

Article

Self-Powered Broadband Photodetector Based on MoSe₂/SnS₂ Van der Waals Heterostructure

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Abstract

The increasing demand for broadband and self-powered optoelectronic devices has stimulated the development of two-dimensional (2D) material-based photodetectors. Here, we construct a self-powered photodetector based on a MoSe₂/SnS₂ van der Waals (vdW) heterostructure. The unique combination of MoSe₂ and SnS₂ provides complementary light absorption and a type-II band alignment, which generates an interfacial built-in electric field to facilitate photogenerated carrier separation and transport, enabling efficient self-powered operation without external bias. The device exhibits a broad spectral photoresponse from ultraviolet (UV) to infrared (IR) wavelengths (350–1050 nm). Under zero bias, the photodetector achieves a responsivity of 0.6 mA/W and a rapid response time of 5.8/6.1 ms (rise/fall) under 405 nm illumination, demonstrating effective self-driven photoresponse. With an applied reverse bias of −2 V, the device further reaches a responsivity of 161 mA/W and a detectivity of 8.6×10^{10} Jones under 405 nm illumination. In addition, the device exhibits a low dark current of 5 pA and a high on/off ratio of 1180. These results demonstrate the potential of the MoSe₂/SnS₂ vdW heterostructure for broadband and self-powered optoelectronic applications.

Keywords: self-powered; 2D materials; heterostructure; type-II band; broad spectral

1. Introduction

With the continuous development of Moore's Law, highly integrated electronic components have been scaled down to the nanometer regime [1–5]. The continuous reduction in device dimensions has imposed higher requirements on photodetectors in terms of low power consumption, miniaturization, and high-density integration. However, conventional photodetectors usually require an external bias to separate and collect photogenerated charge carriers, which increases device power consumption and limits their applications in complex environments. Self-powered photodetectors can realize photoelectric conversion without an external power source and are compatible with micro-nano fabrication processes. Owing to their low energy consumption, compact size, light weight, and ease of integration, they show broad application prospects in complex environments [6–11]. However, the performance of self-powered 2D van der Waals (vdW) photodetectors is still constrained by several factors, including weak driving force for carrier transport without external bias, limited photocurrent generation, and the difficulty in achieving broadband spectral response. These challenges indicate that further exploration of suitable vdW



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material combinations and interface engineering strategies is required for developing multifunctional self-powered photodetection systems. In addition, broadband photodetectors with spectral responsivity (R) covering the ultraviolet (UV) to infrared (IR) range have attracted extensive attention for applications in optical communication, imaging, sensing, and spectroscopy [12–18].

To meet requirements of low-power and broadband photodetection, 2D layered materials have become an important material platform for constructing high-performance photodetectors, owing to their tunable bandgaps, strong light absorption, and excellent carrier transport properties [19–23]. The type-II band offset generates an interfacial built-in field that simultaneously promotes charge separation and passivates recombination, enabling zero-bias self-powered operation [24–28]. SnS_2 exhibits excellent electronic and optical properties and has great potential for photodetector applications [29–31]. Therefore, SnS_2 was selected as the light-absorbing and carrier-transport material to construct an efficient photoelectric conversion channel. To create a photodetector based on a 2D vdW heterostructure with type-II band alignment, MoSe_2 , an n-type semiconductor, was chosen due to its superior near-infrared light absorption, high carrier mobility, and robust environmental stability [32–35]. By combining these two materials through precise vdW assembly, photodetectors based on the $\text{MoSe}_2/\text{SnS}_2$ field-effect transistor (FET) are expected to show promising application prospects.

Here, we systematically studied the preparation and characterization of vertically stacked $\text{MoSe}_2/\text{SnS}_2$ vdW heterostructures, which possess an inherent type-II band alignment and demonstrate significant advantages for broadband self-powered photodetection. The complementary spectral response ranges of SnS_2 and MoSe_2 enabled the heterostructure device to cover a broad spectral region from UV to IR (350–1050 nm). A responsivity of 161 mA/W and a detectivity (D^*) up to 8.6×10^{10} Jones were obtained under 405 nm illumination, along with a fast response time and a low dark current. These experimental findings revealed the considerable potential of $\text{MoSe}_2/\text{SnS}_2$ vdW heterostructures in high-performance photodetectors.

