Research article

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Multifunctional black phosphorus/MoS₂ van der Waals heterojunction

<https://doi.org/10.1515/nanoph-2019-0549>

Received December 26, 2019; revised January 26, 2020; accepted January 27, 2020

Abstract: The fast-developing information technology has imposed an urgent need for effective solutions to overcome the limitations of integration density in chips with smaller size but higher performance. van der Waals heterojunctions built with two-dimensional (2D) semiconductors have been widely studied due to their 2D nature, and their unique electrical and photoelectronic properties are quite attractive in realizing multifunctional devices toward multitask applications. In this work, black phosphorus (BP)/MoS₂ heterojunctions have been used to build electronic devices with various functionalities. A p-n diode is achieved based on the vertically stacked BP/MoS₂ heterojunction exhibiting an ideal factor of 1.59, whereas a laterally stacked BP/MoS₂ heterojunction is implemented to fabricate a photodetector that shows a photodetection responsivity of 2000 mA/W at a wavelength of 1300 nm. Furthermore, a ternary inverter has been realized using a BP field-effect transistor in-series with a lateral BP/MoS₂ heterojunction. Such results have unambiguously demonstrated the superiority of BP/MoS₂ heterojunction in realizing multiple functionalities and have offered a new pathway for the design and engineering of future circuitry and device integration based on novel 2D semiconductors.

Keywords: MoS₂; black phosphorus; heterojunction; diode; photodetector; ternary inverter.

1 Introduction

Two-dimensional (2D) layered materials, such as graphene, transition metal dichalcogenides (TMDCs), black phosphorus (BP), and hexagonal boron nitride (h-BN), offer a unique opportunity for building heterojunction devices due to the absence of dangling bonds on the surface and the weak van der Waals (vdW) interactions between individual layers [1–7]. Although the lack of dangling bonds on the 2D material surface can lead to unexpected interface issues in specific structures such as TMDC/dielectric, functional devices can be achieved based on 2D material heterojunctions without the restraint of lattice mismatch and the need for a complex fabrication process [8]. For example, Lee et al. reported the gate-tunable diode-like current rectification of atomically thin p-n heterojunctions fabricated using the vdW assembly of p-type WSe₂ and n-type MoS₂ [9]. Zhang et al. demonstrated type II MoTe₂/MoS₂ vdW heterostructures that show interlayer optical transition for the creation of an infrared (IR) photodetector beyond the limits of the intrinsic band gap of the constituting material [10]. Srivastava et al. reported binary and ternary inverters with multifunctionality using a p⁺-n-p junction comprising BP (38 nm)/ReS₂/BP (5.8 nm) [11]. Similarly, MoS₂/BP heterostructures have also been prepared and studied. Deng et al. demonstrated a gate-tunable p-n diode based on a p-type BP/n-type monolayer MoS₂ vdW p-n heterojunction, which shows a maximum photodetection responsivity of 418 mA/W under illumination of 633 nm wavelength [12]. Wu et al. leveraged the band-structure alignment properties of narrow-bandgap BP and large-bandgap MoS₂ to realize vertical heterostructures with an ultrahigh rectifying ratio approaching 10⁶ and on-off ratio up to 10⁷ [2]. In addition, they have further designed and fabricated tunable multivalve inverters based on MoS₂/BP heterojunctions [2]. Ye et al. demonstrated a photodetector with visible to near-IR detection range based on the heterojunction fabricated by vdW assembly with few-layer BP and few-layer MoS₂ [13]. Although various 2D material-based

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heterojunctions have been fabricated and tested, there is still a lack of systematic and in-depth analysis and comparison of such structures in fulfilling different nanoelectronic applications, especially focusing on rectifying properties, photoelectric characteristics, and multivalued logic (MVL).

