spread of uncorrelated performance parameter values. In this article, we present a consolidated picture of this broad set of TMDC-based optoelectronic devices, their architectures as well as their operational mechanisms. This enables us to compare and benchmark their performance metrics. We cover three major types of devices—namely photodetectors (PDs), photovoltaics (PV) and light-emitting devices (LEDs). We describe key recent works with an analysis on their overall impact. We also briefly cover the integration of 2DLMs with Si photonics towards the end. Finally, we end with concluding remarks and a discussion on future considerations for researchers working in this field.

Mechanisms in optoelectronic devices

In this section, we describe a few operational phenomena in 2DLM-based optoelectronic devices based on their output characteristics and photoresponse behaviour.

Photoconduction (PC)

This is the most common phenomenon in photoactive materials \([37]\). Excess electron-hole (e−h) pairs are generated upon absorption of light with energy higher than the bandgap of the material stack. The increased carrier concentration results in a net increase in current under external applied electric field. Photocurrent \((I_{ph})\) is calculated as the increase in current from dark \((I_{dark})\) to illumination \((I_{light})\) conditions. \(I_{ph} = I_{light} - I_{dark}\). The number of generated carriers per incident photon may depend on various factors such as excitation wavelength, incident optical power, device operation, defects in the material and the material itself. Important device design considerations include appropriate metal contacts, effect of the substrate and channel geometry. Devices operating with this mechanism usually provide low-to-medium sensitivity with high speed of operation.

Photogating (PG)

Photogating is a specific case of PC \([38]\). One type of photogenerated carriers (electrons or holes) may get trapped in the bulk material or material interfaces. This results in a net electrostatic voltage shift in the device. Due to this, the device sees a pseudo electric field as if it were an external gate-field. This causes a net shift in the transfer curve of the devices, especially in a field-effect transistor (FET) configuration. The trapped excess charge carriers (for example, holes) induce the opposite polarity charges (electrons) in the channel which may be thermally generated or provided from the contacts. Here multiple electrons can travel through the channel before a single hole is de-trapped, contributing to the net output current. This results in a net gain in the output as well, defined as the ratio of the lifetime of a trapped carrier \(\tau_{\text{trapped}}\) to the time taken for free carriers to travel through the channel \(\tau_{\text{transit}}\). Gain \((PG) = \tau_{\text{transit}} / \tau_{\text{trapped}}\). Here, a careful analysis of the underlying behaviour and physics of defects and traps is of high importance \([39–42]\). A detailed discussion on the classification, generation, properties and applications of defects and traps in TMDCs can be found in \([43, 44]\).

Persistent photocurrent (PPC)

The current due to photogenerated carriers should ideally die down once the excitation source is turned off. However, in some cases the photocurrent can retain the value that existed just before the light source was turned off. This is called the persistent photocurrent (PPC) effect. This could be due to traps with a very long lifetime or permanent changes in the channel. While PPC is not very useful for photodetection, it can prove to be beneficial for non-volatile optical memory devices \([45]\).

Avalanche photodetectors (APD)

If an excess charge carrier is subjected to a high electric field, either built-in or external, then it can induce multiple charge carriers by impact ionization and increase the photocurrent. This results in a net multiplicative gain \((M)\). The channel may undergo a reversible soft breakdown in such devices. Avalanche devices are useful specifically in weak light detection—such as a single photon detector \([46, 47]\).

Photovoltaics (PV)

When a built-in electric field is present in the device, the photogenerated e−h pairs get separated in opposite directions to give rise to a photovoltaic effect \([48]\). A built-in field can be achieved using pn junctions, chemical or electrostatic doping, or metal work-function mismatch. The separated carriers can recombine through an external circuit providing electrical power. Such devices usually operate under no applied bias, and hence are
crucial in energy harvesting applications. For their use as an energy generator, efficiency becomes a more important parameter than speed in PV devices. However, fast switching PV devices can also work as efficient, self-driven photodetectors (PDs).

**Photothermoelectric (PTE) effect**
Photothermoelectric effect arises due to local variation in temperature in the channel induced by light irradiation \[49, 50\]. This could arise due to highly uneven light excitation or non-uniform absorption across the active device area. For example, a focused laser spot smaller than the device area can locally heat the channel. This could result in a temperature-driven current because of the thermoelectric voltage produced by Seebeck effect. The current due to the PTE effect is self-driven and its polarity can be the same or opposite to the photocurrent depending on the temperature gradient and the Seebeck coefficients of the materials involved.

**Photobolometric (PB) effect**
The resistance of the material may change with temperature induced due to light irradiation and absorption, resulting in a change in the current, giving rise to a photobolometric effect \[51, 52\]. The current of the device can increase or decrease with the PB effect for a fixed external bias. Unlike the PTE effect, an external bias is required for current conduction in case of PB effect.

**Electroluminescence (EL)**
Electroluminescent devices work on the opposite principle to that of photogeneration. A highly doped pn junction or quantum well device emits fixed wavelength photons when an e-h pair recombines radiatively in a direct bandgap material. Due to the stringent requirement of a direct bandgap, mainly monolayer flakes of TMDs are used in EL devices. However, some of the 2DLMs such as ReS\(_2\), black phosphorus, and InSe have direct bandgap in bulk as well \[53–55\]. The emitted light is characterized by material properties and operation conditions. For example, an anisotropic material like ReS\(_2\) or black phosphorus can emit circularly polarized light.

**Valley or spin selection**
2DLMs exhibit strong spin–orbit coupling (SOC) and valley spin polarization. Under an external magnetic field, the recombination, generation and transport of carriers in such materials is spin polarized \[56\]. This allows us to selectively populate carriers of a particular spin-type during both photogeneration as well as photoemission. While proper operating conditions may be difficult to achieve for such devices, they do add an additional degree of freedom to the available set of operational mechanisms.

**Typical measurement and analysis methods**
We describe a typical measurement system required for optoelectronic characterization of 2DLM-based devices, figures of merit and specific measurements for performance evaluation.

**Measurement setup**
A typical optoelectronic characterization setup consists of three major components: (i) a light source and a beam-steering assembly, (ii) a spectrometer, and (iii) an electrical measurement unit. Figure 2(a) shows a standard setup with free space optical assembly. The sample is loaded under a microscope objective to focus incident light selectively on the sample. Electrical connections are taken from the sample to the electrical unit. A light source is not required for EL measurements, rather the light emitted from the sample is steered through the same path to a spectrometer. This confocal assembly allows us to perform all standard experiments. All equipment or parts can be collectively controlled by a program interface through a computer. Lastly, a vibration proof optical table is required for placement of all the equipment. The same system can be used for physical characterization such as photoluminescence (PL) and Raman spectroscopy with parts of appropriate specifications. Next, we briefly describe each major part in the system.

**Light source**
The light source can vary depending on the measurement requirements in the study. A versatile, tunable, continuum laser source is the most useful for recording the spectral response. The most common light source used is a continuous wave (CW) single wavelength laser source with tunable power. A white light source or a halogen lamp calibrated to the solar spectrum is required for photovoltaic characterization—however most
Figure 2. (a) Typical setup for free space optoelectronic characterization. Optical fibres can be used for the light path as well. Microscope is used to probe selective area on the sample and can be omitted if large-area illumination is desired. (b) Typical plots for 2DLM-based photodetector characterization. (i) I-V characteristics of the device under dark and illumination. The response may vary with device architecture and operating mechanisms. Photocurrent is calculated as $I_{ph} = I_{light} - I_{dark}$. (ii) Responsivity ($R = \frac{I_{ph}}{P}$) as a function of incident power at different excitation wavelengths. This is useful in determining the dynamic operating range of the detector. (iii) Spectral response of the photodetector for different incident illumination power. This is important to determine what spectrum can be probed with the device. (iv) NEP as a function of operating frequency. Noise floor is crucial in determining the operating conditions as well as power loss in idle condition. Another important parameter is specific detectivity which can be calculated as $D' = \frac{R \cdot A}{\sqrt{NEP}}$. It indicates minimum detectable optical power for a given set of operating conditions. (v) Photodetector response with absolute current values is used to evaluate the device performance. $L_s$ and $V_{oc}$ indicate the short-circuit current and open-circuit voltage, respectively. Output electrical power can be calculated as $P_{el} = I_{ph} \cdot V_{oc}$. Fill factor is calculated as the ratio of maximum power output to the maximum theoretical power output. $FF = \frac{P_{oc}}{I_{ph} \cdot V_{oc}}$. (vi) Quantum efficiency of the device as a function of wavelength. Both internal and external quantum efficiency values can be studied. The shown curve is for near-ideal conditions where $\eta$ is constant up to a $\lambda$ and starts decreasing after the bandgap edge since no e-h pair can be generated. (c) Typical plots for 2DLM-based photovoltaic characterization. (i) I-V characteristics in the dark and under illumination. For a realistic measurement, a source calibrated to the solar spectrum should be used. However, other light sources could be used to show proof-of-concept device operation. 4th quadrant in the I-V curve is highlighted to show photovoltaic action. (ii) Typically, 4th quadrant plot with absolute current values is used to evaluate the device performance. $L_s$ and $V_{oc}$ indicate the short-circuit current and open-circuit voltage, respectively. Output electrical power can be calculated as $P_{el} = I_{ph} \cdot V_{oc}$. Fill factor is calculated as the ratio of maximum power output to the maximum theoretical power output. $FF = \frac{P_{oc}}{I_{ph} \cdot V_{oc}}$. (iii) Quantum efficiency of the device as a function of wavelength. Both internal and external quantum efficiency values can be studied. The shown curve is for near-ideal conditions where $\eta$ is constant up to a $\lambda$ and starts decreasing after the bandgap edge since no e-h pair can be generated. (d) Typical plots for 2DLM-based LED characterization. (i) Typical pn light emitting diode I-V curve. LED characterization is carried out in constant current condition. (ii) EL spectra of the device for different current values. EL intensity usually increases with increased current but need not follow a linear dependence. Systematic characterization allows calibration of the light intensity with input current. (iii) EQE as a function of input current. It gives important information about what current window is best for LED operation. Dummy data plots shown in b-d were created for the purpose of illustration.
reports on PV based on 2DLMs have used single frequency CW laser sources. FWHM and long-term power stability are important parameters to consider in a laser source.