2. Materials and Methods

The device fabrication mainly consists of three steps: preparation of 2D materials, construction of the heterostructure, and electrode processing. First, bulk materials of MoSe_2 and SnS_2 (Shenzhen Six Carbon Technology Co., Ltd., Shenzhen, China) were respectively placed onto Scotch tape and repeatedly folded for mechanical exfoliation to obtain few-layer 2D MoSe_2 and SnS_2 flakes. MoSe_2 and SnS_2 flakes with relatively thin and uniform thickness were selected and transferred onto a polydimethylsiloxane (PDMS) film. Subsequently, the 2D SnS_2 was transferred from the PDMS film onto a highly p-doped Si substrate with a SiO_2 oxide layer on the surface. Then, using a microscope and a tweezer transfer stage, the MoSe_2 on the PDMS transparent substrate was stacked vertically with the SnS_2 sample on the target silicon wafer, and a $\text{MoSe}_2/\text{SnS}_2$ vertical heterostructure was fabricated relying on the vdW force between the material layers. Next, LOR 3A and S1805 photoresists (Shanghai Tuotuo Optical Materials Co., Ltd., Suzhou, China) were spin-coated onto the heterostructure surface, respectively. After heating for solidification, electrode patterns were prepared using projection maskless lithography. The patterns were developed using RZX-3038 developer (Ruihong (Suzhou) Electronic Chemicals Co., Ltd., Suzhou, China). After removing the photoresist from the exposed areas, the device was placed into an evaporation chamber for vacuum evaporation, depositing a Cr/Au (5 nm/50 nm) metal stack on the source and drain electrodes, with the Au layer deposited on top of the Cr layer. After evaporation, the remaining photoresist was stripped off using N-methylpyrrolidone (NMP) (Shanghai Aladdin Biochemical Technology Co., Ltd.,

Shanghai, China) remover. Under a microscope, it could be observed that the MoSe₂/SnS₂ heterostructure adhered to the SiO₂/Si substrate, with the ends of the source and drain electrodes located at the two ends of MoSe₂ and SnS₂, respectively. The MoSe₂/SnS₂ heterostructure photodetector was thus successfully constructed.

3. Results

3.1. Characterization Analysis of the MoSe₂/SnS₂ Photodetector

We systematically studied the photoelectric properties of the MoSe₂/SnS₂ vdW heterostructure photodetector. The schematic diagram of the fabricated MoSe₂/SnS₂ FET is presented in Figure 1a. The MoSe₂/SnS₂ heterostructure was mechanically exfoliated and transferred onto a SiO₂/Si substrate [36]. Since the vdW coupling between the two layers is relatively weak, the unique properties of the heterostructure mainly stem from interfacial charge transfer [37–39]. The two-dimensional heterostructure was contacted by metal electrodes, where the left and right electrodes were defined as the source and drain terminals, respectively. The highly doped Si substrate beneath the SiO₂ layer was used as the back-gate electrode, enabling the modulation of carrier transport through an external gate voltage (V_g). During electrical measurements, V_{ds} represents the drain-to-source voltage applied between the drain and source electrodes, with positive and negative values corresponding to opposite bias polarities. Figure 1b shows the optical image of the heterostructure device. The source and drain Au electrodes are distributed on both sides of the heterostructure, and the two ends of the heterostructure are in contact with the electrodes. Figure 1c shows the Raman spectra of the MoSe₂/SnS₂ heterostructure, MoSe₂, and SnS₂. The green line represents the Raman spectrum of pure SnS₂, which exhibits an A_{1g} mode at 310 cm^{−1}, corresponding to the out-of-plane vibration of the Sn–S bond in 2H-SnS₂, consistent with values reported in the literature [40]. The blue line represents the Raman spectrum of pure MoSe₂. The A_{1g}, E_{2g}¹, and B_{2g}¹ peaks of MoSe₂ appear at 241 cm^{−1}, 286 cm^{−1}, and 352 cm^{−1}, respectively, which are consistent with the Raman spectrum of MoSe₂ [41]. The absence of Raman peaks around 286 and 352 cm^{−1} can be attributed to the multilayer thickness of MoSe₂. Previous studies have demonstrated that these modes are mainly associated with monolayer/few-layer MoSe₂ and gradually disappear as the thickness increases toward bulk-like structures [42]. The red line represents the Raman spectrum of the MoSe₂/SnS₂ heterostructure. The Raman features are fully preserved without measurable shifts, confirming the quality of the heterostructure and the low impact of the transfer on the starting materials. Additionally, AFM characterization was performed to determine the thickness of the exfoliated flakes. As shown in Figure 1d, the thicknesses of MoSe₂ and SnS₂ are approximately 39.17 nm and 17.24 nm, respectively, confirming the multilayer nature of the MoSe₂/SnS₂ heterostructure. Combined with the Raman spectra showing the characteristic modes of both materials, these results confirm the successful fabrication of the heterostructure.

3.2. Electrical Characteristics of the Photodetector

The photodetector's electrical performance was systematically characterized through theoretical analysis and experimental measurement. Density functional theory (DFT) calculations were employed to explore the properties of the MoSe₂/SnS₂ heterostructure. To lower computational consumption, a bilayer stacking model consisting of monolayer MoSe₂ and monolayer SnS₂ was adopted for band structure calculations, with structural optimization implemented under equilibrium conditions [43,44]. Figure 2a shows the band alignment of the fabricated heterostructure. The Fermi levels of MoSe₂/SnS₂ tend to align until thermal equilibrium is reached after contact. Benefiting from the suitable band structure, a type-II band alignment of MoSe₂ and SnS₂ is achieved, which enables

more efficient electron transfer from MoSe₂ to SnS₂ at the interface. The band alignment of the MoSe₂/SnS₂ heterostructure was established based on the reported electron affinity and bandgap values of individual materials, together with the calculated Fermi level positions [45–47]. From the band structure in Figure 2b, a small indirect bandgap of 0.19 eV is identified for the MoSe₂/SnS₂ heterostructure, because the VBM and CBM are located at the G and K points, respectively. By effectively limiting carrier recombination, this property contributes positively to the functionality of photodetector devices.

