Journal of Innovation and Development
ISSN: 2958-4752 | Vol. 11, No. 1, 2025

High Performance Photodetectors Based on WTe_2/WS_2 Heterojunction

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Abstract: Two-dimensional (2D) materials have shown broad application prospects in the semiconductor field due to their unique physical and chemical properties, such as high carrier mobility, tunable bandgap, and atomic level thickness. By stacking 2D materials to construct optoelectronic devices such as field-effect transistors and photodetectors, the heterojunction effects can be fully explored, thereby promoting the improvement of their application performance in the fields of optoelectronics and microelectronics. In this work, using 2D semiconductor material WS_2 and semimetal WTe_2 to build a heterojunction, the specific detetectivity (D*) can reach up to 10^{11} Jones at a wavelength of 405 nm, and a fast response time of about 25 ms is achieved, greatly improving the application of photodetectors in optical communication.

Keywords: Two-dimensional materials; semimetal; photodetector.

1. Introduction

As the core component of photoelectric conversion, the physical mechanism of photodetectors lies in the excitation and separation of photo-generated carriers (including photovoltaic and photoconductive effects). Traditional silicon-based photodetectors are limited by the rigid band constraints of single element semiconductors caused by thermodynamic lattice mismatch, making it difficult to adapt to the high integration requirements of emerging applications such as flexible displays and quantum sensing. In this context, two-dimensional (2D) layered semiconductor materials have attracted widespread attention due to their atomic level thickness dependent band gap.[1] Through precise control of the number of layers via mechanical exfoliation or chemical vapor deposition processes, we can achieve accurate design of wavelengths of light response ranging from visible light to near-infrared. Furthermore, by regulating type-II band alignment structures through heteroepitaxial stacking, we can optimize carrier separation efficiency. The key to this material system lies in its weak van der Waals interface interactions between layers and the absence of dangling bonds on the surface, which enables it to construct heterojunctions without the constraints of thermal expansion coefficient matching and lattice mismatch required by traditional heterojunctions, thus achieving van der Waals heterojunctions with low interface defects. This makes 2D materials widely used in optoelectronic devices and provides a physical basis for the full two-dimensional heterogeneous fusion of multifunctional optoelectronic chips.[2]

T_d-WTe_2 is a typical type-II Weyl semimetal material,[3,4] whose unique asymmetric chiral nodes can directly affect electron motion and exhibit significant topological enhancement effects in nonlinear optical responses.[5-7] WS_2 is a representative member of the transition metal dichalcogenides (TMDCs), characterized by its two-dimensional layered structure. Due to its relatively small electron effective mass, it exhibits higher carrier mobility compared to other TMDC materials. In this work, by building a heterojunction of WTe_2/WS_2, we have developed a high performance of photodetector. For example, a specific detection rate of 10^{11} Jones and a fast response time of about 25 ms is achieved at a wavelength of 405 nm. This work provides a universal approach to improve the photodetection property toward highly efficient photodetector applications.

2. Results and Discussion

Figure 1a shows the three-dimensional structure of the 2H-WS_2/T_d-WTe_2 heterojunction photodetector designed. To achieve photoelectric detection, T_d-WTe_2 was combined with 2H-WS_2, and the few layers of WTe_2 and WS_2 were sequentially transferred onto a Si/SiO_2 substrate using dry transfer method to form a van der Waals heterojunction. The optical microscope image is shown in Figure 1b.

Next, we conducted optoelectronic performance tests on the heterojunction. Figure 1c shows the photoelectric measurement results of the device. The device was tested at wavelengths of 405 nm with optical power densities of 144.0 mW/cm^2. The I-V characteristic curves are shown in Figure 1c. From the figure, it can be seen that there is a significant increase in current at 405 nm wavelength. The I-T curves of the device at wavelength of 405 nm are shown in Figures 1d. It can be seen that the maximum I_{light}/I_{dark} value can reach up to 1.2×10^4 at a wavelength of 405 nm and an optical power density of 144 mW/cm^2. In addition, both open-circuit voltage (V_{oc}) and short-circuit current (I_{sc}) at wavelength of 405 nm are extracted shown in Figure 1e and 1f, which can reach up to about 0.16 V and 3.7×10^{-11} A, respectively, implying an improved photovoltaic characteristic.