As we know, MoS₂ is an n-type semiconductor with reasonably high electron mobility and a bandgap ranging from 1.2 to 1.8 eV [14, 15]. Few-layer BP has a narrow bandgap of ~0.3 eV, and it is a p-type semiconductor with high carrier mobility [7, 16–24]. Therefore, the integration of two materials to form a heterojunction can enable a large bandgap offset achieving good rectifying characteristics. The p-n junction is one of the basic building blocks of modern semiconductor device and circuit technology. Whereas, in the conventional p-n homojunction, the p- and n-type regions are formed by chemical doping in a bulk semiconductor creating a graded junction region, p-n heterojunctions can be realized by epitaxially growing an n-type semiconductor on another p-type semiconductor or vice versa forming abrupt p-n junctions [12]. As mentioned above, the p-n junction built on BP/MoS₂ vdW interaction can be achieved without extra engineering on lattice mismatches between materials. Moreover, the formation of analogous heterojunctions between BP and MoS₂ would be possible via band engineering to open up new realms in the application of photodetectors covering from the visible to the mid-IR spectral range. At present, photodetectors are mostly based on silicon, crystalline InGeAs/HgCdTe, or other inorganic semiconductor materials. However, silicon-based photodetectors are limited to the visible region due to the band gap of silicon corresponding to a wavelength of ~900 nm, and long-wavelength photodetector products based on crystalline InGeAs/HgCdTe suffer from either expensive fabricating process or rigorous operation requirements [13]. In contrast, fabricating photodetectors with 2D materials can take advantage of their unique optoelectronic properties and simple preparation process. In the field of logic devices, MVL devices have been emerging in recent years as the next-generation candidates to overcome the bottleneck of integration density due to their capability in handling and processing more information with reduced number of interconnected lines. However, the shortcoming is the relatively high power dissipation [25], which can be readily addressed by integrating 2D material-based heterojunction field-effect transistors (FETs).

In this work, various heterostructures based on BP/MoS₂ have been fabricated and characterized. We first studied the electrically tunable BP/MoS₂ vertical vdW heterojunction-based p-n diode. An ideal factor

of 1.59 has been achieved. Then, MoS₂/BP lateral vdW heterojunction-based photodetector is demonstrated with a maximum responsivity of 8500 and 2000 mA/W at the wavelength of 500 and 1300 nm, respectively. Finally, we demonstrate an MoS₂/BP heterojunction-based MVL device with the structure of ternary inverter.

2 Results and discussion

To fully explore the electrical characteristics and photoelectric characteristics of MoS₂/BP heterojunctions, we designed the vertical p-n junction structure, the lateral heterojunction FET (HJFET) structure, and the multivalued inverter structure. Figure 1A shows the optical images of one of the devices, which was fabricated by stacking an MoS₂ flake and a BP flake using a dry-transfer technique (see Experimental methods for details). MoS₂ and BP are well aligned as indicated by the regions marked by red and green dashed lines (Figure 1A), respectively. Raman spectra of MoS₂, BP, and heterojunction are shown in Figure 1B. Peaks observed at ~383 and ~408 cm⁻¹ correspond to the E_{2g}¹ and A_{1g} phonon modes of MoS₂, respectively, whereas peaks observed at ~361, ~439, and ~466 cm⁻¹ correspond to the A_g¹, B_{2g}, and A_g² phonon modes of BP [26]. The peaks of both MoS₂ and BP can be observed in the overlapped region with a very small shift from that obtained at the nonoverlapped regions, indicating good quality of the strain-free heterojunction with vdW interaction. Figure 1C shows the atomic force microscopy (AFM) image of one of the MoS₂/BP heterojunctions. The thickness of the structure is shown in Figure 1D, which was measured along the direction indicated in Figure 1C. The thickness of the MoS₂, BP flakes, and MoS₂/BP heterostructure were found to be 4.6, 5.9, and 10.5 nm, respectively.

The schematic structure of a vertical p-n diode is shown in Figure 2A, which consists of a BP flake on top of an MoS₂ flake. A drain voltage (V_d) is applied across the diode, and a back-gate voltage (V_g) is applied to the p⁺-doped silicon as a back gate, which is expected to electrically modulate the device. To better understand the electrical mechanisms of the device, we plotted the energy band diagram of the heterojunction. According to previous works [27, 28], the energy band alignment of MoS₂/BP can be obtained, as shown in Figure 2B. The electron affinity (EA), bandgap, and work function of BP (~6 nm) are 4.10, 0.3, and 4.3 eV, respectively, whereas the EA, bandgap, and work function of MoS₂ (~4 nm) are 4.30, 1.82, and 4.5 eV, respectively. The band alignment of

Figure 1: Physical characterizations of the BP/MoS₂ heterostructure.