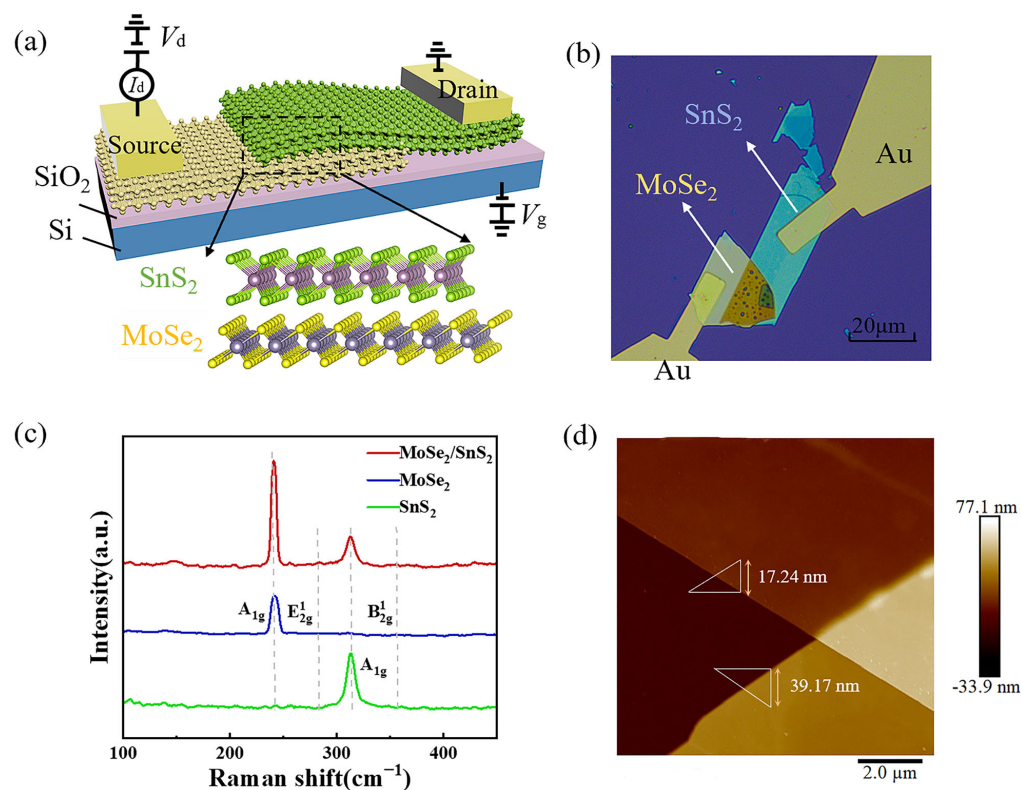


Figure 1. MoSe₂/SnS₂ heterostructure photodetector device: (a) Schematic diagram of the structure; (b) Optical image; (c) Raman spectra of SnS₂ (green line), MoSe₂ (blue line), and the MoSe₂/SnS₂ heterostructure (red line); (d) AFM analysis and height profiles of few-layer-thick MoSe₂ (~39.17 nm) and SnS₂ (~17.24 nm).

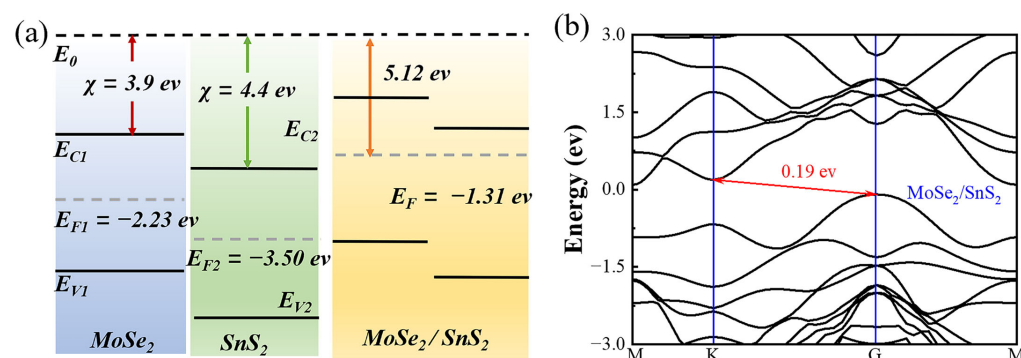


Figure 2. Band alignment diagrams of the heterostructure: (a) individual band diagrams of MoSe₂ and SnS₂; (b) band diagram of the MoSe₂/SnS₂ heterostructure.

