

## Ultrasensitive and broad-spectrum photodetectors based on InSe/MoTe<sub>2</sub> heterostructure

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**Abstract:** The photogating effect based on the vertical structure of a two-dimensional material allows high-sensitivity and broad-spectrum photodetector. A high-sensitivity photodetector based on the vertical heterostructure of indium selenide (InSe)/molybdenum ditelluride (MoTe<sub>2</sub>) is reported, which exhibits excellent broad-spectrum detection capability from 365 to 965 nm. The top layer of InSe was used as the grating layer to regulate the channel current, and MoTe<sub>2</sub> was used as the transmission layer. By combining the advantages of the two materials, the photodetector has a fast response time of 21.6 ms and achieves a maximum detectivity of  $1.05 \times 10^{13}$  Jones under 365 nm laser irradiation. Under the illumination of 965 nm, the detectivity still achieves the order of  $10^9$  Jones. In addition, the InSe/MoTe<sub>2</sub> heterostructure exhibits an external quantum efficiency of  $1.03 \times 10^5$  %, demonstrating strong photoelectric conversion capability.

**Key words:** two-dimensional material, broadband photodetectors, photogating effect, ultrasensitive

## 基于 InSe/MoTe<sub>2</sub> 异质结构的超灵敏宽光谱光电探测器

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**摘要:** 基于光栅效应的二维材料垂直结构可实现高灵敏度和宽光谱光探测器。本文报告了一种基于硒化铟(InSe)/二碲化钼(MoTe<sub>2</sub>)垂直异质结构的高灵敏度光电探测器, 该探测器在 365~965 nm 波长范围内具有出色的宽光谱探测能力。顶层的 InSe 用作调节沟道电流的光栅层, MoTe<sub>2</sub> 则用作传输层。通过结合两种材料的优势, 该光电探测器的响应时间为 21.6 ms, 比探测率在 365 nm 光照下可以达到  $1.05 \times 10^{13}$  Jones, 在 965 nm 光照下也可达到  $10^9$  Jones 数量级。外量子效率可达  $1.03 \times 10^5$  %, 显示出强大的光电转换能力。

**关键词:** 二维材料; 宽带光电探测器; 光栅效应; 超灵敏

中图分类号: TN214

文献标识码: A

Received date: 2023- 07- 26, revised date: 2024- 03- 02

收稿日期: 2023- 07- 26, 修回日期: 2024- 03- 02

**Foundation items:** Supported by the National Natural Science Foundation of China (60908012, 61575008, 61775007, 61874145, 62074011, 62134008); National Key Research and Development Program of China (2018YFA0209000, 2021YFC2203400, 2021YFA1200804); the Beijing Natural Science Foundation (4172011, 4202010) and Beijing Nova Program (Z201100006820096).

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## Introduction

Two-dimensional (2D) materials, such as graphene, BP, and transition metal dichalcogenides (TMDCs), the research of 2D materials has become a top priority in the field of optoelectronics due to their excellent optical and electrical properties<sup>[1]</sup>. TMDCs materials have high mobility and high On/Off ratios because they can achieve large modulation through the gate field effect<sup>[2]</sup>. These characteristics enable them to be widely used in photodetectors. However, most photodetectors based on TMDCs, such as those based on MoTe<sub>2</sub> and WSe<sub>2</sub>, can only operate in the visible region due to their relatively large bandgap<sup>[3-5]</sup>. Therefore, it is significant to explore and manufacture photodetectors with a broader spectrum, higher sensitivity and high responsivity using two-dimensional materials.

2D van der Waals (vdW) heterojunctions offer an ideal platform to overcome the limitations of single materials and enhance device performance. In vdW heterojunctions, the individual components are stacked using weak vdW forces between the layers<sup>[6-7]</sup>, effectively avoiding the limitations of lattice matching and other factors in traditional heterojunctions. In recent years, the bandgap of MoTe<sub>2</sub> materials has been found to range from 0.83 eV for bulk materials to 1.1 eV for monolayers<sup>[8-9]</sup>, which is narrower than that of other commonly used TMDCs materials such as MoS<sub>2</sub> and ReS<sub>2</sub><sup>[10]</sup>. Broad-spectrum photodetectors (600-1550 nm) based on MoTe<sub>2</sub> materials have been successfully demonstrated. Yin *et al.*<sup>[11]</sup> reported a multilayer MoTe<sub>2</sub> device with high responsivity to visible light at large back-gate voltages. However, the device's detectivity may be severely degraded due to its high dark current. Previous studies have utilized various materials, such as MoS<sub>2</sub><sup>[12]</sup>, graphene<sup>[13]</sup>, and Ge<sup>[14]</sup>, to form heterojunction photodetectors with MoTe<sub>2</sub>. The high carrier mobility of MoTe<sub>2</sub> enables the photodetectors to have faster response times<sup>[15]</sup>. In addition, indium selenide (InSe) has recently gained attention in optoelectronics and nanoelectronics due to its high electron mobility and broadband optical absorption. The InSe-based photodetectors exhibit outstanding performance in broadband photodetection (400-1000 nm) and fast response times, as low as 87  $\mu$ s<sup>[16-18]</sup>. This combination of InSe and MoTe<sub>2</sub> advantages enhances the overall performance of the photodetector. Currently, there is limited research on the photodetection capability of InSe/MoTe<sub>2</sub> heterojunctions. Sun *et al.*<sup>[19]</sup> proposed an InSe/MoTe<sub>2</sub> heterojunction photodetector for photodetection under two types of laser irradiation, 405 nm and 635 nm. The photodetector achieved high detectivity, but the maximum responsivity was limited to 15.4 mA/W.