(A) Optical image of a BP/MoS₂ heterostructure on the SiO₂/P⁺-Si substrate. (B) Raman spectra obtained from MoS₂, BP, and the overlapped regions. (C) AFM image of MoS₂/BP flakes. (D) AFM height profile of MoS₂/BP flakes along the dashed line in (C).

Figure 2: The energy band diagrams and I - V characteristics of the vertical p-n diode.

(A) Schematic of the vertical p-n diode structure. (B) Energy band alignment of MoS₂/BP. (C) Band diagrams explaining the carrier transport in the device under on-state (left) and off-state (right). (D) Gate-tunable I - V characteristics of the device. (E) I - V characteristics in log scale. (F) I - V characteristic at $V_g = -30$ V, which is in good agreement with the fitting results of the volt-ampere characteristic function.

MoS₂/BP at the p-n junction interface can be modulated by V_g and V_d , as shown in Figures S1 and S2. When applying positive voltage to the drain electrode (BP) and back-gate electrode, the electrons tend to be driven from MoS₂ to BP. In contrast, when applying negative voltage to the drain electrode and back-gate electrode, only electrons above the conduction band of MoS₂ are thermally injected into BP, leading to ultra-low current due to the scarcity of available electrons at high energies above the Fermi level, as shown in Figure 2C. Figure 2D shows the gate-tunable current-voltage (I - V) characteristics of the p-n diode, and the log-scale I - V curves are shown in Figure 2E. The current-rectifying characteristic can be modulated by V_g , as shown in Figure S3. When $V_g = 10$ V, a rectification ratio of 182 is obtained at $V_d = -1/+1$ V. To specify the ideal factor (n) of the p-n diode, we fitted the experimental output results at different V_g in the volt-ampere characteristic function [Equation (S1)] [29]. It is found that the experimental data fit well with the function, and a minimum value of 1.59 is achieved when $V_g = -30$ V, as shown in Figure 2F and Figure S4. Such ideal factor is better than that of the reported 2D material-based junctions [12].

The schematic structure of a lateral HJFET and the measurement setup are shown in Figure 3A. The optical microscopic image of the device is shown in Figure S5. To protect BP from deterioration under long-term test, we introduced graphene electrode to contact with BP. A h-BN flake is covered on the channel of BP. Besides, the two metal electrodes are separately located on the graphene and MoS₂ flakes, away from the overlapped junction region. The MoS₂ channel, heterojunction, and BP channel are directly exposed to a light beam. The transfer characteristics in dark current are plotted in Figure S6. It is found that the current modulation is nonmonotonic due to the nonuniformity of the channel [2], and the current increases with increasing V_d . This can be explained by considering the energy band diagram shown in Figure S7. The electrons tend to be driven more easily from MoS₂ to BP under larger V_d . The transfer characteristics of the device with $V_d = 0.7$ V in the dark and under illumination with 500 nm wavelength are illustrated in Figure 3B. The results clearly show a distinct photocurrent even with a light intensity of 0.75 nW. The maximum photocurrent is observed at $V_g = 25$ V (Figure S8) and the corresponding photoresponsivity is calculated up to 8500 mA/W with $V_d = 0.7$ V. Figure 3D

Figure 3: The photoelectric characteristics of the lateral BP/MoS₂ heterojunction.

(A) Schematic of the lateral BP/MoS₂ heterojunction and the measurement setup. (B) I_d - V_g transfer curves in log scale obtained in the dark and under illumination with 500 nm wavelength. (C) Photodetection responsivity (R) vs. V_d , which ranges from 100 to 700 mV. (D) R vs. wavelength with 500 to 1300 nm.

summarizes the relationship between the photoresponsivity and the wavelength. Our device can exhibit sufficiently high sensitivity in visible and near-IR wavelength, and the obtained results are better than that of the most reported photodetectors based on 2D materials, as shown in Table S1 [30, 31]. It is also worth mentioning that the properties are also comparable to that of most reported photodetectors based on hybrid perovskite [32–35].