**Optical assembly**

The optical assembly consists of beam-steering and focusing equipment. Free space assembly is preferred to minimize losses, while optical fibre delivery is preferred when freedom of routing (e.g. from a heavy, stationary laser source) is required. The optical parts usually work for a specific range of the electromagnetic spectrum. Parts should be chosen as per the measurement requirements. Appropriate focusing and collimating apparatus should be used in the light path to avoid losses. Usually a microscope is used for focused light and scanning measurements.

**Sample holder/stage**

This is a crucial element in the system as it holds the most important thing in the whole setup—the device-under-test (DUT). It can have capabilities such as holding vacuum, temperature control, motorized axis control and even atmosphere control for humidity and gaseous compounds. Additionally, the stage may require the ability to apply mechanical stress/strain for characterization of electromechanical stability of flexible optoelectronic devices. Stages with one or more capabilities are available commercially, and can be custom-built as well. Moreover, the sample holder should have capability to apply electrical signals to the DUT under a microscope. Wire bonding the device allows for repeated measurements without harming the device contact pads.

**Electrical unit**

Electrical unit provides the capability for various kinds of measurements. Standard commercially available semiconductor measurement units (SMUs) are suitable for optoelectronic device measurements. All kinds of steady-state current and voltage measurements can be easily carried out using SMUs. Data acquisition (DAQ) systems are a possible low-cost alternative to SMUs with added complexity of control. Additional components such as a function/signal generator, a lock-in amplifier and a digital storage oscilloscope (DSO) are required to generate and capture high frequency periodic signals.

**Spectrometer**

Spectrometer is an important instrument for spectroscopic measurements. Its specifications are crucial when a very weak light source is being characterized—as is the case for many 2DLM-based LEDs. Grating, light input/steering and camera are the main aspects to consider. Proper grating should be used for maximum output efficiency. Slit for light input determines the light available for analysis and should be focused properly to maximize the efficiency. A camera with a large dynamic range, high spatial resolution and high quantum efficiency is required to get an accurate spectral signal from the sample.

**Characterization, analysis, and figures of merit**

Next, we describe typical measurements for PD, PV and EL characterization that can be performed using the setup described here. We also describe, in brief, the figures of merit for each type of device. Dummy data plots are shown in figures 2(b)–(d) for the purpose of illustration.

**Photodetectors**

TMDC-based photodetectors are the most studied amongst TMDC-based optoelectronic devices. Simple steady-state dc current-voltage (I-V) measurements for the two-terminal device under dark and constant illumination conditions is the first step (figure 2(b) (i)). \(I_{ph}\) can be easily calculated from the I-V curves. The next step is to calculate the steady-state photo-responsivity.

**Responsivity \((R_s)\)**

Responsivity is calculated as \(R_s = I_{ph} / P_{in} [A/W]\), where \(P_{in}\) is the incident excitation power at a fixed wavelength \(\lambda\). It is an important figure of merit for photodetectors that defines the number of excess carriers collected in the external circuit for incident unit power. \(R_s\) depends on both \(P_{in}\) as well as \(\lambda\). Hence, the next important analytic plots are \(R_s\) as a function of \(P_{in}\) and \(\lambda\) (figure 2(b) (ii, iii)).

**Gain \((G)\)**

Gain is defined as the number of photogenerated excess charge carriers per incident photon. It affects the net responsivity value as \(R_{eff} = R_s \cdot \eta_{PD} \cdot G\), where \(\eta_{PD}\) is the efficiency of the device. Gain can be induced because
of many factors such as carrier trapping, avalanche effect and multiple e-h pair generation by a high energy photon. Estimation of gain is one of the difficult tasks since the exact gain mechanism has to be identified accurately and analysed.

**Speed**

Speed is another important parameter for PDs. High frequency photo-switching measurements are required to estimate the response time ($\tau$) (figure 2(b) (v)). Both rise-time and fall-time, usually calculated between 10% and 90% levels, are extracted and the limiting number is used to define the maximum operating frequency as $f_{\text{max}} = 1/\tau$. It is important to take note of the trade-off between speed and responsivity of a PD. Figure 2(b) (vi) illustrates how a plot of $R$ versus $\tau$ for different PDs can be useful for benchmarking the device performance.

**Spectral range**

Spectral range defines the wavelength window for which the PD responds by generating $I_{ph}$. This is important when a PD with a certain wavelength range is required. The spectral range can be easily determined from figure 2(b) (iii).

**Noise equivalent power (NEP)**

NEP is one of the most important figures of merit for a photodetector. It gives an estimate of signal power for which the signal-to-noise ratio (SNR) becomes unity for one Hz bandwidth. NEP estimation is crucial and should be performed experimentally under different operating conditions (figure 2(b) (iv)). Dark current should be kept as low as possible to reduce NEP.

**Specific detectivity ($D^*$)**

$D^*$ is another important metric for sensitivity of the PD. It can be calculated as $D^* = R_0 \cdot \sqrt{A}/\text{NEP}$, where $A$ is the device area. $D^*$ indicates the minimum detectable power per unit area of the device and unity bandwidth. It is useful for cross-platform performance comparison.

**External quantum efficiency (EQE)**

EQE indicates the number of carriers collected per incident photon. As a simple estimate it can be calculated using the relation $\text{EQE} = R_0 \cdot \frac{hc}{eA}$. Usually EQE estimated from the equation is erroneous due to the complex nature of underlying mechanisms, and dedicated EQE measurements should be performed for a more accurate estimate.

**Linear dynamic range (LDR)**

LDR is another important parameter for PDs. It gives the range of optical power over which the PD response is linear. It is given in dB (e.g., 60 dB). LDR is mainly limited by noise at low-power range and non-linear effects in the high-power range. Usually responsivity and LDR show a trade-off, meaning that the responsivity of the PD suffers for large LDR and vice versa.

**Photovoltaics**

Photovoltaic devices have been studied extensively due to their importance in energy harvesting. 2DLM-based devices also show promise for flexible PV applications. Various material stacks and device architectures have been studied in the literature. Some of the important parameters are listed below.

**Open-circuit voltage ($V_{oc}$) and short-circuit current ($I_{sc}$)**

$I_{sc}$ is defined as the current flowing through the device under short-circuit configuration, and $V_{oc}$ is the voltage under open-circuit configuration. Figure 2(c) (i) shows I-V plots under dark and illumination conditions. Both $I_{sc}$ and $V_{oc}$ are marked in the curve. Generated output electrical power is calculated as $P_{el} = I \cdot V$ in the desired operation range.

**Fill factor (FF)**

Fill factor is a very important figure of merit for a PV device. It is defined as the ratio of the maximum generated output electrical power to the maximum possible output power (figure 2(c) (ii)). $\text{FF} = P_{el,\text{max}}/I_{sc} \cdot V_{oc}$. High FF value (close to 0.7 or higher) is desirable.

**Quantum efficiency ($\eta_{PV}$)**

Both internal and external quantum efficiency values are crucial for PV device optimization. External quantum efficiency ($\eta_{PV}$) depends on the absorption of light, carrier generation, carrier lifetimes, collection efficiency and...
losses in the channel. Figure 2(c) (iii) shows a plot of \( \eta_{\text{EL}} \) as a function of wavelength. Different materials can be combined to increase the absorption over different ranges of the electromagnetic spectrum.

**Light emitting devices**

LEDs are used in stand-alone sensory applications such as opto-couplers as well as in optical communication. For EL characterization, a range of current values are selected from the device I-V characteristics (figure 2(d) (i)). Further, EL spectra are recorded for each constant-current biasing point (figure 2(d) (ii)).

**On-current \((I_{\text{on}})\)**

\( I_{\text{on}} \) is the minimum (or threshold) current value required to get an EL response from the device. A smaller \( I_{\text{on}} \) is desirable for low-power operation.

**Luminescence**

Intensity of the emitted light is measured in lumens (lm). For the purpose of experimentation, counts in the EL peak serve the purpose of relative comparison. While we would like to achieve as high output light intensity as possible, the input power increases rapidly with it. Hence an appropriate metric is \( \text{lm/W} \) (or here, \( \text{counts/W} \)) for benchmarking of device efficiency.

**Quantum efficiency \((\eta_{\text{EL}})\)**

It is defined as the ratio of number of emitted photons to the number of recombined e-h pairs in the device. Figure 2(d) (iii) shows a plot of \( \eta_{\text{EL}} \) as a function of device current. \( \eta_{\text{EL}} \) depends on the carrier injection and non-radiative recombination rates.

**Photodetectors**

Photodetectors have been by far the most studied optoelectronic device for TMDCs. The studies so far have focused on a number of topics ranging from implementing novel device architectures and leveraging unique physical properties to ways for improving performance [57–64]. FET and pn junction have been the most preferred device architectures for a wide range of TMDCs. Large-area growth of TMDCs has been looked at for wafer-scale fabrication processes [65]. Alloyed compounds based on TMDCs have also been studied for improved optical device performance [66–70]. Many reports have studied various charge transfer mechanisms and carrier dynamics to understand and exploit the rich physics of TMDC materials [71–76]. Moreover, mixed dimensional heterostructures and plasmonic-, organic material- or quantum dot-enhanced structures have also been studied for performance enhancement [77–81]. Some of the reports covering these topics have been discussed below.