In this paper, a photodetector based on InSe/MoTe<sub>2</sub> vertical heterojunction is fabricated, in which MoTe<sub>2</sub> serves as the transmission layer and InSe serves as the grating layer to regulate the channel current. The photodetector exhibits excellent photodetection performance due to its vertical structure and high-quality interface. The detectivity of the photodetector shows an ultrahigh value of over  $1.05 \times 10^{13}$  Jones, surpassing that of other

reported photodetectors based on 2D materials<sup>[12-14, 20-25]</sup>. Ultraviolet (100-400 nm) photodetectors have attracted extensive attention in many fields, such as space exploration, biological analysis, environmental sensors, communication, and imaging<sup>[26]</sup>. In addition, the photodetectors reported in this paper have photoresponses ranging from ultraviolet (365 nm) to near-infrared (965 nm). The photodetector exhibits an ultra-high external quantum efficiency (EQE) of  $1.03 \times 10^5 \%$ , resulting in extremely high photoelectric conversion. By modulating the gate voltage, the responsivity can reach 300.57 A/W. The heterojunction photodetector also exhibits outstanding detection performances with a fast response.

## 1 Device Fabrication and Characterization

The vertically structured InSe/MoTe<sub>2</sub> heterojunction was fabricated using a deterministic dry transferred technique. First, 300 nm silicon oxide insulation layer was deposited on a silicon wafer by plasma-enhanced chemical vapor deposition. The BN thin layer was removed by mechanical stripping and placed on the SiO<sub>2</sub>/Si substrate to provide a clean and flat interface. Then MoTe<sub>2</sub> nanoflakes were mechanically exfoliated from the bulk crystals to the polydimethylsiloxane (PDMS) films and transferred onto the SiO<sub>2</sub>/Si substrate. Next, several layers of mechanical peeling InSe flakes were artificially stacked on the MoTe<sub>2</sub> flakes under the optical microscope (OM, BX51, OLMPUS) assisted by an aligned transfer system. The two-dimensional materials mentioned in the text are commercially available bulk crystals. Finally, multiple electrode patterns were defined by standard electron beam lithography (EBL, Raith eLine Plus), then Ti/Au (10 nm/60 nm) metal stacks were deposited by electron beam evaporation (Ulvac Ei-5z) to form source and drain electrodes. The thickness of the photodetector was determined by AFM (Dimension ICON, American Bruker). Raman spectra were carried out using a Raman spectrometer system (Raman, LABRAM HR, Japan Horriba-JY) with a 532 nm laser source. The atomic structure features of the heterojunction were examined using HRTEM (Talos). The composition and element distribution of the heterojunction were analyzed via EDS mapping on the HRTEM. Before the HRTEM test, the photodetector's surface was coated with a conductive layer of elemental Cr to facilitate the positioning of the cut sample and the deposition of the protective layer under the focused ion beam (FIB) microscope. The electrical transport properties of the photodetector were carried out by Keithley 2612B and 2400 at room temperature.