The electronic transport behavior of the photodetector was investigated using electrical measurements on a back-gated FET in ambient air. Figure 3a presents the output characteristic curves of the device. At a drain-source bias voltage (V_{ds}) of -2 V, the dark current is as low as -5 pA. This is attributed to the built-in electric field inside the device,

which suppresses dark current generation. When V_{ds} increases, the built-in electric field inside the device decreases, causing the diffusion motion of electrons to be greater than the drift motion. At this point, a net diffusion current starts to flow from MoSe₂ to SnS₂, which increases with a further increase in V_{ds} , and the device turns on. As V_{ds} decreases, the reverse trend takes place. The current declines progressively and tends toward zero, thereby rendering the device off and endowing it with rectification characteristics. Figure 3b shows the transfer characteristic curves of the device. The MoSe₂/SnS₂ heterostructure field-effect transistor exhibits significant n-type transport characteristics under dark conditions. This is because as the gate voltage (V_{gs}) increases, the Fermi level of the few-layer SnS₂ is modulated and the electron concentration increases, leading to an increase in the current (I_{ds}). The I_{ds} - V_{ds} characteristics were measured at $V_{gs} = 10, 5, -5$, and -10 V (Figure 3c). With increasing V_{gs} , the drain current at a given V_{ds} (away from zero) rises. Conversely, reducing V_{gs} makes the current curve flatter. Thus, the V_{gs} on the Si substrate effectively tunes the device performance. The applied V_{gs} can regulate the I_{ds} - V_{ds} characteristics by modulating the carrier distribution in the MoSe₂/SnS₂ heterostructure. Although the gate electrode is located at the backside of the Si substrate, the 285 nm SiO₂ dielectric layer enables effective electrostatic coupling between the gate and the heterostructure. The gate-induced electric field modifies the carrier concentration and transport properties of the heterostructure, resulting in the observed modulation of the I_{ds} - V_{ds} characteristics.

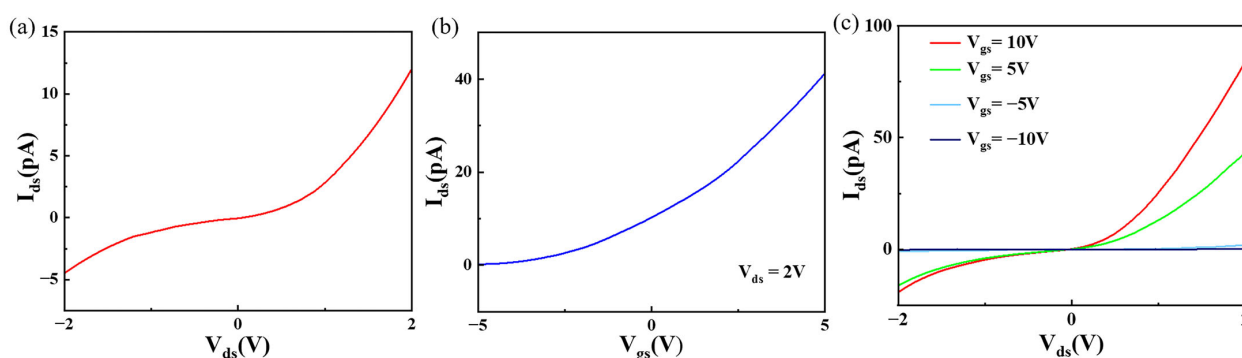


Figure 3. Electrical characterization of the device: (a) output characteristic curves; (b) transfer characteristic curves; (c) output characteristic curves under different gate voltages.

3.3. Photoresponse Characteristics of the MoSe₂/SnS₂ Photodetector

We then investigated the optoelectronic response of the MoSe₂/SnS₂ FETs. To cover the main absorption regions of ultrathin MoSe₂ and SnS₂, we used laser wavelengths spanning 350–1050 nm. Figure 4a shows the output characteristic curves of the MoSe₂/SnS₂ photodetector under illumination with different wavelengths. The device, held at zero gate bias, was illuminated by light covering 350–1050 nm with a power density (P) of 100 mW/cm². The device shows a broadband UV-IR photoresponse, with a peak light-induced current of -5.9 nA under 405 nm illumination, a dark current of -5 pA, and an on/off ratio of 1180. The broadband photoresponse of the MoSe₂/SnS₂ heterostructure originates from the complementary absorption of the two components. SnS₂ mainly contributes to the UV-visible region, while few-layer MoSe₂ extends the optical response toward the near-infrared region due to its narrower bandgap. Therefore, the photoresponse beyond 800 nm is mainly attributed to the intrinsic absorption of MoSe₂ [47].