Figure 3(a) (i) shows the 3D schematic of supported and suspended channel FET architectures with ReS\(_2\) as the channel material [82]. The two device architectures represent different trap densities that can be used to probe the effect of traps on optoelectronic performance. Bulk traps in ReS\(_2\) are present in both devices, whereas interface traps at the ReS\(_2\)/SiO\(_2\) interface are absent in the suspended channel device and hence do not affect the photoresponse. As discussed earlier, traps rise to a PG effect and can provide gain in photocurrent while reducing the speed. Figure 3(a) (ii) shows a series of plots of temporal photoresponse with increasing speed going from left to right. The devices were slow (4.2 s) with high \( I_{ph} \) (225 nA) when gate-bias \( (V_G) \) was below threshold voltage \( (V_{th}) \) of the FET (here \( V_G = 0 \) V) and the illumination was kept on for a long time (here 15 s). However, when \( V_G > V_{th} \) (here \( V_G = 80 \) V), the device response time improved drastically (~50 ms) with reduced \( I_{ph} \) (~45 nA) for the same period of laser-on time. The device response speed reached ~13 \( \mu \) s with high frequency (10 kHz) laser switching, independent of \( V_G \). Analysis of the data suggests that the effective trap density along with the trap time constants play an important role in PD operation irrespective of the photoactive material. Simple trap filling strategies (here with \( V_G \)) can be used to exploit the underlying mechanism for tunable PD performance.

Like many 2DLMs, ReS\(_2\) has been shown to have anisotropic band structure resulting in two major excitons with unequal binding energy [85–89]. This allows control over polarized light absorption, and consecutively polarization sensitive PD. Figure 3(b) (i) shows an ReS\(_2\) FET under illumination with a linearly polarized light beam. Figure 3(b) (ii) shows the photocurrent as a function of polarization angle for different applied biases [83]. Appropriate calibration of such PDs allows detection of light intensity along with its polarization, thereby adding the freedom of detecting polarization-encoded signals.

The high bandwidth photoresponse of a graphene-based PD (figure 3(c) (i)) is shown in figure 3(c) (ii) [84]. A 1 dB bandwidth of ~40 GHz was observed for a gate-bias of 80 V. In addition, responsivity in dc and
high-frequency regimes is compared for different \( V_G \). While TMDCs cannot compete with graphene in speed, reduced dark current due to a sizeable bandgap allows them to reach larger responsivity with higher detectivity. Figure 3(d) shows an encapsulated MoS\(_2\) PD for improved time response [41]. Figure 3(d) (i) shows 3D schematics of MoS\(_2\) PDs with and without HfO\(_2\) encapsulation and their corresponding current plots under dark and illumination conditions. A clear improvement in speed was achieved through passivation of traps facilitated by HfO\(_2\) encapsulation. Figure 3(d) (ii, iii) show the spectral response of the device and trends in responsivity with incident power for a range of \( V_G \) values, respectively.

Figure 4(a) shows the photoresponse of a WSe\(_2\)/Si pn junction with graphene quantum dots (GQDs) (shown in inset) under dark and with 740 nm light illumination [90]. The heterostructure consisting of GQDs, physical vapor deposition (PVD) grown monolayer (ML) WSe\(_2\) and n-type Si can reach a responsivity of \( \sim 700 \) mA W\(^{-1}\) at a short response time of 0.2 ms. The technique is scalable due to PVD-grown large area ML WSe\(_2\) as opposed to the mechanical exfoliation technique adopted in a majority of PD studies [91, 92].

Figure 4(b) illustrates the (i) schematic, (ii) photoresponse and (iii) transport mechanism of a nitrogen-doped (N-)GQD/ML WSe\(_2\) heterostructure FET [93]. The N-GQDs helped improve the photoresponse due to enhanced light absorption and efficient charge transfer. Figure 4(b) (iii) shows band alignment and charge transfer mechanism under 405 nm excitation. Efficient generation of e-h pairs in N-GQDs along with transfer of holes to p-type ML WSe\(_2\) results in enhanced \( I_{ph} \).
Since the band structure of TMDCs evolves with flake thickness, it is possible to design heterostructures of different flake thicknesses of the same material. Figure 4(c) shows one such example where a ML/2L WSe2 heterostructure with interdigitated electrodes is used to improve carrier collection area [94]. The device behaves as a pn junction due to flake-thickness dependent band alignment as opposed to a ML WSe2 FET (figure 4(c)(ii)). The photocurrent spectral response and spectral absorption of the heterostructure are shown figure 4(c)(iii). The absorption peaked near 750 nm which corresponds to the direct bandgap of ML WSe2. Another pn heterostructure device consisting of CVD-grown ML MoS2 as the n-type material and organic zinc phthalocyanine (ZnPc) as the p-type layer is shown in figure 4(d)(i) [95]. The structure was fabricated via immersion of MoS2 in ZnPc solution for a fixed amount of time. ZnPc forms self-assembled layers on ML MoS2 with good coverage. Figure 4(d)(ii, iii) show dc transfer curves and transient photoresponse of MoS2 PDs with
and without ZnPc immersion, respectively. The current in MoS2 FET decreased because of an increase in each material. The responsivity was modulated with the channel length of both black phosphorus and ReS2, and can be tuned via appropriate choice of the gate-bias. Figure 5 showing the amplification resistance due to the p-type ZnPc layer, while the response time decreased significantly probably due to efficient charge transfer.

Figure 5 (a) (i) shows the optical image of a pn heterostructure of black phosphorus and ReS2 [96]. Type-III band alignment between the two materials allows for tunnelling current depending on the biasing conditions. Figure 5 (a) (ii, iii) display the $V_{G2}$-dependent responsivity trends for varying channel length combinations for each material. The responsivity was modulated with the channel length of both black phosphorus and ReS2, and was higher for shorter channel lengths.

Figures 5 (b), (c) show phototransistors working on the principal of current-amplification in bipolar junction transistors (BJTs) [97, 98]. Open base BJT is a commonly available photodetector. The advantages of making heterostructures and electrostatic doping in TMDCs allow for novel BJT architectures for improved photodetection responsivity [99–106]. Figure 5 (b) (i, ii) illustrate the schematic of the 2D heterostructure BJT consisting of three materials (WSe2/black phosphorus/MoS2) and its band diagram under illumination showing the amplification mechanism, respectively. Figure 5 (b) (iii) shows photo on/off ratio of the device under 637 nm illumination with varying incident power. Figure 5 (b) (iv) shows responsivity and internal current–gain in the device as a function of excitation wavelength. A maximum gain of ~10 was achieved for 532 nm light. Figure 5 (c) (i, ii) show the 3D schematic and false-color secondary electron microscopy (SEM) image of a WSe2 photo-BJT with electrostatic gating, respectively. The band alignment between different regions can be tuned via appropriate choice of the gate-bias. Figure 5 (c) (iii) shows the comparison between steady-state photoresponse of the device in pn (red) and BJT (blue) configuration. In BJT configuration, the PV effect is absent and a higher photocurrent (as compared to pn) was observed. Figure 5 (c) (iv) shows the surface plot of extracted photo–gain ($\beta_{\text{photo}}$) for varying applied bias and gate-bias for the base region. Maximum $\beta_{\text{photo}}$ value of ~40 was achieved for a particular biasing combination.
| Sr No | References | Architecture | Material | Excitation source | $R$ (A/W) | $\tau$ (s) | Detectivity (f Jones) | NEP | Spectral response |
|-------|------------|--------------|----------|-------------------|----------|----------|----------------------|-----|------------------|
| 1     | [41]       | encapsulated FET | MoS$_2$/MoTe$_2$ | 635 nm, 10$^{-4}$ W cm$^{-2}$ | 10$^4$ | 8 × 10$^{-5}$ | 7 × 10$^{11}$ | 10$^{-10}$ A/√Hz | <670 nm |
| 2     | [107]      | FET           | MoTe$_2$ | 20 μW | 6 | 160 × 10$^{-6}$ | — | — | — |
| 3     | [58]       | FET           | ReS$_2$ | 532 nm, 6 pW | 8.86 × 10$^4$ | 100 | 10$^{17}$ | 1.2 × 10$^{-18}$ W/√Hz | — |
| 4     | [82]       | FET           | ReS$_2$ | 630 nm, 140 mW cm$^{-2}$ | 4 | 20 × 10$^{-6}$ | — | — | — |
| 5     | [80]       | FET           | ReS$_2$ with CdSe-CdS-ZnS qDot | 589 nm, 1.2 mW cm$^{-2}$ | 654 | 3 | — | — | — |
| 6     | [95]       | FET           | MoS$_2$ + organic molecules | 532 nm, 3.64 mW cm$^{-2}$ | 8 | 0.100 | 10$^{11}$ | — | — |
| 7     | [62]       | hybrid FET    | MoS$_2$ on Gr channel | 633 nm, 0.645 μW | 10 | 1.5 | — | — | <750 nm |
| 8     | [108]      | vertical FET  | Gr-MoTe$_2$/Gr | 1064 nm, 1 μW | 0.110 | 46 × 10$^{-6}$ | — | — | — |
| 9     | [109]      | FET           | WSe$_2$ 2D/2D contacts | 740 nm, 0.46 μW | 0.600 | 8 × 10$^{-6}$ | 10$^{13}$ | — | — |
| 10    | [93]       | FET           | N-doped GQD/WSe$_2$ | 405 nm, 170 μW/cm$^2$ | 0.240 | 1 | — | — | — |
| 11    | [110]      | pn HS         | MoS$_2$/MoTe$_2$ | 637 nm, 2.43 mW | 0.0436 | 60 × 10$^{-6}$ | 1.06 × 10$^8$ | — | 750–1200 nm |
| 12    | [111]      | pn HS         | SnSe/MoS$_2$ | 532 nm, 1 mW cm$^{-2}$ | 100 | 15 × 10$^{-3}$ | — | — | — |
| 13    | [112]      | pn HS         | WSe$_2$/SnS$_2$ | 550 nm, 3.77 mW cm$^{-2}$ | 11.5 | 0.25 | 1.29 × 10$^{13}$ | — | 400–900 nm |
| 14    | [65]       | pn HS         | GaTe/MoS$_2$ | 633 nm, 100 mW cm$^{-2}$ | 1.365 | <0.01 | — | — | — |
| 15    | [61]       | pn HS         | WSe$_2$/GaSe | 520 nm, 0.2 μW | 6 | 30 × 10$^{-6}$ | — | — | — |
| 16    | [60]       | pn HS (T = 300 K) | GaTe/MoS$_2$ | 473 nm, 12.77 mW | 21.83 | 7 × 10$^{-3}$ | 8.40 × 10$^{13}$ | — | — |
| 17    | [94]       | HS            | 1 L/2 L WSe$_2$ | 532 nm | 110 | 0.29 | 4.0 × 10$^{11}$ | — | — |
| 18    | [65]       | CVD grown vertical pn HS | SnS$_2$/WSe$_2$ | 520 nm, 10 mW cm$^{-2}$ | 0.110 | 6 × 10$^{-4}$ | 5 × 10$^{10}$ | — | — |
| 19    | [113]      | HS            | Organic/Inorganic hybrid | 365 nm, 0.53 W cm$^{-2}$ | 4 | 0.08 | 4 × 10$^{11}$ | — | — |
| 20    | [90]       | HS            | GQD/WSe$_2$/Si | 740 nm, 2.77 mW cm$^{-2}$ | 0.707 | 2 × 10$^{-4}$ | 4.51 × 10$^{9}$ | — | 350–950 nm |
| 21    | [114]      | HS            | BP-Si photonics | 1550 nm | 150 MHz | — | — | — | — |
| 22    | [97]       | HS            | WSe$_2$/BP/MoS$_2$ | 532 nm, 13.5 mW | 6.32 | — | 1.25 × 10$^{11}$ | 10$^{-12}$ A/√Hz | up to 1550 nm |
| 23$^a$| FDS010     | pn            | Si | 730 nm | 0.44 | 10$^{-9}$ | — | — | 5.0 × 10$^{-14}$ W/√Hz | 200–1100 nm |
| $^{b}$| FDS015     | pn            | Si | 740 nm | 0.36 | 200 × 10$^{-12}$ | — | — | 8.6 × 10$^{-15}$ W/√Hz | 400–1100 nm |
| 24$^b$| S1226–18BK | pn            | Si | 720 nm | 0.36 | 1.5 × 10$^{-7}$ | — | — | 1.6 × 10$^{-15}$ W/√Hz | 320–1000 nm |
| 25    | S8385      | p-i-n         | Si | 960 nm | 0.48 | 25 MHz | — | — | 1.0 × 10$^{-14}$ W/√Hz | 320–1100 nm |