## 2 Results and Discussion

The vertically stacked heterostructure based on InSe/MoTe<sub>2</sub> is shown in Fig. 1(a). The Ti/Au electrodes were placed on the MoTe<sub>2</sub>. The thicknesses of the MoTe<sub>2</sub> and InSe flakes are 8 nm and 15 nm, respectively, as shown in Fig. 1(b) and (c). The morphological characteristics of the InSe/MoTe<sub>2</sub> heterojunction are shown in the inset of Fig. 1(b), which displays a flat surface that did not sus-

tain any damage during material peeling and transfer. Fig. 1(d) shows the results of high-resolution transmission electron microscopy (HRTEM). The interfaces of all layers are clear, flat, and uncontaminated, indicating good interface quality. The thickness of each layer has been verified, and is consistent with the AFM test results. Fig. 1(e) shows the detailed energy-dispersive X-ray spectroscopy (EDS) elemental mapping, which demonstrates uniform distribution of all elements in the MoTe<sub>2</sub> and InSe layers without diffusion. Raman spectra of individual materials and the overlapped region are displayed in Fig. 1(f). Specifically, for pristine InSe (red line), four prominent peaks are centered at 116 cm<sup>-1</sup>, 178 cm<sup>-1</sup>, 200 cm<sup>-1</sup> and 227 cm<sup>-1</sup>, corresponding to A<sub>1</sub>' , E''(TO), E''(LO), and A<sub>1</sub> modes<sup>[27]</sup>. The Raman signatures of MoTe<sub>2</sub> (green line) are typically observed at 232 cm<sup>-1</sup> (E<sub>2g</sub><sup>1</sup>), 171 cm<sup>-1</sup> (A<sub>1g</sub>), and 288 cm<sup>-1</sup> (B<sub>2g</sub><sup>1</sup>)<sup>[28]</sup>. These peaks were also observed in the spectra of the overlapped region, indicating good quality of thin flakes in the junction region after layer exfoliation and device fabrication.

The electrical properties of the InSe/MoTe<sub>2</sub> heterojunction photodetector were tested under dark conditions. Fig. 2 shows the electrical characteristic curve of the InSe/MoTe<sub>2</sub> heterojunction photodetector with an increase in the back gate voltage from -60 to 60 V. The output characteristic curve ( $I_{ds}-V_{ds}$ ) of the InSe/MoTe<sub>2</sub> heterojunction photodetector is shown in Fig. 2(a). As the current increases and the temperature rises, the resistance of the device also increases<sup>[27,29]</sup>, resulting in non-linearity in the output characteristics. Fig. 2(b) shows

the transfer characteristic curve ( $I_{ds}-V_g$ ) of the InSe/MoTe<sub>2</sub> heterojunction device in the dark state. The current of the device initially decreases and then increases with the gate voltage changing, indicating that the device exhibits bipolar behavior.

To investigate the optoelectronic performance of InSe/MoTe<sub>2</sub> heterojunction photodetectors under the illumination, we measured the  $I_{ds}-V_{ds}$  curves (Fig. 3(b)) and the  $I_{ds}-V_g$  curves (Fig. 3(c)) of InSe/MoTe<sub>2</sub> heterojunction devices at different incident optical powers density under 365nm light source ( $V_g=0$  V). Fig. 3(a) shows a schematic diagram of the device under laser irradiation. The output  $I-V$  curve in Fig. 3(b) demonstrates that the current in the channel increases as the incident optical power density increases. This indicates that more photogenerated carriers are produced in the channel with an increase in incident optical power density. Additionally, the photocurrent  $I_{ph}$  ( $I_{ph}=I_{illumination}-I_{dark}$ ) is positively correlated with  $V_{ds}$  (where  $I_{illumination}$  and  $I_{dark}$  are  $I_{ds}$  with and without illumination). Fig. 3(c) shows the  $I_{ds}-V_g$  curves. The current in the channel is positively correlated with the incident optical power density. The  $I_{ds}$  of the device increases significantly under laser irradiation, indicating that the photocurrent always dominates throughout the operating range of the device. In the conducting state (when  $V_g > V_{th}$ ), the built-in field of the heterojunction increases as the Fermi level of MoTe<sub>2</sub> shifts in the conduction band due to the accumulation of electrons, leading to more efficient electron-hole pairs separation and an increase in the optical response<sup>[30]</sup>. The energy band diagram of the electrical transport mechanism of the