2D semiconductors have been widely studied for various logic functions, which are critical and essential in future fast-speed and low-power electronics applications [36–38]. We have further fabricated a ternary inverter based on lateral MoS₂/BP HJFET, which is connected in-series to a BP FET. The device structure is schematically illustrated in Figure 4A, and the corresponding optical microscopic image and equivalent circuit diagram of the ternary inverter are shown in Figure S9. Figure 4B displays the transfer characteristics of the lateral HJFET and BP FET at $V_d = 2$ V. As shown in Figure 4C, typical inverter logic functions with multiple logic states have been achieved: V_{out} is in the logic state 1 with -25 V $< V_{in} < -20$ V, V_{out} is in the logic state 0 with -7 V $< V_{in} < -5$ V, and V_{out} is in the logic state 1/2 with -15 V $< V_{in} < -13$ V. It should be mentioned here that the difference among the logical levels is

relatively small. This is due to the low on/off ratio of BP FET, which is due to the intrinsic instability of BP flake in ambient atmosphere. Moreover, these FETs show low switching in gate modulation due to the SiO₂ dielectric, leading to a low voltage gain in the inverter (Figure 4D). Nevertheless, the ternary inverter clearly exhibit three distinguishable logic states compared to the conventional binary inverter (Figures S10 and S11). The separation among the logic states and the voltage gain can be expected to improve by further device structure engineering with high- κ dielectrics and optimized fabrication process with effective protection from the oxygen and moisture in ambient environment.

3 Conclusion

In summary, we have demonstrated multifunctional devices using BP/MoS₂ heterojunctions. The vertically stacked BP/MoS₂ heterojunction exhibits gate-tunable current-rectifying I - V characteristics, and an ideal factor of 1.59 has been achieved. High-performance photodetector based on the laterally stacked BP/MoS₂ heterojunction

Figure 4: The electrical characteristics of the ternary inverter.

(A) Schematic view of a ternary inverter. (B) I_d - V_g transfer curves in log scale of the lateral HJFET and BP FET at $V_d = 2$ V. (C) Plot of V_{out} vs. V_{in} of the ternary inverter at $V_d = 2$ V. (D) Voltage gain for the ternary inverter at $V_d = 2$ V.

shows a photodetection responsivity of 2000 mA/W at the wavelength of near-IR. Furthermore, a ternary inverter has been realized by connecting a BP FET in-series with a BP/MoS₂ heterojunction. Although further device and material engineering is required to improve the performance of the devices, our device concept has paved an attractive pathway for the realization of novel 2D electronic, optoelectronic, and MVL device toward system-level applications.

4 Experimental methods

4.1 Materials

BP was synthesized by an improved mineralizer-assisted chemical vapor transport method using tin tetraiodide, tin, and red phosphorus as source materials according to a previous report [39]. The bulk MoS₂ crystal was purchased from Six Carbon Technology.

4.2 Device fabrication

First, MoS₂ and BP were mechanically exfoliated from bulk MoS₂ and bulk BP onto the heavily doped silicon wafer covered with 285 nm SiO₂. The thickness of BP flakes was controlled in a small range of 5 to 10 nm, and MoS₂ flakes were controlled in a small range of 1 to 5 nm. The flakes should be large enough to form a heterojunction and keep space for depositing metal electrodes on the flakes. Then, a transfer technique was employed to achieve the MoS₂/BP structure through vdW interactions onto the heavily doped silicon wafer covered with 90 nm SiO₂. Subsequently, the standard electron beam lithography process was used to define contact patterns and pads, including the source, drain, and V_{out} electrode. A 10/70 nm Ti/Pt was deposited as metal contacts by sputtering.

4.3 Characterization

Electrical measurements were performed using Agilent B1500A semiconductor analyzer in ambient atmosphere. Optoelectronic measurements were performed by an HSX-F300 xenon lamp source. A monochromator and optical attenuation devices were used to produce the illumination from 200 to 2500 nm with the same intensity of 0.75 mW/cm², considering the 100 μm² active region of the device. All the lights were regarded as effective incidence

when calculating the responsivities of the device. Raman spectroscopy was measured on LabRAM HR800 (Horiba Jobin Yvon) with an excitation wavelength of 532 nm. AFM images were processed by WSxM 5.0 Develop 8.1.

Acknowledgments: This research was supported by the National Key Research and Development Program of China (grant 2018YFB2202800), the Shanghai Municipal Science and Technology Commission (grant 18JC1410300), the National Natural Science Foundation of China (grants 61904033, 61522404, 61704030, and 61974144), the Shanghai Rising-Star Program (grant 19QA1400600, Funder Id: <http://dx.doi.org/10.13039/501100013105>), and the Basic Research Project of Shanghai Science and Technology Innovation Action (grant 17JC1400300).