Commercial photodiodes available at *thorlabs.com, and$^b$hamamatsu.com.
Table 1 lists key reports on PDs consisting of TMDC materials. The following conclusions can be made from the listed data.

i. It is evident that a majority of the reports are on FET and pn heterostructures. However, novel device operation and material processing methods have been used for increasing responsivity or improving speed.

ii. The excitation range used is mainly in the ultraviolet or visible range. Light in infrared range is rarely used. This limits the analysis and hence possible applications in medium range infrared light communication.

iii. Incident power used is typically very low resulting in high responsivity values. This might not be feasible in practical scenarios and hence characterization of responsivity for an appropriate range of incident optical power is required to clearly establish the LDR along with nonlinear operation for higher optical power.

iv. The speed and responsivity values are spread over a wide range reflecting largely varying measurement conditions. Benchmarking is difficult in such a scenario. Experimental determination of universal metrics like gain bandwidth product (GBP) and detectivity (D) are much needed in future studies.

v. Detailed NEP characterization in dark state is present only in a handful of reports. Most reports calculate NEP in shot-noise limited regime using the equation $\text{NEP} = \sqrt{2\hbar f I_{\text{dark}}}$, which is not suitable for the entire range of operating frequency.

vi. Lastly, spectral response of the detectors is important for probing the underlying physics as well as for determining the suitable wavelength operation range.

The above-mentioned points bring out critical gaps that need to be incorporated while planning future experiments and in the analysis of experimental data.

**Flexible devices**

TMDCs present a good alternative to the conventional semiconductors for flexible optoelectronics owing to their better mechanical flexibility and robustness [26, 115, 116]. Flexible PDs on substrates like polyimide (PI), polyethylene terephthalate (PET) and polyethylene naphthalate (PEN) have been demonstrated using TMDC materials. In addition to the measurements discussed so far, electromechanical flexibility and repeatability measurements are also required as described in the following reports. The applied strain ($\varepsilon$) can be calculated as $\varepsilon = t / (2r)$, where $t$ is the thickness of the sample and $r$ is the bending radius.

Figure 6(a) shows results for a hybrid structure of organic graphitic carbon nitride ($\text{g-C}_3\text{N}_4$) and inorganic MoS$_2$ layered sheets [113]. A homogeneous mixture of the two materials was created by liquid phase exfoliation method and carefully transferred onto a nylon membrane filter paper. As a result, a 1 $\mu$m thick film of homogeneous non-aggregated mixture of both materials was achieved with desired weight ratio. The fabrication process is illustrated in figure 6(a) (i, ii). Further, the optoelectronic performance was probed under 532 nm and 365 nm excitation. The results for $I_{\text{ph}}$, $R$ and $D^*$ are plotted in figure 6(a) (iii, iv) for a range of incident power values. Good $D^*$ in the range of $10^4$ Jones was achieved with high $R$ in the range of 1–10 A W$^{-1}$ in both cases. Furthermore, dependence of the on–off current ratio on bending radius (figure 6(a) (v)) and the number of bending cycles (figure 6(a) (vi)) was low.

Figure 6(b) (i) shows flexible MoS$_2$ PDs fabricated on a PI substrate [117]. High quality MoS$_2$ layers were grown by CVD directly on the PI substrate, followed by photolithography for contact patterning. Figure 6(b) (ii) displays the setup used for bending the substrate with control over the bending radius. Stability of the PD arrays was confirmed via data shown in figure 6(b) (iii). Photoresponse from a device before bending was compared with its photoresponse after $10^4$ cycles of bending at a radius of 5 mm. Little change in rise time or fall time was observed with slight degradation in the saturation value of the photocurrent. Depending on the quality coverage of the CVD process, this approach is well suited for bulk processing of PD arrays based on TMDCs. Similarly, figure 6(c) (i) shows the optical image of a MoTe$_2$/graphene heterostructure PD on flexible PEN substrate [118]. The individual flakes were mechanically exfoliated and the heterostructure was achieved by wet-transfer process. Figure 6(c) (ii) shows good repeatability in the photoresponse (with 1064 nm, 378.2 $\mu$W) of the device after 5000 cycles of bending with applied strain of up to 1.2%.

**Photovoltaics**

Photovoltaics is advancing rapidly for application in energy harvesting as clean, renewable energy sources are being investigated globally. Si PV technology holds more than 95% share worldwide with efficiencies reaching
up to 26% [119]. Efficiency and cost have emerged as key metrics for any alternate technology. TMDC-based PV devices with good performance and tunability have been demonstrated [110, 120–125]. The following discussion on several studies on 2D-PV devices helps us get an idea of the current status and future path for the field.

Figure 7(a) (i) shows the schematic and an optical image of a fabricated ReS2/ReSe2 PV heterostructure [126]. The contacts for n-type ReS2 and p-type ReSe2 use different metals for better carrier selectivity. Figure 7(a) (ii) shows the I-V under dark and illumination with varying white-light intensity in the voltage range of interest. Various PV parameters extracted from the I-V for incident light intensity are plotted in figure 7(a) (iii).

Figure 7(b) (i) illustrates a novel p-g-n PV device where a graphene flake is sandwiched between n-type MoS2 and p-type WSe2 flakes to form an out-of-plane heterostructure [127]. Zero bandgap graphene helps in extending the spectral absorption range of the device limited by semiconducting materials. The device was shown to respond to a wide spectral range of 400–2400 nm. Efficient separation of e-h pairs in the hetero-overlap area was achieved by the high electric field at the abrupt p-n junction across graphene. A fast response time in the range of ∼50 µs was attributed to instantaneous separation of the excess charge carriers. Figure 7(b)
Figure 7. (a) (i) Schematic of a ReS$_2$/ReSe$_2$ heterostructure based device under illumination and an optical microscope image of the heterostructure with electrodes. (ii) $I$–$V$ curves of the ReS$_2$/ReSe$_2$ vdW heterostructure showing photovoltaic effect under various light intensities. Inset image shows the band diagram of the heterojunction under illumination. (iii) Experimentally extracted photovoltaic parameters ($V_{oc}$, $I_{sc}$, FF, and PCE) with respect to the incident light power density. Reprinted (adapted) from [126]. Copyright © 2017, Authors, under a Creative Commons Attribution (CC BY) license. (b) (i) Schematic drawing of the p–g–n heterostructure for photodetection. (ii) Photocurrent mapping results for a typical device at $V_{ds} = 0$ V with $V_{gs} = 0$ V. Measurements were performed under an 830 nm laser at a power of $\sim$20.5 mW in ambient conditions. The photocurrent maps show the strongest photoreponse within the overlapped p–g–n region (highlighted by gray dashed lines). (iii) Optical microscopy image of the device with the measurements performed. MoS$_2$, graphene, and WSe$_2$ are highlighted by yellow, light gray, and green dashed lines, respectively. Scale bar is 5 $\mu$m. Reprinted (adapted) from [127] with permission. Copyright © 2016, American Chemical Society. (c) (i) Schematic illustration of a WSe$_2$/MoS$_2$ vertical heterojunction device that shows a transferred MoS$_2$ flake on synthetic WSe$_2$ forming a vertical heterojunction. (ii) False colour SEM image of the WSe$_2$/MoS$_2$ vertical heterojunction device. The scale bar is 3 $\mu$m. (iii) Experimental output characteristic of the vertical heterojunction device in the dark (black) and under illumination (wavelength: 514 nm; power, 5 $\mu$W). Inset: temporal response of the photocurrent under 514 nm illumination (10 $\mu$W). (iv) Power-dependent EQE of the heterojunction device under 514 and 633 nm laser excitation wavelengths at $V_{ds} = 0$ V and $V_{gs} = 0$ V. A maximum EQE of 12% was observed. Reprinted (adapted) from [128] with permission. Copyright © 2014, American Chemical Society. (d) (i) Device schematic; and (ii) optical image of a WSe$_2$ flake (outlined in red) on top of h-BN (outlined in green) on local gates. The leads, gates, and different flakes are labelled for clarity. (iii) I–$V$ characteristics in pn configuration under illumination with different incident powers $P$ on the device, ranging up to 4.8 W cm$^{-2}$. Inset shows the electrical power $P_{el}$ generated by the device, calculated as $P_{el} = V_{oc}I_{sc}$. The maximum electrical power generated is around 170 pW. (iv) Open circuit voltage ($V_{oc}$, left axis, red squares) and short-circuit current ($I_{sc}$, right axis, black circles) against power density $P$, extracted from the data in (iii). $I_{sc}$ follows a linear dependence on the power (linear fit, black line), whereas $V_{oc}$ follows a logarithmic dependence (logarithmic fit, red line). Reprinted (adapted) from [30] with permission. Copyright © 2014, American Chemical Society. (e) (i) Flow chart for fabricating PV devices with plasma-treated MoS$_2$ photoactive layers: 1. preparation of an untreated (pristine) MoS$_2$ ingot stamp; 2. plasma-assisted treatment of the top surface layers of the MoS$_2$ stamp; 3. mechanical exfoliation printing of protrusive mesas (i.e., multilayer MoS$_2$ flakes) with plasma-treated surfaces in contact with the underlying Au electrodes; 4. fabrication of ITO electrodes in contact with the untreated surfaces of the MoS$_2$ flakes; 5. photovoltaic characterization using a standard AM1.5 G solar simulator. (ii) EQE measurements for further confirming the high $J_{sc}$ values measured using an AM1.5 G solar simulator: (a) EQE spectra, measured at wavelengths $\lambda = 300$–800 nm, of a CHF$_3$ plasma-treated PV device (red circles) and an untreated PV device (blue triangles). Both devices have the same MoS$_2$ layer thickness of 120 nm. (iii) Integral of the overlap between the measured EQE data and the standard AM1.5 G spectrum over a wavelength range of 300 to 800 nm, which yields calculated $J_{sc}$ values of 18.7 mA cm$^{-2}$ and 11.2 mA cm$^{-2}$ for the plasma-treated PV device and the untreated control device, respectively. Reprinted (adapted) from [129] with permission. Copyright © 2014, American Chemical Society.
Table 2. Summary of key reports on photovoltaics and their performance parameters.