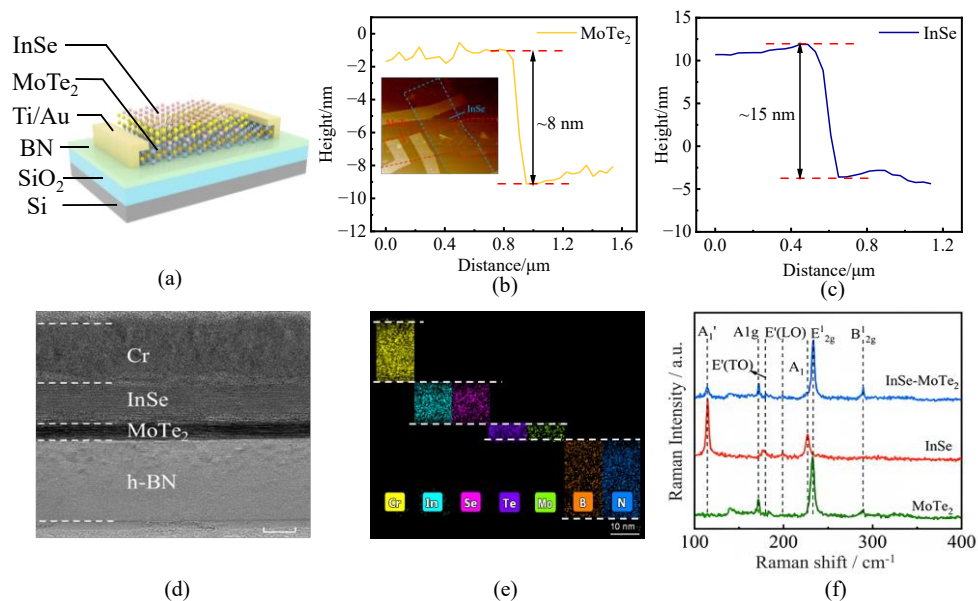


Fig. 1 Characterization of InSe/MoTe<sub>2</sub> heterostructure: (a) Schematic diagram of the InSe/MoTe<sub>2</sub> heterostructure; (b) The AFM image of MoTe<sub>2</sub> flakes. Inset: morphological characteristics of the InSe/MoTe<sub>2</sub> heterojunction; (c) The AFM image of InSe flakes; (d) HRTEM image; (e) EDS of the corresponding elements of the photodetector; (f) Raman spectra of pristine InSe, MoTe<sub>2</sub> and overlapped region.

图1 InSe/MoTe<sub>2</sub> 异质结构的表征: (a) InSe/MoTe<sub>2</sub> 异质结构示意图; (b) MoTe<sub>2</sub> 材料的 AFM 图像, 插图: InSe/MoTe<sub>2</sub> 异质结的形貌特征图; (c) InSe 材料的 AFM 图像; (d) HRTEM 图像; (e) 光电探测器各层元素的 EDS 图像; (f) 原始 InSe、MoTe<sub>2</sub> 和重叠区域的拉曼光谱

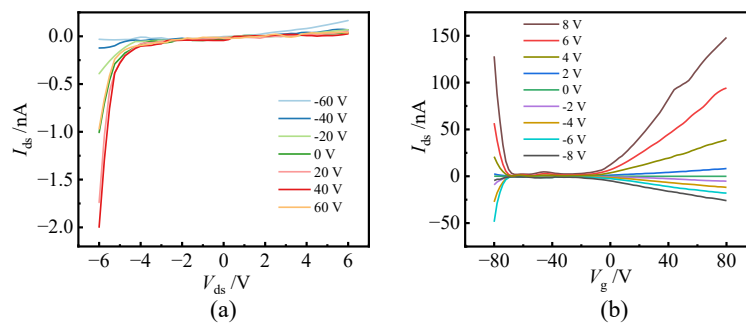


Fig. 2 Electrical  $I$ - $V$  characteristics of the device based on InSe/MoTe<sub>2</sub> heterostructure under non-illumination condition: (a)  $I_{ds}$ - $V_{ds}$  output characteristics under various back gate voltages; (b)  $I_{ds}$ - $V_g$  transfer curves at various drain voltages.

图2 基于InSe/MoTe<sub>2</sub>异质结构器件在无光照条件下的电学 $I$ - $V$ 特性:(a) 不同背栅电压下的 $I_{ds}$ - $V_{ds}$ 输出特性曲线;(b) 不同漏极电压下的 $I_{ds}$ - $V_g$ 转移特性曲线

device is shown in Figure S1 (Supporting Information).

The non-linear relationship between the photocurrent and optical power density can be well fitted with the power law equation<sup>[31]</sup>:

$$I_{ph} = aP^\theta, \quad (1)$$

where  $a$  is a constant for a certain wavelength,  $P$  is the incident power density and the exponent  $\theta$  determines the photoelectric conversion efficiency. Fig. 3(d) shows the relationship between photocurrent and different incident power density at  $V_{ds}=6$  V. As the incident power density increases, the photocurrent in the channel also increases. The photocurrent data can be well fitted with incident

power density, and the obtained  $\theta$  value of 0.93 ( $<1$ ) verifies the presence of the photogating effect<sup>[32]</sup>. Demonstrating the presence of carrier trapping in the top InSe layer to photocurrent as a grating layer, inducing more electron production in the channel to further modulate the channel conductance.