References

- [1] Geim AK, Grigorieva IV. van der Waals heterostructures. *Nature* 2013;499:419–25.
- [2] Huang M, Li S, Zhang Z, Xiong X, Li X, Wu Y. Multifunctional high-performance van der Waals heterostructures. *Nat Nanotechnol* 2017;12:1148–54.
- [3] Novoselov KS, Mishchenko A, Carvalho A, Castro Neto AH. 2D materials and van der Waals heterostructures. *Science* 2016;353:461.
- [4] Fan T, Zhou Y, Qiu M, Zhang H. Black phosphorus: a novel nanoplatform with potential in the field of bio-photonics nanomedicine. *J Innov Opt Heal Sci* 2018;11:1830003.
- [5] Luo M, Fan T, Zhou Y, Zhang H, Mei L. 2D black phosphorus-based biomedical applications. *Adv Funct Mater* 2019;1808306.
- [6] Zhang B, Fan T, Xie N, Nie G, Zhang H. Versatile applications of metal single-atom @ 2D material nanoplatforms. *Adv Sci* 2019;6:1901787.
- [7] Fan T, Xie Z, Huang W, Li Z, Zhang H. Two-dimensional non-layered selenium nanoflakes: facile fabrications and applications for self-powered photo-detector. *Nanotechnology* 2019;30:114002.
- [8] Nourbakhsh A, Zubair A, Dresselhaus MS, Palacios T. Transport properties of a MoS₂/WSe₂ heterojunction transistor and its potential for application. *Nano Lett* 2016;16:1359–66.
- [9] Lee CH, Lee GH, van der Zande AM, et al. Atomically thin p-n junctions with van der Waals heterointerfaces. *Nat Nanotechnol* 2014;9:676–81.
- [10] Zhang K, Zhang T, Cheng G, et al. Interlayer transition and infrared photodetection in atomically thin type-II MoTe₂/MoS₂ van der Waals heterostructures. *Acs Nano* 2016;10:3852–8.
- [11] Srivastava PK, Hassan Y, Gebredingle Y, et al. Multifunctional van der Waals broken-gap heterojunction. *Small* 2019;15:e1804885.
- [12] Deng YX, Luo Z, Conrad NJ, et al. Black phosphorus-monolayer MoS₂ van der Waals heterojunction p-n diode. *Acs Nano* 2014;8:8292–9.