| Sr No | References | Architecture | Material | Excitation source | Voc | Isc | Pel,max (PEC) | FF | EQE/PCE |
|-------|------------|--------------|----------|-------------------|-----|-----|--------------|----|---------|
| 1     | [121]      | pn HS        | MoS$_2$/WSe$_2$ | Halogen lamp, 6400 W m$^{-2}$ | 0.55 | 50 pA | 14 pW | 0.5 | —       |
| 2     | [57]       | pn HS        | BP/MoS$_2$ | 633 nm, 8 μW | 0.3 | 17 nA | 1.7 nW | 0.5 | 0.3% PCE |
| 3     | [110]      | pn HS        | MoS$_2$/MoTe$_2$ | 637 nm, 5.46 μW | 0.51 | 1.09 μA | — | — | — |
| 4     | [123]      | pn HS        | α-MoTe$_2$/MoS$_2$ | 800 nm, 120 mW | 0.32 | 150 nA | — | — | — |
| 5     | [128]      | pn HS        | MoS$_2$/CVD WSe$_2$ | 514 nm, 5 μW | 0.27 | 0.22 μA | — | — | 11% EQE |
| 6     | [60]       | pn HS (T = 80 K) | GaTe/MoS$_2$ | 473 nm, 12.77 nW | 0.22 | 1.8 nA | 80 pW | 0.21 | — |
| 7     | [126]      | pn HS        | ReS$_2$/ReSe$_2$ | 633 nm, 3.34 W m$^{-2}$ | 0.17 | 50 pA | 3 pW | 0.37 | 0.5% PCE |
| 8     | [122]      | pn HS        | ReS$_2$/WSe$_2$ | 405 nm, 12.7 W m$^{-2}$ | 0.58 | 14 pA | 4.5 pw | 0.56 | 1.5% PCE |
| 9     | [120]      | pn HS        | WSe$_2$/MoSe$_2$ | 633 nm, 320 W cm$^{-2}$ | 0.46 | 40 pA | — | — | — |
| 10    | [59]       | pn HS        | BP/WS$_2$ | 690 nm, 1.2 μW | 0.35 | 0.6 μA | — | — | — |
| 11    | [130]      | pn HS        | p-MoS$_2$/n-MoS$_2$ | 530 nm, 14 mW cm$^{-2}$ | 0.57 | 250 pA | 75 pW | 0.52 | — |
| 12    | [129]      | vertical pn homojunction | p-MoS$_2$/n-MoS$_2$ | AM1.5 G, 100 mW cm$^{-2}$ | 0.28 | 20.9 mA cm$^{-2}$ | — | — | 0.47 |
| 13    | [124]      | g-p-n vertical HS | WSe$_2$/MoS$_2$ | 633 nm, 740 W cm$^{-2}$ | 0.35 | 10 μA | <2 uW | 0.6 | 3.4% PCE |
| 14    | [127]      | p-p-n         | MoS$_2$:g-WSe$_2$ | 830 nm, 20.5 μW | 0.2 | 50 nA | — | — | — |
| 15    | [50]       | electrostatic pn | WSe$_2$ | 640 nm, 4.8 W cm$^{-2}$ | 0.7 | 0.5 nA | 170 pW | 0.5 | 0.14% PCE |
| 16    | [131]      | —             | multicrystalline Si | global AM1.5 spectrum (1000 W m$^{-2}$) | 0.6742 | 41.08 mA cm$^{-2}$ | — | 0.805 | 22.3% EQE |
|       |            | cell          | Perovskite | global AM1.5 spectrum (1000 W m$^{-2}$) | 1.125 | 24.92 mA cm$^{-2}$ | — | 0.745 | 20.9% EQE |
Atomically thin, monolayer TMDCs Light emitting devices have been relatively less studied because of difficulty in handling and processing monolayer TMDCs—where they exhibit a direct bandgap necessary for radiative carrier recombination. Atomically thin, flexible and transparent LEDs for use in suitable applications will drive the efforts further. There are significant opportunities for novel device architectures as discussed below.

Figure 7(c) (i, ii) show the 3D schematic and a false-colour SEM image of a pn heterostructure PV device [128]. Here, a thin MoS2 flake was transferred onto a CVD-grown WSe2 flake to make the heterostructure. Steady-state I-V data in dark and under 514 nm illumination is shown in figure 7(c) (iii) along with the dynamic photoresponse. Figure 7(c) (iv) plots the calculated EQE for two different excitation wavelengths. Experimental determination of EQE over a wide spectral range should be considered in future studies. Figure 7(d) (i, ii) show the schematic and an optical image of an electrostatically defined pn homojunction PV device on WSe2 [50]. 2DLM hexagonal boron nitride (hBN) was used as the gate dielectric. This makes it possible to fabricate the entire structure on flexible substrates for all-2D devices. Figure 7(d) (ii, iii) show steady state I-V under dark and 640 nm illumination and the extracted Voc and I_sc values as a function of incident laser power, respectively. It should be noted that these values can further be controlled by the two bottom gates (lg and rg in figure 7(d) (i)) for a tunable PV device.

The PV devices discussed so far need lateral current transport that increases recombination probability in the quasi-neutral region. Device efficiency can be enhanced by improving carrier collection using completely vertical pn junctions. Figure 7(e) (i) shows the fabrication process flow for such a device architecture that relies on selectively doping the upper surface of patterned n-type MoS2 flakes p-type using CHF3 plasma treatment [129]. Indium tin oxide (ITO) was used as a transparent top contact to facilitate light absorption. Thus, the device doesn’t suffer from the shadow effect due to metal contacts, and at the same time, a uniform built-in electric field helps collect the charge carriers efficiently throughout the device area. Figure 7(e) (ii, iii) compare the EQE and integrated current density of the MoS2 devices with and without plasma treatment.

Table 2 lists key performance parameters from several reports on PV devices based on TMDCs. The following observations help benchmark and provide guidance for achieving performance similar to state-of-the-art PV devices.

i. While a large number of combinations can be achieved by making pn heterostructures, ways for scalable manufacture should also be considered.

ii. Novel material combinations can lead to augmented capabilities such as fully transparent PV devices. The structures should facilitate series-connected operation for high power-output in real-life use.

iii. A standard light source calibrated to the solar spectrum that can provide better-suited, area-normalized performance analysis is rarely used for PV characterization. This will also allow for more accurate EQE determination.

iv. Other aspects of PV devices such as contacts, carrier lifetime and transport behaviour, and ways to improve light absorption are less studied in 2D PV devices. These can be easily adapted from the well-developed Si PV industry, and would help in achieving higher quantum and power conversion efficiencies for high performance, flexible PV devices.

Light emitting devices

Light emitting devices have been relatively less studied because of difficulty in handling and processing monolayer TMDCs—where they exhibit a direct bandgap necessary for radiative carrier recombination. As mentioned earlier, TMDCs can exhibit valley and spin selective interaction with light. WSe2 is one such example which has spin-polarized valleys [137–140]. For example, all the electrons in the K-valley are spin-up and in the K’-valley are spin-down in ML WSe2. This is due to broken inversion symmetry in monolayer flakes.

Table 2

| Material | Efficiency (%) | EQE (%) | Current Density (mA/cm^2) |
|----------|----------------|---------|---------------------------|
| MoS2     | 13.2           | 45.6    | 23.5                      |
| WSe2     | 14.3           | 48.2    | 26.9                      |
| MoS2/WSe2| 15.7           | 50.1    | 28.3                      |

As mentioned earlier, TMDCs can exhibit valley and spin selective interaction with light. WSe2 is one such example which has spin-polarized valleys [137–140]. For example, all the electrons in the K-valley are spin-up and in the K’-valley are spin-down in ML WSe2. This is due to broken inversion symmetry in monolayer flakes.
In addition, ML WSe₂ can behave as an ambipolar transport channel allowing to accumulate/inject both electrons and holes in the channel. Figure 8(c)(i) shows an electric-double-layer transistor (EDLT) under ambipolar charge accumulation at high applied bias [134]. Figure 8(c)(ii) displays a schematic band diagram of the EDLT-induced p-i-n junction. Carrier recombination in ML WSe₂ is spin selective and can be probed by controlling the direction of current flow (figure 8(c)(iii)). As shown, the contribution to EL intensity from either spin-up or spin-down valley can be modulated by changing the current-flow direction resulting in circularly polarized light output.
Another interesting way to realize an EL signal through ML TMDCs is by transient switching as shown in figure 8(d) [135]. The device schematic (figure 8(d) (i)) and a map of normalized EL counts for varying biasing condition (figure 8(d) (ii)) is shown for WSe$_2$ as an example. Figure 8(d) (iii) shows the PL and EL spectra for four ML TMDCs with the same device architecture. Charge accumulation due to high frequency (∼MHz) switching in ML TMDCs near Schottky metal contacts enables sufficient carrier lifetime (∼ns) for radiative recombination.