To evaluation the performance of the heterojunction photodetector, the responsivity ( $R$ ), detectivity ( $D^*$ ), external quantum efficiency (EQE), and response time ( $\tau$ ) as evaluation metrics, which are be defined by the following equations:

$$R = I_{ph}/P_{in}A, \quad (2)$$

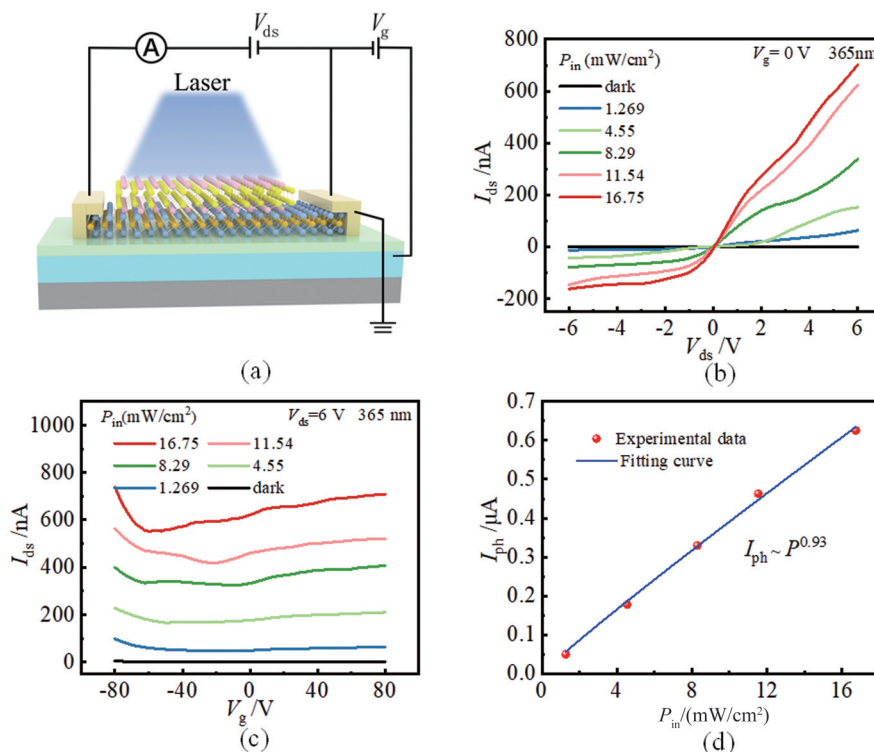


Fig. 3 (a) Schematic structure of the device under laser irradiation; (b) Photo-response of the  $I_{ds}$ - $V_{ds}$  output characteristics with different incident light power under 365 nm illumination ( $V_g = 0$  V); (c) Photo-response of the  $I_{ds}$ - $V_g$  transfer characteristics with different incident light power under 365 nm illumination ( $V_{ds} = 6$  V); (d) The  $I_{ph}$  as a function of incident light power at  $V_{ds} = 6$  V

图3 (a)激光照射下的器件结构示意图;(b) 在365 nm光照下不同入射光功率的 $I_{ds}$ - $V_{ds}$ 输出特性曲线( $V_g = 0$  V);(c) 在365 nm光照下 不同入射光功率下 $I_{ds}$ - $V_g$ 转移特性曲线( $V_{ds} = 6$  V);(d)  $V_{ds} = 6$  V时, $I_{ph}$ 与入射光功率的函数关系



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

$$\text{EQE} = hcR\lambda^{-1}e^{-1} \quad , \quad (4)$$

$$\text{NEP} = A^{1/2}/D^* \quad , \quad (5)$$

where  $P_{\text{in}}$  is the incident optical power density,  $A$  is the effective illumination area,  $c$  is the speed of light,  $\lambda$  is the incident light wavelength and  $h$  is Planck's constant.

Fig. 4(a) shows the relationship between responsivity and gate voltage under different optical power density when  $V_{\text{ds}}=6$  V. The responsivity decreases with increasing incident light power, which is consistent with previous studies<sup>[32]</sup>. It's mainly due to the enhancement of carrier scattering and recombination rates under higher incident light power densities. The InSe/MoTe<sub>2</sub> heterojunction photodetectors exhibit a responsivity of 300.57 A/W when  $V_{\text{g}}=-80$  V and  $P_{\text{in}}=1.269$  mW/cm<sup>2</sup>. Fig. 4(b) shows the relationship between detectivity and incident light power density. Detectivity decreases as incident light power density increases. The highest detectivity of  $1.05 \times 10^{13}$  Jones was obtained at  $V_{\text{ds}}=6$  V,  $V_{\text{g}}=-15$  V, and  $P_{\text{in}}=1.269$  mW/cm<sup>2</sup>. The high detectivity can be mainly attributed to the arrangement of the heterojunction energy bands, which allows the electrons in MoTe<sub>2</sub> to naturally flow into InSe, reducing the  $I_{\text{dark}}$ . Fig. 4(c) shows the variation of EQE with respect to the gate voltage under different power irradiation. The EQE of the photodetector reaches a maximum of  $1.03 \times 10^5\%$  at the lowest incident power density of 1.269 mW/cm<sup>2</sup>. The results demonstrate a strong photoelectric conversion capability, as evidenced by the high EQE. Fig. 4(d) shows the dependence of NEP on the incident power density at