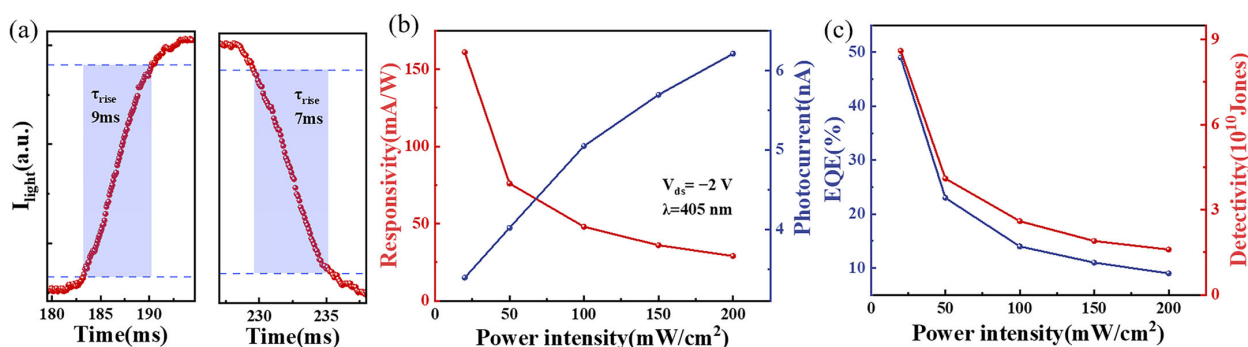


Figure 4. Photoresponse characteristics of the MoSe₂/SnS₂ device. (a) I_{ds} - V_{ds} curves of the device under illumination with different wavelengths; (b) enlarged I_{ds} - V_{ds} curves near 0 V bias from (a); (c) I_{ds} - V_{ds} curves of the device under 405 nm illumination with different optical powers; (d) enlarged I_{ds} - V_{ds} curves near 0 V bias from (c).

Correspondingly, the photoresponse was further measured under 405 nm illumination with different P values. Meanwhile, the device exhibits self-powered characteristics, as shown in Figure 4b. Subsequently, we investigated in detail the self-powered photoresponse of the MoSe₂/SnS₂ device at 405 nm, as shown in Figure 4c. Under different P values (20–200 mW/cm²), the photocurrent increases with V_{ds} , indicating that the device generates more charge carriers under higher optical power. An enlarged view of the I_{ds} - V_{ds} curve near zero bias is shown in Figure 4d. At 0 V, a photocurrent exists, with an open-circuit voltage (V_{oc}) of 28.6 mV and a short-circuit current (I_{sc}) of 21 pA.

To comprehensively evaluate the broadband detection capability of the MoSe₂/SnS₂ heterostructure, wavelength-dependent photoresponse measurements were carried out from 350 to 1050 nm. The photocurrent, responsivity, and detectivity under different illumination wavelengths are summarized in Figure 5. The device exhibits measurable photoresponse across the whole investigated spectral range, demonstrating its broadband photodetection capability. The wavelength-dependent photoresponse is determined by the combined effects of the optical absorption characteristics of MoSe₂/SnS₂ and the photocarrier generation and transport processes within the heterostructure. Bias-dependent I - V measurements under 405 nm illumination (Figure 5d) reveal the influence of the external electric field and interfacial built-in electric field on photocarrier transport.

The response speed is a key performance metric, strongly influenced by the efficiency of charge transport and the device's ability to collect photons. The response time was uniformly defined throughout this work. The rise time (τ_{rise}) represents the time required for the photocurrent to increase from 10% to 90% of the steady-state photocurrent after illumination, while the fall time (τ_{fall}) represents the time required for the photocurrent to decrease from 90% to 10% of the steady-state value after turning off the illumination. As shown in Figure 6a, under an external bias voltage of -2 V, the device exhibits rise and fall times of 9 ms and 7 ms, respectively. The built-in electric field and type-II band alignment at the MoSe₂/SnS₂ interface enable this rapid switching behavior, confirming efficient separation and collection of photogenerated carriers. The photodetector performance was evaluated under 405 nm illumination. We evaluated the key performance metrics of the device, including responsivity, external quantum efficiency, and specific detectivity [48,49]. Among them, R quantifies the ability to convert an optical signal into an electrical current and is calculated using Equation (1):

$$R = I_{ph}/PS \quad (1)$$

where I_{ph} , P , and S denote the photocurrent, optical power density, and effective area, respectively. The effective area was taken as the laser spot on the device, with a diameter of $\sim 21.36 \mu\text{m}$.