Quantum well structures using ML TMDCs can be used to enhance the quantum yield in the EL signal. Figure 8(e) (i, iv) show the schematics of single quantum well (SQW) and multi quantum well (MQW) vertical structures, respectively, using only 2DLMs [136]. ML TMDCs were used as light emitting layers, whereas hBN was used as dielectric and graphene was used for metallic contacts. Figure 8(e) (iii, ii) show the I-V and EL intensity map and a comparison of PL and EL spectra for the SQW device with ML WS$_2$ as the light emitting layer. The SQW device emitted light at ∼2.0 eV corresponding to bandgap of ML WS$_2$. Similarly, PL and EL spectra for a MQW structure with four ML MoS$_2$ layers is shown in figure 8(e) (v). The device showed an EL peak at slightly lower energy (∼50 meV) than the PL peak.

Table 3 lists reports of EL studies on TMDCs with their device architecture and important performance parameters. The following inferences can be made from the table.

i. ML TMDCs, due to their direct bandgap range, emit light in the range of 650–1200 nm. This is suitable for short-to-medium range communication as well as standalone visible light LED applications.

ii. ML TMDCs are poorer current conductors than their bulk counterparts due to various reasons. Better device architecture and processing can result in higher current carrying capacity with negligible losses to enhance LED performance.

iii. Reported EQE values are rather low. Ways of enhancing emission efficiency are required to increase the luminescence of TMDC-based LEDs.

iv. Output-light direction and angular spread are additional aspects of device design that need to be looked at for better integrability with planar circuits.

### Integration with silicon photonics

The integration of 2DLM materials or devices based on them with Si photonics to augment or enhance its capabilities is one possible approach for commercial acceptance of these materials. Likewise, existing Si photonic technology can also be leveraged to enable 2DLM-based optical and photonic devices and circuits. We show

| Sr No | References | Architecture | Material | Emission wavelength (nm) | EQE | On current |
|-------|------------|--------------|----------|--------------------------|-----|------------|
| 1     | [135]      | M-S-I-M      | ML WSe$_2$ | 738                      | 1%  | —          |
|       |            |              | superacid treated ML WS$_2$ | 620 | 3% | —          |
| 2     | [133]      | pn           | MoS$_2$-p+Si | 694 | —  | 109 nA    |
| 3     | [128]      | pn HS        | ML MoS$_2$/ML WSe$_2$ | 792 | —  | 100 μA    |
| 4     | [141]      | electrostatic pn | ML MoS$_2$ | 690 | —  | 100 μA    |
| 5     | [132]      | electrostatic pn | ML WSe$_2$ | 801 | 0.10% | 50 nA    |
| 6     | [142]      | electrostatic pn | ML WSe$_2$ | 752 | 1%  | 100 nA    |
| 7     | [136]      | HS SQW       | ML MoS$_2$ | 670 | 1%  | 0.72 μA/μm$^2$ |
|       |            | HS MQW       | ML MoS$_2$ | 670 | 8.40% | 1.8 nA m$^{-2}$ |
| 8     | [134]      | EDLT         | ML WSe$_2$ | 747 | 0.01% | 5 μA     |
| 9     | [143]      | split-gate MoTe$_2$ with Si photonics | Bilayer MoTe$_2$ | 1175 | 5%  | 2.3 μA    |
| 10*   | LED555L    | TO-18 package with a spherical glass lens | GaP | 555 | —  | 20 mA     |
|       | LED750L    | TO-18 package with a spherical glass lens | AlGaAs | 750 | —  | 50 mA     |
|       | LED1550L   | TO-18 package with a spherical glass lens | InGaAsP/InP | 1550 | —  | 50 mA     |
|       | LED SW30   | surface mount | GaN | —  | 150 mA |

* Commercial LEDs available at thorlabs.com.
select examples on graphene, black phosphorus and MoTe$_2$ here, but the idea is expandable to any 2DLM with appropriate set of properties.

Figure 9(a) (i) shows the 3D schematic of a single-layer graphene (SLG) Schottky contact PD over a patterned silicon-on-insulator (SOI) waveguide [144]. The graphene layer, as mentioned before, enables absorption over a wide spectral range and can couple to the waveguide easily. Moreover, scalable CVD process for graphene
deposition is compatible with Si processing. Figure 9(a) (ii) shows a comparison in responsivity values of the structure with and without the SLG layer. The data shows significant enhancement (∼10 ×) in responsivity for the same optical power. In another example, three-dimensional integration of a black phosphorus FET with plasmonic grating with a Si waveguide was demonstrated. This illustrates how simple FET architecture can be incorporated into commercial technology with little modification. Schematic of the device structure is shown in figure 9(b) (i) [114]. The simulated transmission spectra for different plasmonic grating thicknesses is shown in figure 9(b) (ii) with a peak at 1.55 μm due to resonance. Figure 9(b) (iii, iv) show the photocurrent dependence on the biasing condition. The $I_{ph}$ peaks near the maximum transconductance ($g_{m}$) value as expected in a FET.

Similarly, TMDCs can be used for light emission in conjunction with Si photonics. An electrostatically modulated bilayer MoTe$_2$ LED over a Si photonic-crystal (PhC) waveguide is shown in figure 9(c) (i, ii) [143]. The LED response along with the PL signal for low temperature (6 K) and room temperature (300 K) is plotted in figure 9(c) (iii) showing overlapping normalized EL and PL peaks. Figure 9(c) (iv) shows the EL emission image at room temperature overlaid on a false-colour optical image. In addition to the EL signal from the device area, two spots from the grating couplers (centres of the two circular rings) suggest good optical coupling of the light source and the Si waveguide.

Conclusions and outlook

In summary, we have discussed the progress and scope for 2DLM-based optoelectronics with specific emphasis on TMDCs. The prospects of realizing versatile, low-cost, flexible optoelectronic devices and their integration with mature technologies are high. In optoelectronics, photodetector is the most studied device type with TMDCs followed by photovoltaics and light-emitting devices. Rise of data-hungry models with ever increasing connectivity and high-quality growth for scalable fabrication technology. Unlike graphene, TMDCs and other 2DLMs have not been grown on a large scale yet. Also, material defects and traps significantly affect the behaviour and performance of optoelectronic devices based on TMDCs. More systematic and detailed studies that target understanding the origin of traps, their energy distribution and effective ways for leveraging/passivating them are of high interest. Fabricating good quality ohmic contacts to TMDCs (especially mono- to tri-layer flakes) is another important aspect that impacts device performance. Understanding metal contacts to TMDCs and lowering contact resistance are crucial for the realization of high performance optoelectronic and photonic devices. TMDCs are well suited for flexible electronic applications due to intrinsic material properties. This also means that their interaction with flexible organic substrates and their suitability in flexible device processing needs to be studied in detail. Additionally, lack of standard models for these materials in device simulation tools (like TCAD) limits the simulations to first principle studies, which are computationally complex, time consuming and can, at times, lead to incorrect or unrealistic results. Simulation platforms with calibrated TMDC material models will significantly aid research on TMDC devices. From a device and future technology points-of-view, it is important to have simple device operation as opposed to complex device architectures for achieving performance goals. Furthermore, secondary effects such as thermal losses, heat dissipation, external noise etc need to be looked at and accounted for during device performance analysis. Lastly, the ultimate gap between research and application as commercial products based on TMDCs (and 2DLMs in general) can only be bridged with constructive collaboration between academia and industry [146]. A recent review article has proposed a technology roadmap to help introduce 2DLMs in CMOS-compatible technologies [147]. Devices that demonstrate novel physical properties hitherto unrealized in the electronics industry with conventional materials, along with ease of scalable processing, will help the TMDCs (and 2DLMs in general) to be accepted and deployed commercially.

Acknowledgments

KT acknowledges support from Visvesvaraya PhD scheme from the Ministry of Electronics and Information Technology (MeitY), Govt. of India.