$V_{\text{ds}}=6$  V and  $V_{\text{g}}=-15$  V. The achieved NEP value is  $4.75 \times 10^{-17}$  W/Hz<sup>1/2</sup>. The photoswitching characteristics at different incident powers are shown in Fig. 4(e). Under 365 nm light, the photocurrent rapidly increases and stabilises at a high value. When the light source is switched off, the photocurrent rapidly disappears. The device remains stable and variable, even after several tests, demonstrating the excellent stability and reliability of this heterojunction photodetector. This paper presents the switch characteristic curve with an optical power of 16.75 mW/cm<sup>2</sup> (Fig. 4(f)). As shown in Fig. 4(f), the response time (rise and fall) of the InSe/MoTe<sub>2</sub> heterojunction photodetector is 21.6 ms. This response speed is much improved compared to other reported heterojunction photodetectors based on grating effect<sup>[13, 23, 34-36]</sup>.

The band gaps of MoTe<sub>2</sub> and InSe materials can be adjusted depending on their thickness, which extends the light detection range of the InSe/MoTe<sub>2</sub> heterojunction photodetector to the near-infrared. Fig. 5 shows the output characteristic curves ( $V_{\text{g}}=0$  V), and the transfer characteristic curves ( $V_{\text{ds}}=6$  V) of the InSe/MoTe<sub>2</sub> heterojunction photodetector under different incident light wavelengths. The output  $I$ - $V$  curves indicate that the photocurrent of the heterojunction photodetector increases as the drain voltage increase, The maximum photocurrent is achieved under 365 nm light irradiation.

The optical switching characteristics of InSe/MoTe<sub>2</sub> heterojunction photodetectors under different laser wavelengths are shown in Fig. 6(a). Under 365-965 nm light irradiation, the current sharply increases and remains at

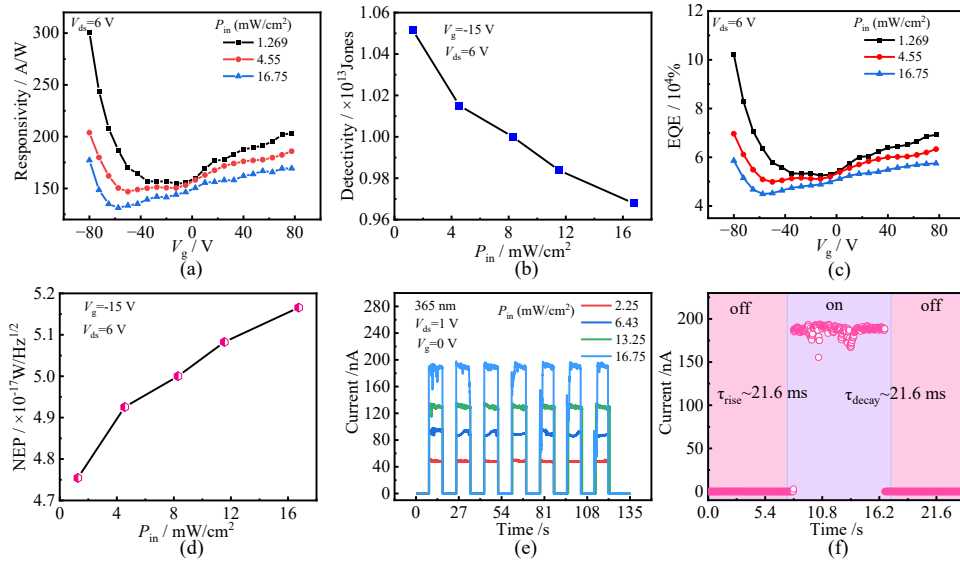


Fig. 4 (a) Responsivity as a function of the gate voltage under different incident light powers ( $V_{\text{ds}}=6$  V); (b) Detectivity as a function of incident light power density ( $V_{\text{ds}}=6$  V,  $V_{\text{g}}=-15$  V); (c) EQE as a function of the gate voltage under different incident light powers ( $V_{\text{ds}}=6$  V); (d) Noise equivalent power (NEP) as a function of illumination power intensity ( $V_{\text{g}}=-15$  V,  $V_{\text{ds}}=6$  V); (e) Time-dependent photocurrent response under switched-on/off light irradiation with different power intensities at  $V_{\text{ds}}=1$  V,  $V_{\text{g}}=0$  V; (f) The rise and decay times of the photocurrent under the power intensity of 16.75 mW/cm<sup>2</sup> at  $V_{\text{ds}}=1$  V