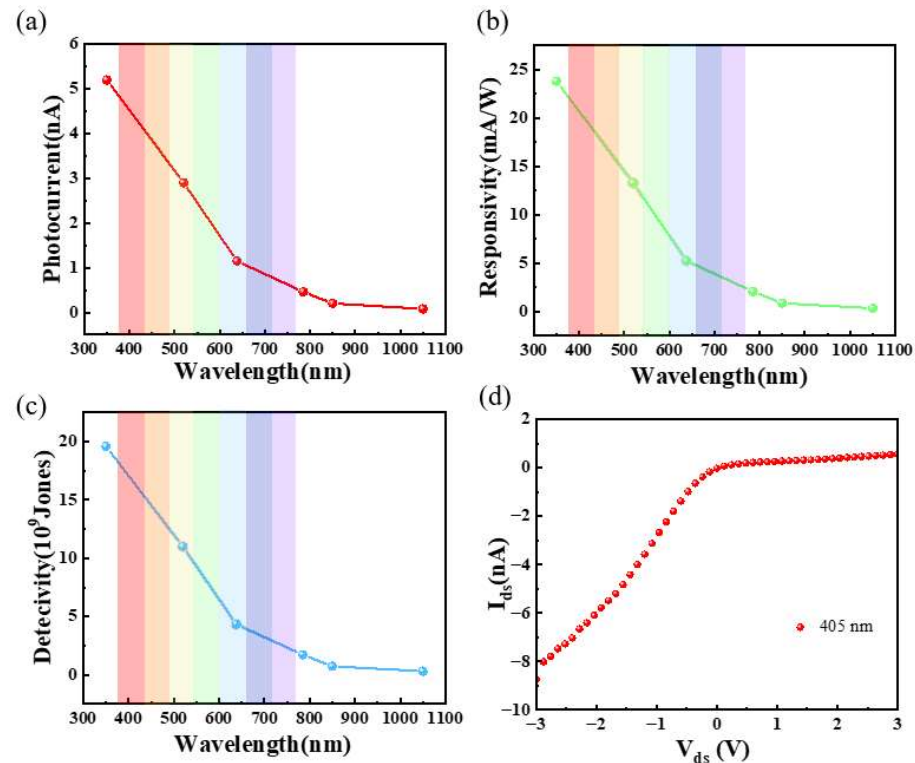


Figure 5. Photoresponse characteristics of the MoSe₂/SnS₂ heterostructure photodetector. (a) Wavelength-dependent photocurrent. (b) Wavelength-dependent responsivity. (c) Wavelength-dependent detectivity of the device. (d) Current–voltage characteristics under 405 nm illumination.

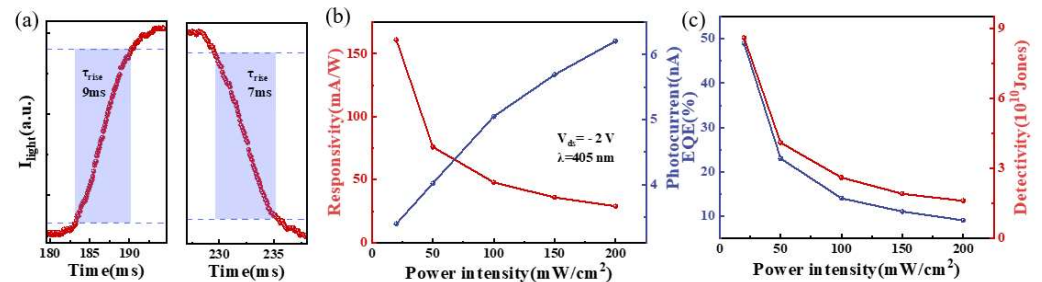


Figure 6. Performance of the detector at 405 nm wavelength under an external bias voltage of -2 V : (a) rise time and fall time; (b) photocurrent and corresponding R ; (c) D^* and EQE.

The EQE describes the fraction of incident photons that generate collected charge carriers, typically given as a percentage. A higher EQE signifies better photodetector performance [50], and its value is determined by Equation (2):

$$EQE = (hcR)/(e\lambda) \quad (2)$$

where h is Planck's constant, c the speed of light, e the elementary charge, and λ the excitation wavelength. D^* is a key metric that quantifies the minimum detectable optical power [51], calculated as

$$D^* = (RS^{1/2})/(2eI_{dark})^{1/2} \quad (3)$$

I_{dark} denotes the dark current, which was about $5 \times 10^{-12} \text{ A}$ in the present study.

Under 405 nm light and using a 21.36- μm -diameter spot, Figure 6b presents the photocurrent at different power densities (P) and the corresponding calculated R . R increases as P decreases, reaching a maximum R of 161 mA/W at a light intensity of 20 mW/cm². Figure 6c shows the curves of D^* and EQE corresponding to four different optical powers. The maximum D^* and EQE obtained at a light intensity of 20 mW/cm² are 8.6×10^{10} Jones and 49%, respectively. From the figure, R and D^* clearly decrease as the incident power grows, implying a decline in photodetector performance at higher light levels. This is because an increase in light intensity leads to intensified carrier recombination, affecting the device response.