ORCID iDs

Kartikey Thakar © https://orcid.org/0000-0002-7617-3827
Saurabh Lodha © https://orcid.org/0000-0002-0690-3169
References

[1] Britnell L et al 2013 Strong light–matter interactions in heterostructures of atomically thin films Science 340 1311–4
[2] Naumis G G, Barraza-Lopez S, Oliva-Leyva M and Terrones H 2017 Electronic and optical properties of strained graphene and other 2D materials: a review Rep. Prog. Phys. 80 096501
[3] Xia F, Wang H, Xiao D, Dubey M and Ramasubramanian A 2014 Two-dimensional material nanophotonics Nat. Photonics 8 899–907
[4] Yu S, Wu X, Wang Y, Guo X and Tong L 2017 2D materials for optical modulation: challenges and opportunities Adv. Mater. 29 1606128
[5] Zhang W, Wang Q, Chen Y, Wang Z and Wee A T S 2016 Van der Waals stacked 2D layered materials for optoelectronics 2D Mater. 3 022001
[6] Schneider C, Glazov M M, Korn T, Hofling S and Urbaszek B 2018 Two-dimensional semiconductors in the regime of strong light–material coupling Nat. Commun. 9 1–9
[7] Mak K F, Lee C, Hone J, Shan J and Heinz T F 2010 Atomically thin MoS2: a new direct-gap semiconductor Phys. Rev. Lett. 105 136805
[8] Splendiani A, Sun L, Zhang Y, Li T, Kim J, Chiu C-Y, Galli G and Wang F 2010 Emerging photoluminescence in monolayer MoS2 Nano Lett. 10 1271–5
[9] Mudd G W et al 2016 The direct-to-indirect band gap crossover in two-dimensional van der Waals Indium Selenide crystals Sci. Rep. 6 39619
[10] Allen M J, Tung V C and Kaner R B 2010 Honeycomb carbon: a review of graphene Chem. Rev. 110 132–45
[11] Krishnan S K, Singh E, Singh P, Meyyappan M and Nawha H S 2019 A review on graphene-based nanocomposites for electrochemical and fluorescent biosensors RSC Adv. 9 8778–881
[12] Lee H C, Liu W-W, Chai S-P, Mohamed A R, Aziz A, Khe C-S, Hidayah N M S and Hashim U 2017 Review of the synthesis, transfer, characterization and growth mechanisms of single and multilayer graphene RSC Adv. 7 156464–93
[13] Haastrecht S et al 2018 The computational 2D materials database: high-throughput modeling and discovery of atomically thin crystals 2D Mater. 5 042002
[14] Ahmed S and Yi J 2017 Two-dimensional transition metal dichalcogenides and their charge carrier mobilities in field-effect transistors Nano-Micro Letters 9 50
[15] Xu Y, Shi Z, Shi X, Zhang K and Zhang H 2019 Recent progress in black phosphorus and black phosphorus-analogues materials: properties, synthesis and applications Nanoscale 11 14491–527
[16] Li B et al 2019 Black phosphorus, a rising star 2D nanomaterial in the post-graphene era: synthesis, properties, modifications, and photocatalysis applications Small 15 1804565
[17] Molle A, Graziani A, Chiappe D, Cinquanta E, Fanciulli M, Tallarida G and Faggioni M 2013 Hindering the oxidation of silicene with electron beam irradiation Nanoscale 10 11166–23
[18] Goyal N, Kaushik N, Jawa H and Lodha S 2018 Enhanced stability and performance of few-layer black phosphorus transistors by electron beam irradiation Nanoscale 10 8072–81
[19] Goyal N, Parihar N, Jawa H, Mahapatra S and Lodha S 2019 Accurate threshold voltage reliability evaluation of thin Al2O3 top-gated dielectric black phosphorous FETs using ultrafast measurement pulses ACS Appl. Mater. Interfaces 11 23673–80
[20] Gong C, Zhang Y, Chen W, Chu J, Lei T, Pu J, Dai L, Wu C, Cheng Y and Zhai T 2017 Electronic and optoelectronic applications based on 2D novel anisotropic transition metal dichalcogenides Advanced Science 4 1700231
[21] Long M, Wang P, Fang H and Hu W 2018 Progress, challenges, and opportunities for 2D material based photodetectors Adv. Funct. Mater. 29 1803807
[22] Lee J, Shin J-H, Lee G-H and Lee C-H 2016 Two-dimensional semiconductor optoelectronics based on van der Waals heterostructures Nanomaterials 6 193
[23] Mathieu I E M, Vieira A B, Vieira L F M, Vieira M A M and Gnawali O 2019 Visible light communication: concepts, applications and challenges IEEE Communications Surveys & Tutorials 1
[24] Karande S D, Kaushik N, Narang D S, Late D and Lodha S 2016 Thickness tunable transport in alloyed WSX2 field effect transistors Appl. Phys. Lett. 109 142101
[25] Chen Y F, Wen W, Zhu Y M, Mao N N, Feng Q L, Zhang M, Huo H P, Zhang J, Huang Y S and Xie L M 2016 Temperature-dependent photoluminescence emission and Raman scattering from Mo1 layers Nanotechnology 27 445705
[26] Akinwande D, Petrone N and Hone J 2014 Two-dimensional flexible nanoelectronics Nat. Commun. 5 5678
[27] Cui Y, Zhou Z, Li T, Wang K, Li J and Wei Z 2019 Versatile crystal structures and (Opto) electronic applications of the 2D Metal Mono-, Dir-, and Tri-Chalcogenide nanosheets Adv. Funct. Mater. 29 1900040
[28] Wang J, Verzhbitkii I and Eda G 2018 Electroluminescent devices based on 2D semiconducting transition metal dichalcogenides Adv. Mater. 30 1802687
[29] Das S, Kim M, Lee J-W and Choi W 2014 Synthesis, properties, and applications of 2D materials: a comprehensive review Crit. Rev. Solid State Mater. Sci. 39 231–52
[30] Kim J H, Jeong J H, Kim N, Jishi R and Lee G-H 2019 Mechanical properties of two-dimensional materials and their applications J. Phys. D: Appl. Phys. 52 083001
[31] Li H, Pam M E, Shi Y and Yang H Y 2017 A review on the research progress of tailoring photoluminescence of monolayer transition metal dichalcogenides FlatChem 4 48–53
[32] Ogletree D F et al 2013 Revealing optical properties of reduced-dimensionality materials at relevant length scales Adv. Mater. 27 5699–719
[33] Liu B, Abbas A and Zhou C 2017 Two-dimensional semiconductors: from materials preparation to electronic applications Advanced Electronic Materials 3 1700045
[34] Mueller T and Malic E 2018 Exciton physics and device application of two-dimensional transition metal dichalcogenide semiconductors npj 2D Materials and Applications 2 9
[35] Margapoti E, Asmar M M and Ulloa S E 2016 The Effects of Substrates on 2D Crystals 67–113
[36] Wang D and Sundaramaran R 2019 Substrate effects on charged defects in two-dimensional materials Physical Review Materials 3 083803
[37] Buscema M, Island O, Groenendijk D J, Blanter S I, Steele G A, van der Zant H S J and Castellanos-Gomez A 2015 Photocurrent generation with two-dimensional van der Waals semiconductors Chem. Soc. Rev. 44 3691–718
[38] Fang H and Hu W 2017 Photogating in low dimensional photodetectors Advanced Science 4 1700323
Zhao Q, Wang W, Carrascoso-Plana F, Jie W, Wang T, Castellanos-Gomez A and Friednan R 2019 The role of traps in the photocurrent generation mechanism in thin InSe photodetectors *Materials Horizons* (https://doi.org/10.1039/C9MH01020C)

Furchi M M, Polyushkin D K, Pospischil A and Mueller T 2014 Mechanisms of photoc conductivity in atomically thin MoS2 *Nano Lett.* 14 6165–70

Kulfer D and Konstantatos G 2015 Highly sensitive, encapsulated MoS2 photodetector with gate controllable gain and speed *Nano Lett.* 15 7307–13

Shim J et al 2016 High-performance 2D Rhenium Disulphide (ReS2) transistors and photodetectors by oxygen plasma treatment *Adv. Mater.* 28 6985–92

Lin Z, Carvalho B R, Kahn E, Lv R, Rao R, Terrones H, Pimenta M A and Terrones M 2016 Defect engineering of two-dimensional transition metal dichalcogenides 2D Mater. 3 022002

Hu Z, Wu Z, Han C, He J, Ni Z and Chen W 2018 Two-dimensional transition metal dichalcogenides: interface and defect engineering *Chem. Soc. Rev.* 47 3100–28

Zhou F, Chen J, Tao X, Wang X and Chai Y 2019 2D materials based on optoelectronic memory: convergence of electronic memory and optical sensor *Research* 2019 940913

Li T, Mao D, Petrone N W, Grassi R, Hu H, Ding Y, Huang Z, Lo G-Q, Hone J C and Low T 2018 Spatially controlled electrostatic doping in graphene pin junction for hybrid silicon photodiode npi 2D Materials and Applications 2 36

Lei S et al 2015 An atomically layered InSe avalanche photodetector *Nano Lett.* 15 3048–53

Das S, Pandey D, Thomas J and Roy T 2019 The role of graphene and other 2D materials in solar photovoltaics *Adv. Mater.* 31 1802722

Buscema M, Barkelid M, Zwiller V, van der Zant H S J, Steele G A and Castellanos-Gomez A 2013 Large and tunable photothermoelectric effect in single-layer MoS2 *Nano Lett.* 13 558–63

Groenendijk D J, Buscema M, Steele G A, de Vasconcellos S M, Bratschitsch R, van der Zant H S J and Castellanos-Gomez A 2014 Photovoltaic and photothermoelectric effect in a double-gated WSe2 device *Nano Lett.* 14 5846–52

Freitag M, Lovre T, Xia F and Avouris P 2012 Photoconductivity of biased graphene *Nat. Photonics* 7 53–9

Wang Y, Yin H, Han Q, Yang X, Ye H, Li Y and Qin D 2016 Bolometric effect in a waveguide-integrated graphene photodetector *Chin. Phys. B* 25 118103

Li D, Xu J-R, Ba K, Xuan N, Chen M, Sun Z, Zhang Y-Z and Zhang Z 2017 Tunable bandgap in few-layer black phosphorus by electrical field 2D Mater. 4 030109

Li Y et al 2018 Ultrasensitive tunability of the direct bandgap of 2D InSe flakes via strain engineering 2D Mater. 5 021002

Tongay S et al 2014 Monolayer behaviour in bulk ReS2 due to electronic and vibrational decoupling *Nat. Commun.* 5 3252

Schalbeyer J R, Yu H, Clark G, Rivera P, Ross J S, Seyler K L, Yao W and Xu X 2016 Valleytronics in 2D materials *Nature Reviews Materials* 1 16055

Deng Y, Luo Z, Conrad N J, Liu H, Gong Y, Najmaei S, Ajayan P M, Lou J, Xu X and Ye P D 2014 Black phosphorus–monolayer MoS2 van der Waals Heterojunction p–n Diode *ACS Nano* 8 8292–9

Liu E F et al 2016 High responsivity phototransistors based on few-layer ReS2 for weak signal detection *Adv. Funct. Mater.* 26 1938–44

Dastgeer G et al 2018 Temperature-dependent and gate-tunable rectification in a black phosphorus/WS2 van der Waals heterojunction diode *ACS Appl. Mater. Interfaces* 10 13150–7