- [13] Ye L, Li H, Chen Z, Xu J. Near-infrared photodetector based on MoS₂/black phosphorus heterojunction. *ACS Photonics* 2016;3:692–9.
- [14] Radisavljevic B, Radenovic A, Brivio J, Giacometti V, Kis A. Single-layer MoS₂ transistors. *Nat Nanotechnol* 2011;6:147–50.
- [15] Xu J, Chen L, Dai YW, et al. A two-dimensional semiconductor transistor with boosted gate control and sensing ability. *Sci Adv* 2017;3:e1602246.
- [16] Li L, Yu Y, Ye GJ, et al. Black phosphorus field-effect transistors. *Nat Nanotechnol* 2014;9:372–7.
- [17] Huang W, Xie Z, Fan T, Li J, et al. Black-phosphorus-analogue tin monosulfide: an emerging optoelectronic two-dimensional material for high-performance photodetection with improved stability under ambient/harsh conditions. *J Mater Chem C* 2018;6:9582–93.
- [18] Xie Z, Chen S, Duo Y, et al. Biocompatible two-dimensional titanium nanosheets for multimodal imaging-guided cancer theranostics. *ACS Appl Mater Interfaces* 2019;11:22129–40.
- [19] Xie Z, Peng Y-P, Yu L, et al. Solar- inspired water purification based on emerging 2D materials: status and challenges. *Solar RRL* 2020;e1900400.
- [20] Xie Z, Wang D, Fan T, et al. Black phosphorus analogue tin sulfide nanosheets: synthesis and application as near-infrared photothermal agents and drug delivery platforms for cancer therapy. *J Mater Chem B* 2018;6:4747–55.
- [21] Xie Z, Xing C, Huang W, et al. Ultrathin 2D nonlayered tellurium nanosheets: facile liquid-phase exfoliation, characterization, and photoresponse with high performance and enhanced stability. *Adv Funct Mater* 2018;28:e1705833.
- [22] Xie Z, Zhang F, Chen H, Li J, Zhang H, Liang Z. Revealing of the ultrafast third-order nonlinear optical response and enabled photonic application in two-dimensional tin sulfide. *Photonics Res* 2019;7:494.
- [23] Xing C, Huang W, Xie Z, et al. Ultrasmall bismuth quantum dots: facile liquid-phase exfoliation, characterization, and application in high-performance UV-vis photodetector. *ACS Photonics* 2017;5:621–9.
- [24] Xing C, Xie Z, Liang Z, et al. 2D nonlayered selenium nanosheets: facile synthesis, photoluminescence, and ultrafast photonics. *Adv Opt Mater* 2017;5:e1700884.
- [25] Gaikwad VT, Deshmukh DPR. Multi-valued logic applications in the design of switching circuits. *Int J Adv Res Comput Sci Softw Eng* 2012;2:446.
- [26] Lee G, Pearton SJ, Ren F, Kim J. Two-dimensionally layered p-black phosphorus/n-MoS₂/p-black phosphorus heterojunctions. *ACS Appl Mater Interfaces* 2018;10:10347–52.
- [27] Jiang X, Shi X, Zhang M, et al. A symmetric tunnel field-effect transistor based on MoS₂/black phosphorus/MoS₂ nanolayered heterostructures. *ACS Appl Nano Mater* 2019;2:5674–80.
- [28] Liu X, Qu D, Li HM, et al. Modulation of quantum tunneling via a vertical two-dimensional black phosphorus and molybdenum disulfide p-n junction. *Acs Nano* 2017;11:9143–50.
- [29] Tang Y, Wang Z, Wang P, et al. WSe₂ photovoltaic device based on intramolecular p-n junction. *Small* 2019;15:e1805545.
- [30] Buscema M, Groenendijk DJ, Blanter SI, Steele GA, van der Zant HS, Castellanos-Gomez A. Fast and broadband photoresponse of few-layer black phosphorus field-effect transistors. *Nano Lett* 2014;14:3347–52.
- [31] Walmsley TS, Chamlagain B, Rijal U, Wang T, Zhou Z, Xu YQ. Gate- tunable photoresponse time in black phosphorus-MoS₂ heterojunctions. *Adv Opt Mater* 2018;7:e1800832.
- [32] Zhang Y, Lim C-K, Dai Z, et al. Photonics and optoelectronics using nano-structured hybrid perovskite media and their optical cavities. *Phys Rep* 2019;795:1–51.
- [33] Guo S, Zhang Y, Ge Y, Zhang S, Zeng H, Zhang H. 2D V-V binary materials: status and challenges. *Adv Mater* 2019;e1902352.
- [34] Ou Q, Zhang Y, Wang Z, et al. Strong depletion in hybrid perovskite p-n junctions induced by local electronic doping. *Adv Mater* 2018;e1705792.
- [35] Liu J, Xue Y, Wang Z, et al. Two-dimensional CH₃NH₃PbI₃ perovskite: synthesis and optoelectronic application. *Acs Nano* 2016;10:3536–42.
- [36] Pu J, Funahashi K, Chen CH, Li MY, Li LJ, Takenobu T. Highly flexible and high-performance complementary inverters of large-area transition metal dichalcogenide monolayers. *Adv Mater* 2016;28:4111–9.
- [37] Shim J, Oh S, Kang DH, et al. Phosphorene/rhenium disulfide heterojunction-based negative differential resistance device for multi-valued logic. *Nat Commun* 2016;e13413.
- [38] Zhao M, Ye Y, Han Y, et al. Large-scale chemical assembly of atomically thin transistors and circuits. *Nat Nanotechnol* 2016;11:954–9.
- [39] Xu Y, Yuan J, Zhang K, et al. Field-induced n-doping of black phosphorus for CMOS compatible 2D logic electronics with high electron mobility. *Adv Funct Mater* 2017;27:e1702211.

Supplementary Material: The online version of this article offers supplementary material (<https://doi.org/10.1515/nanoph-2019-0549>).