In addition, the self-powered behavior of the MoSe₂/SnS₂ heterostructure photodetector was measured. Figure 7a shows the time-resolved photoresponse of the device to a pulsed signal with a frequency of 0.2 Hz. Under a constant wavelength of 405 nm and $V_{ds} = 0$ V, the on/off ratio under varying light intensities is tested. Six cycles are measured, with an on/off delay of 5 s per cycle. From the I–t curve, it can be seen that the current increases with increasing optical power. After each light switching, the device exhibits a fast and stable photoresponse. Figure 7b shows the response time of the device under self-powered conditions. Under self-powered operation (0 V bias), the device exhibits rise and fall times of 5.8 ms and 6.1 ms, respectively. The faster transient response under self-powered conditions is attributed to the carrier separation and extraction assisted by the internal electric field of the MoSe₂/SnS₂ heterointerface. To evaluate the stability of the device, a 405 nm laser with a power density P of 200 mW/cm² was used to perform 50 repeated on–off switching cycles at $V_{ds} = 0$ V, as shown in Figure 7c. The photocurrent shows minimal drift over repeated measurements, verifying the device’s reliable and repeatable operation. Figure 7d shows the photocurrent of the device and the corresponding R . The maximum photocurrent is 21 pA. At an optical power of 20 mW/cm², the R reaches 0.58 mA/W.

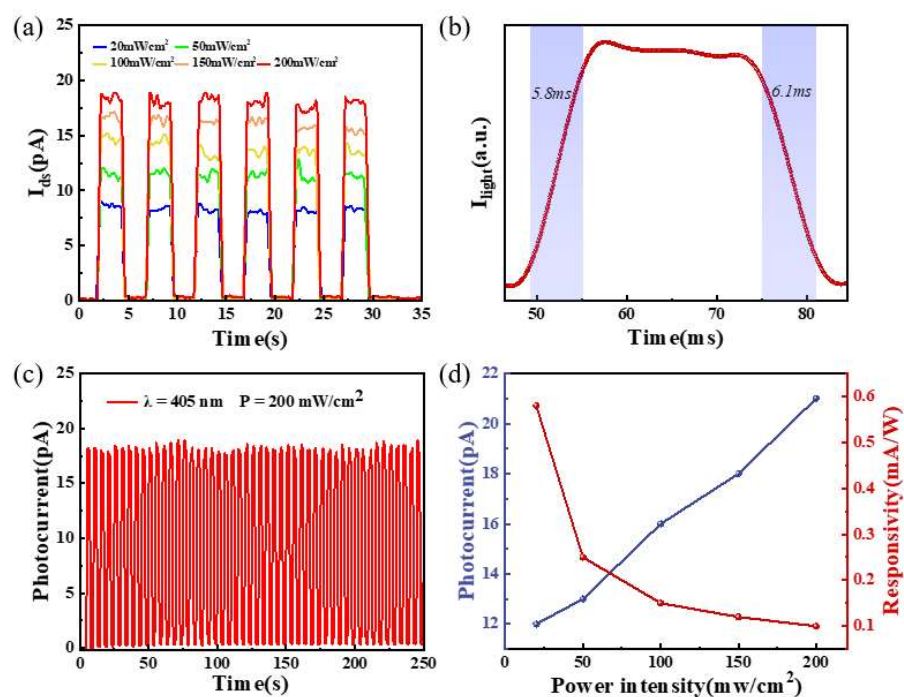


Figure 7. Performance of the device at zero bias under 405 nm wavelength under self-powered operation: (a) photoresponse capability of the MoSe₂/SnS₂ device under different optical power densities from 20 to 200 mW/cm²; (b) rise time and fall time; (c) 50 cycles of I–T photoswitching; (d) photocurrent and corresponding R .

The photoresponse characteristics of the device can be further analyzed by photocurrent mapping [52]. Figure 8a shows the photocurrent map measured under zero bias ($V_{ds} = 0$ V and $V_{gs} = 0$ V) at an optical power of 1 μ W under 405 nm laser illumination. The photocurrent mapping was obtained using a MStarter 200 high-precision photocurrent scanning system, where the laser spot was fixed, and the sample was moved by a piezoelectric scanning stage. The overlapping MoSe₂/SnS₂ area produces a larger net current, owing to the local electric field that results from the bandgap mismatch and aids the separation of photocarriers. Figure 8b shows the photocurrent map measured at an optical power of 5 μ W. The device also exhibits a good photoresponse, and the short-circuit current of the device varies with the light intensity. Notably, photocurrent is observed only in the overlapping region of the flakes, while no photocurrent is observed in the remaining regions of the device. This indicates that the interfacial region plays a dominant role in the zero-bias photoresponse. The spatially localized photocurrent can be attributed to the built-in electric field generated by interfacial charge redistribution, which promotes photogenerated carrier separation and transport without external bias.