Wang F, Wang Z, Xu K, Wang F, Wang Q, Huang Y, Yin L and He J 2015 Tunable GaTe-MoS2 van der Waals p–n Junctions with novel optoelectronic performance *Nano Lett.* 15 7558–66

Wei X, Yan G C, Lv Q S, Shen C and Wang K Y 2017 Fast gate-tunable photodetection in the graphene sandwiched WSe2/GaSe heterojunctions *Nanoscale* 9 8386–92

Xu H, Wu I X, Feng Q L, Mao N N, Wang C M and Zhang J 2014 High responsivity and gate tunable graphene-MoS2 hybrid phototransistor *Small* 10 2300–6

Yang S X et al 2016 Self-driven photodetector and ambipolar transistor in atomically thin GaTe-MoS2 p–n vdW heterostructure *ACS Appl. Mater. Interfaces* 8 2533–9

Varghese A, Saha D, Thakar K, Jindal V, Ghosh S, Medhekar N V, Ghosh S and Lodha S 2019 arXiv preprint arXiv:1912.12386

Yang T et al 2017 Van der Waals epitaxial growth and optoelectronics of large-scale WSe2/SnS2 vertical bilayer p–n junctions *Nat. Commun.* 8 1906

Komsa H P and Krasheninnikov A V 2012 Two-dimensional transition metal dichalcogenide alloys: stability and electronic properties *The Journal of Physical Chemistry Letters* 3 3652–6

Li H L et al 2014 Growth of alloy MoS2Sn1−xSe2 nanosheets with fully tunable chemical compositions and optical properties *J. Am. Chem. Soc.* 136 3756–9

Lin J, Zhang Y, Zhou W and Pantelides S T 2016 Structural flexibility and alloying in ultrathin transition-metal chalcogenide nanowires *ACS Nano* 10 2782–90

Tannara M, Patanaiya P, Solanki G K, Babu Pillai S, Patel K D, Jha P K and Pathak V M 2018 Influence of alloy engineering on structural and photo detection properties of SnSe2 ternary alloys *Appl. Surf. Sci.* 462 856–61

Zankat C K, Patanaiya P, Solanki G K, Patel K D and Pathak V M 2018 Alloy engineering for enhanced photodetection in VxSn1−xSe2 ternary crystals *Mater. Lett.* 221 35–7

Gong F et al 2016 High-sensitivity floating-gate phototransistors based on WS2 and MoS2 *Adv. Funct. Mater.* 26 6084–90

Wang W, Klots A, Prasai D, Yang Y, Boletin K I and Valentine J 2015 Hot electron-based near-infrared photodetection using bilayer MoS2 *Nano Lett.* 15 7440–4

Wang Y et al 2018 Negative photoconductance in van der Waals heterostructure-based floating gate phototransistor *ACS Nano* 12 9513–20

Kunstmann J et al 2018 Momentum-space indirect interlayer excitons in transition-metal dichalcogenide van der Waals heterostructures *Nat. Phys.* 14 801–5

Fang H et al 2014 Strong interlayer coupling in van der Waals heterostructures built from single-layer chalcogenides *Proc. Natl Acad. Sci.* 111 6198–202

Lien D H et al 2015 Engineering light outcoupling in 2D materials *Nano Lett.* 15 1356–61

Liu X et al 2016 Epitaxial ultrathin organic crystals on graphene for high-efficiency phototransistors *Adv. Mater.* 28 5200–5

Ni Z et al 2017 Plasmonic silicon quantum dots enabled high-sensitivity ultrabroadband photodetection of graphene-based hybrid phototransistors *ACS Nano* 11 9854–62
Mater. Res. Express 108 117 100

109 114

115

102

106

110

112

111

117

103

105

108

101

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79

808

89

82

91

85

90

81

97

87

93

88

96

94

95

79
[118] Yu W, Li S, Zhang Y, Ma W, Sun T, Yuan J, Fu K and Bao Q 2017 Near-Infrared photodetectors based on MoTe₂/Graphene heterostructure with high responsivity and flexibility Small 13 1700268

[119] Photovoltaics Report. Fraunhofer Institute for Solar Energy Systems, ISE and PSE Conferences & Consulting GmbH 2019 https://ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf

[120] Flory N, Jain A, Bharadwaj P, Parzeffal M, Taniguchi T, Watanabe K and Novotny L 2015 A WSe₂/MoS₂ heterostructure photovoltaic device Appl. Phys. Lett. 107 123106

[121] Furchi M M, Pospszchil A, Libisch F, Burgdorfer J and Mueller T 2014 Photovoltaic effect in an electrically tunable van der Waals heterojunction Nano Lett. 14 4785–91

[122] Park C, Dzung N T, Bang S, Nguyen D A, Oh H M and Jeong M S 2018 Photovoltaic effect in a few-layer ReS₂/WSe₂ heterostructure Nanoscale 10 20306–12

[123] Pezeski A, Shokoh S H H, Nazari T, Oh K and Im S 2016 Electric and photovoltaic behavior of a few-layer α-MoTe₂/MoS₂ dichalcogenide heterojunction Adv. Mater. 28 3216–22

[124] Wong J, Jarivala D, Taglibue G, Tat K, Davoyan A R, Sherrer M C and Atwater H A 2017 High photovoltaic quantum efficiency in Ultrathin van der Waals heterostructures ACS Nano 11 7230–40

[125] Pataniya P M, Zankat C K, Tamarama M, Patel A, Narayan S, Solanki G K, Patel K D, Jha P K and Pathak V M 2019 Photovoltaic activity of WSe₂/Si hetero junction Mater. Res. Bull. 120 110682

[126] Cho A-J, Namgung S D, Kim H and Kwon J-Y 2017 Electric and photovoltaic characteristics of a multi-layer ReS₂/ReSe₂ heterostructure APL Mater. 5 076101

[127] Long M et al 2016 Broadband photovoltaic detectors based on an atomically thin heterostructure Nano Lett. 16 2254–9

[128] Cheng R, Li D, Zhou H, Wang C, Yin A, Jiang S, Liu Y, Chen Y, Huang Y and Duan X 2014 Electroluminescence and photocurrent generation from atomically sharp WSe₂/MoS₂ heterojunction p–n diodes Nano Lett. 14 5590–7

[129] Wi S, Kim H, Chen M, Nam H, Guo I J, Meyhofer E and Liang X 2014 Enhancement of photovoltaic response in multilayer MoS₂ induced by plasma doping ACS Nano 8 5270–81

[130] Reuter C, Friensd R, Lin D-Y, Ko T-S, Perez de Lara D and Castellanos-Gomez A 2017 A versatile scanning photocurrent mapping system to characterize optoelectronic devices based on 2D materials Small Methods 1 1700119

[131] Green M A, Dunlop E D, Levi D H, Hohl-Ebinger J, Yoshita M and Ho-Baillie A W Y 2019 Solar cell efficiency tables (version 54) Prog. Photovoltaics Res. Appl. 27 565–75

[132] Pospszchil A, Furchi M M and Mueller T 2014 Solar–energy conversion and light emission in an atomic monolayer p–n diode Nat. Nanotechnol. 9 257–61

[133] Lopez-Sanchez O, Alarcon Llado E, Koman V, Fontcuberta i Morral A, Radenovic A and Kis A 2014 Light generation and harvesting in a van der Waals heterostructure ACS Nano 8 3042–8

[134] Zhang Y J, Oku T, Suzuki K, Ye J T and Iwasa Y 2014 Electrically switchable chiral light-emitting transistor Science 344 725–8

[135] Lien D H, Amani M, Desai S B, Ahn G H, Han K, He J H, Ager J W, Wu M C and Javey A 2018 Large-area and bright pulsed electroluminescence in monolayer WSe₂ embedded in a van der Waals heterostructure Nano Lett. 18 14681–6

[136] Withers F, Del Pozo-Zamudio O, Mishchenko A, Rooney A, Gholinia A, Watanabe K, Taniguchi T, Haigh S, Geim A and Tartakovskii A 2015 Light-emitting diodes by band-structure engineering in van der Waals heterostructures Nat. Mater. 14 301

[137] Chakraborty C, Mukherjee A, Qiu L and Vamivakas A N 2019 Electrically tunable valley polarization and valley coherence in monolayer WSe₂ embedded in a van der Waals heterostructure Opt. Mater. Express 9 1479

[138] Hsu W-T, Chen Y-L, Chen C-H, Liu P-S, Hou T-H, Li L-J and Chang W-H 2013 Optically initialized robust valley-polarized holes in monolayer WSe₂ Nat. Commun. 4 2563

[139] Krol M et al 2019 Valley polarization of exciton–polaritons in monolayer WSe₂ in a tunable microcavity Nanoscale 11 9574–9

[140] Shimokita K, Wang X, Mitsuhashi Y, Watanabe K, Taniguchi T and Matsuda K 2019 Continuous control and enhancement of excitonic valley polarization in monolayer WSe₂ by electrostatic doping Adv. Funct. Mater. 29 1900260

[141] Sundaram R S, Engel M, Lombardo A, Kruppe R, Ferrari A C, Avouris P and Steiner M 2013 Electroluminescence in Single Layer MoS₂ Nano Lett. 13 1416–21

[142] Baugher B W H, Churchill H O H, Yang Y F and Jariño-Herrero P 2014 Optoelectronic devices based on electrically tunable p–n diodes in a monolayer dichalcogenide Nat. Nanotechnol. 9 262–7

[143] Bie Y Q et al 2017 A MoTe₂-based light-emitting diode and photodetector for silicon photonic integrated circuits Nat. Nanotechnol. 12 1124

[144] Goykhman I et al 2016 On-Chip integrated, Silicon-Graphene Plasmonic Schottky photodetector with high responsivity and avalanche photogain Nano Lett. 16 3005–13

[145] Konstantatos G 2018 Current status and technological prospect of photodetectors based on two-dimensional materials Nat. Commun. 9 5266

[146] Park S 2016 The puzzle of graphene commercialization Nature Reviews Materials 1

[147] Akinwande D, Huygebaert C, Wang C-H, Serna M I, Goossens S, Li J-L, Wong H S P and Koppens F H L 2019 Graphene and two-dimensional materials for silicon technology Nature 573 507–18