图4 (a) 不同入射光功率下的响应度与栅极电压的关系 ( $V_{\text{ds}}=6$  V); (b) 探测率与入射光功率密度的函数关系 ( $V_{\text{ds}}=6$  V,  $V_{\text{g}}=-15$  V); (c) 外量子效率在不同入射光功率下与栅极电压的函数关系 ( $V_{\text{ds}}=6$  V); (d) 噪声等效功率与入射光功率密度的函数关系 ( $V_{\text{g}}=-15$  V,  $V_{\text{ds}}=6$  V); (e) 不同功率强度下的光开关特性 ( $V_{\text{ds}}=1$  V,  $V_{\text{g}}=0$  V); (f) 光功率密度为 16.75 mW/cm<sup>2</sup> 时光电流的上升和衰减时间 ( $V_{\text{ds}}=1$  V)

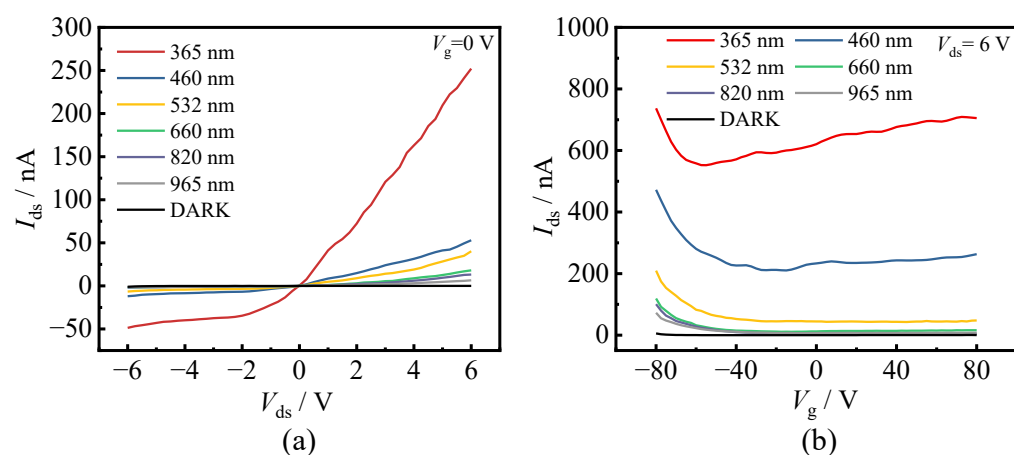


Fig. 5 (a) Photo-response of the  $I_{ds}$ - $V_{ds}$  output characteristics ( $V_g = 0$  V); (b) Photo-response of the  $I_{ds}$ - $V_g$  transfer characteristics ( $V_{ds} = 6$  V) under different incident light wavelengths.

图5 (a) 不同光照波长下的  $I_{ds}$ - $V_{ds}$  输出特性 ( $V_g = 0$  V); (b) 不同光照波长下  $I_{ds}$ - $V_g$  转移特性曲线 ( $V_{ds} = 6$  V)