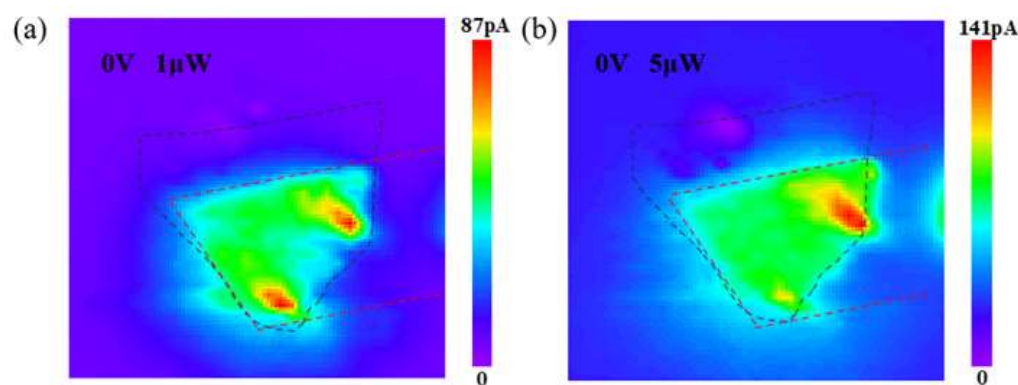


Figure 8. Photocurrent mapping of the MoSe₂/SnS₂ device at zero bias under 405 nm wavelength: (a) photocurrent image of the device at an optical power of 1 μ W; (b) photocurrent image of the device at an optical power of 5 μ W.

Among the numerous 2D heterostructures reported, we selected representative devices that share at least one constituent material (MoSe₂ or SnS₂) with our system, or are widely recognized in the field, including graphene/MoS₂, GaSe/MoS₂, GaSe/InSe, SnS₂/InSe, MoSe₂, SnS₂, GaSe/MoSe₂ and GaS_{0.3}Se_{0.7}/SnS₂ Table 1. For instance, SnS₂/InSe contains SnS₂, while GaSe/MoS₂ contains a Mo-based chalcogenide; both serve as reasonable references. Although direct reports on MoSe₂/SnS₂ heterostructure photodetectors are still rare, our device exhibits a responsivity of 0.161 A/W, a detectivity of 8.6×10^{10} Jones, an external quantum efficiency of 49%, and a fast response time of 9 ms. These values are superior or comparable to those of the selected reference devices, particularly in terms of broadband detection (350–1050 nm). Compared with individual MoSe₂ and SnS₂ devices, the enhanced performance of our heterostructure device originates from the synergistic effects of the MoSe₂/SnS₂ interface. The complementary absorption of MoSe₂ and SnS₂ extends the photoresponse range, while the interfacial band alignment and built-in electric field promote efficient photocarrier transport, resulting in improved broadband photodetection performance.

Table 1. Comparison of photodetection performance of 2D heterostructure photodetectors.

Device	Bias Voltage (V)	R (A/W)	D* (Jones)	EQE (%)	Response Time	Wavelength	Spectral Range	Refs.
Graphene/MoS ₂	1	0.104	—	—	273 ms	450 nm	450–660 nm	[53]
GaSe/MoS ₂	2	0.0226	8.54×10^7	—	20 ms	532 nm	375–633 nm	[54]
GaSe/InSe	0	0.021	2.2×10^{12}	—	2 μ s	410 nm	270–920 nm	[55]
SnS ₂ /InSe	1	0.014	2.2×10^8	3.7	—	460 nm	460–625 nm	[56]
MoSe ₂	−3	0.0262	—	5.1	20 ms	638 nm	405–785 nm	[57]
SnS ₂	2	100	—	—	—	420 nm	420–800 nm	[58]
GaSe/MoSe ₂	2	0.47	9.65×10^9	74.4	24.6 ms	785 nm	520–850 nm	[45]
GaS _{0.3} Se _{0.7} /SnS ₂	1	0.34	4.32×10^{11}	—	37 ms	405 nm	—	[59]
MoSe ₂ /SnS ₂	−2	0.161	8.6×10^{10}	49	9 ms	405 nm	350–1050 nm	This work

4. Conclusions

In this study, a MoSe₂/SnS₂ heterostructure photodetector was constructed. Vertical stacking of the 2D materials was achieved by mechanical exfoliation and dry transfer techniques, and the device's promise for photodetection applications was verified through device characterization and performance testing. From the perspective of material properties, the high carrier mobility of MoSe₂ complemented that of SnS₂, and the interface built-in electric field facilitated efficient separation and transport of photogenerated charge carriers. The experimental results showed that the detector exhibited a responsivity of 161 mA/W and a 9 ms response time under 405 nm illumination, with a significant photoresponse over a broad spectral range of 350–1050 nm. Moreover, the device showed favorable self-powered photoresponse and retained good stability and repeatability after 50 testing cycles. This study not only provides an experimental basis for the application of 2D material heterostructures in the field of photodetection but also offers insights into the design of broadband, high-performance optoelectronic devices.

Author Contributions: T.F.: conceptualization, methodology, formal analysis, data curation, resources, funding acquisition, writing—original draft. Z.L.: conceptualization, methodology, investigation, data curation, writing—original draft. X.Z.: investigation and data curation. J.S., L.Z., D.L.: formal analysis, writing—review and editing. D.W.: supervision, funding acquisition. All authors have discussed the results of this manuscript. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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