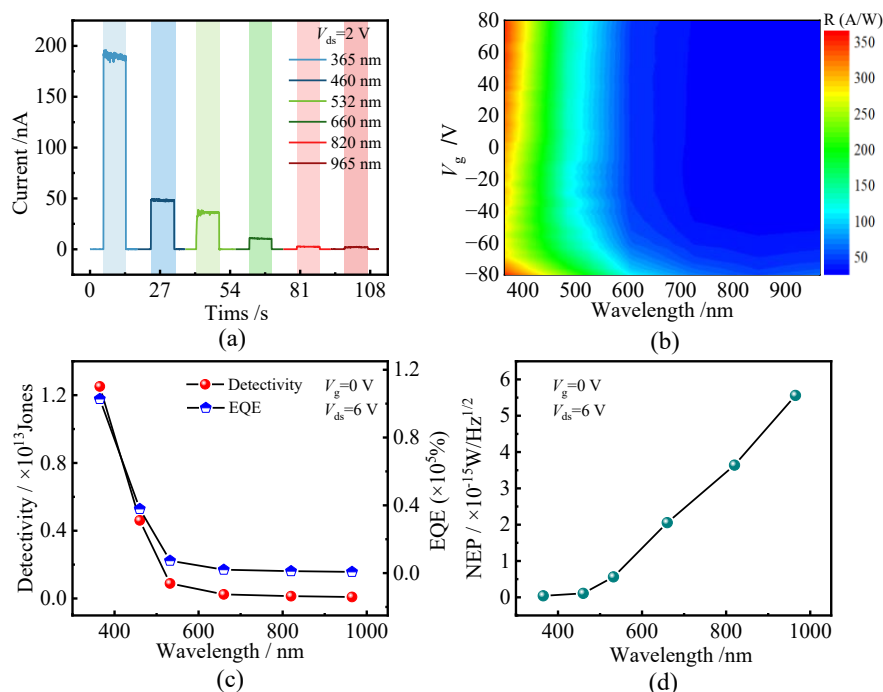


Fig. 6 (a) Time-dependent photocurrent response with different wavelengths at  $V_{ds} = 2$  V; (b) 2D plot of responsivity as a function of incident light wavelength and gate voltage at  $V_{ds} = 6$  V; (c)  $D^*$  and EQE as a function of incident light wavelength at  $V_{ds} = 6$  V and  $V_g = 0$  V of InSe/MoTe<sub>2</sub> heterojunction photodetector; (d) Dependence of NEP on the different wavelengths at  $V_{ds} = 6$  V and  $V_g = 0$  V

图6 (a) 不同波长照射下的光开关特性 ( $V_{ds} = 2$  V); (b) 响应度随入射光波长和栅极电压变化的二维函数图像; (c) 探测率和外量子效率与入射光波长的函数关系 ( $V_{ds} = 6$  V,  $V_g = 0$  V); (d) 噪声等效功率与不同入射光波长的函数关系

a high value. When the light source is switched off, the current rapidly decreases and the test results remain stable during repeated operation (see Figure S2 in the Supporting Information). It demonstrates that the heterojunction photodetector maintains excellent stability and reliability in the 365-965 nm wavelength range. The dependence of responsivity on gate voltage at different wavelengths is shown in Fig. 6(b). The device achieves its highest responsivity value at 365 nm wavelength laser within the range of -80 V to 80 V with gate voltage modu-

lation. And the maximum value of 300.57 A/W obtained at  $V_g = -80$  V, indicating that the InSe/MoTe<sub>2</sub> heterojunction produces the most photogenerated electron-hole pairs under 365 nm wavelength light. Fig. 6(c) shows the dependence of  $D^*$  and EQE on different incident different light wavelengths at  $V_{ds} = 6$  V and  $V_g = 0$  V. The detectivity at 365 nm and 965 nm are  $1.25 \times 10^{13}$  Jones and  $1.12 \times 10^{11}$  Jones, respectively. The photodetector based on 2D materials has a higher result than most reported broad-spectrum photodetectors<sup>[13,35-36]</sup>. The EQE curve

has a similar dependency to the detectivity curve, with a maximum EQE value of  $1.03 \times 10^5\%$  at 365 nm incident wavelength, which exceeds most of the reported photodetectors<sup>[38-39]</sup>, demonstrating excellent photo conversion capability. Fig. 6(d) shows the NEP as a function of wavelength at  $V_{ds} = 6$  V, demonstrating an ultralow noise equivalent power.

### 3 Conclusions

In summary, the vertically stacked InSe/MoTe<sub>2</sub> heterojunction photodetector has been fabricated and systematically investigated, where InSe serves as the grating layer to regulate the channel photocurrent through localized or released holes. In terms of photoelectric performance, the InSe/MoTe<sub>2</sub> heterojunction photodetector has a fast response time of 21.6 ms at 365 nm, and by modulating the gate voltage and incident optical power, it can achieve a response rate of 300.57 A/W, a maximum detectivity of  $1.05 \times 10^{13}$  Jones, and an external quantum efficiency value of  $1.03 \times 10^5\%$ . The photodetector has excellent performance with broadband photodetection from 365 to 965 nm. Under the irradiation of 965 nm laser, the detectivity can reach of  $8.99 \times 10^9$  Jones. Our results open a way to improve photoresponsivity and reduce response time in high performance 2D optoelectronic devices.

### Acknowledgment

The authors would like to thank the Nano Fabrication Facility, Vacuum Interconnected Nanotech Workstation at Suzhou Institute of Nano-Tech and Nano-Bionics, Chinese Academy of Sciences, and Laboratory of Nanodevices and Applications, Suzhou Institute of Nano-Tech and Nano-Bionics, Chinese Academy of Sciences for their technical supports.

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