In order to further analyze the performance of two-dimensional heterojunctions, photo-responsivity (R), external quantum efficiency (EQE), and specific detectivity (D^*) are used as three key parameters to describe the output signal intensity, electron generation efficiency under illumination, and weak illumination detection ability, respectively. The calculation formulas are as follows:

$$R = I_{ph}/\left(P_\lambda \cdot S\right)$$

$$EQE^{*} = Rhc/\left(q\lambda\right)$$

$$D* = \frac{R\sqrt{S}}{\sqrt{2eI_{dark}}}$$

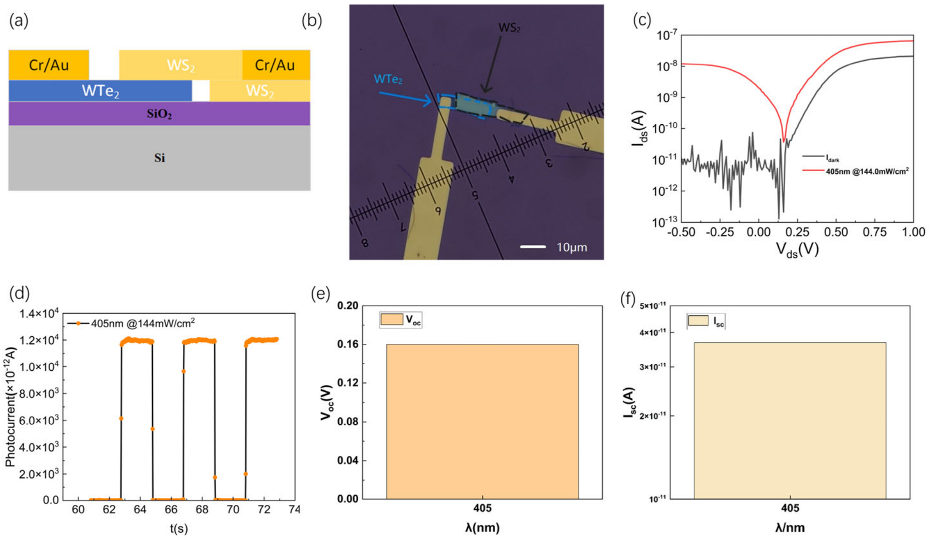

Figure 1. The structure of WTe_2/WS_2 photodetector and corresponding characterization images (a) Three dimensional structure diagram of the device. (b) Optical image of the device. (c) The I-V characteristic curves of the device at different wavelengths. (d) I-t curves of the device at 405nm. (e-f) The open circuit voltage V_{oc} and short-circuit current I_{sc} of the device at 405nm.

Among them, I_{ph} is defined as the net photocurrent, I_{light} as the current measured under light conditions, I_{dark} as the current measured under dark conditions, incident light power as, $P_{\lambda} \bullet S$ as the light power density per unit area incident on the device, S as the effective illuminated area of the device, h as the Planck constant with a value of 6.626×10^{-34} J·s, c indicates the speed of light, e indicates the single electron charge, and λ indicates the wavelength of incident light. R refers to the ratio of photocurrent to incident light power, reflecting the ability of a photodetector to generate photocurrent per unit of light power. EQE is used to measure the ability of photons to excite electron hole pairs in photodetectors. D* can reflect the detection ability of photodetectors for weak signals. For photodetectors based on the photovoltaic effect, the space charge region in the device can suppress dark current, so photodetectors based on the photovoltaic effect have the potential to achieve high specific detection rate.

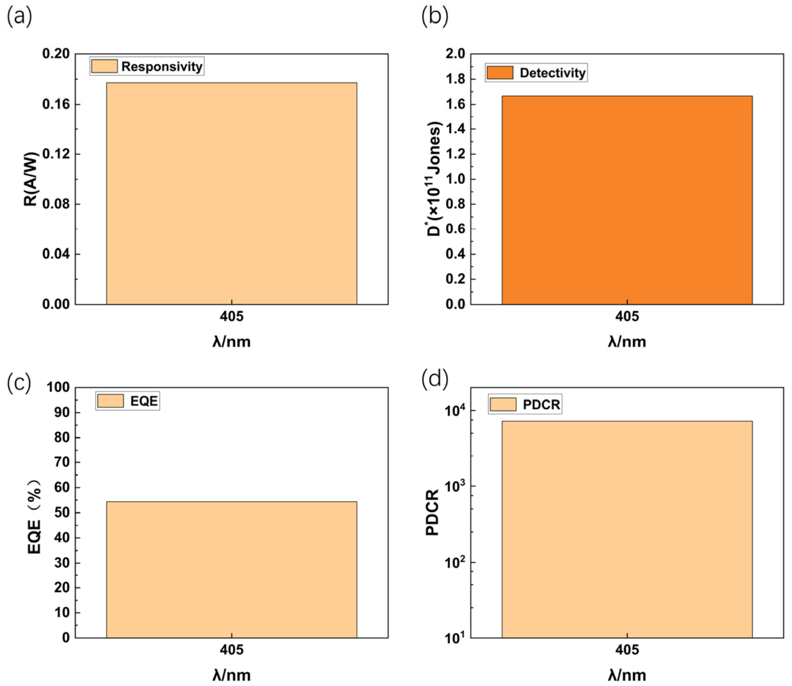

Figure 3. WTe_2/WS_2 photodetectors of (a) Responsivity R. (b) Detectivity D^* (c) External quantum efficiency EQE. (d) Photo-dark current ratio PDCR.

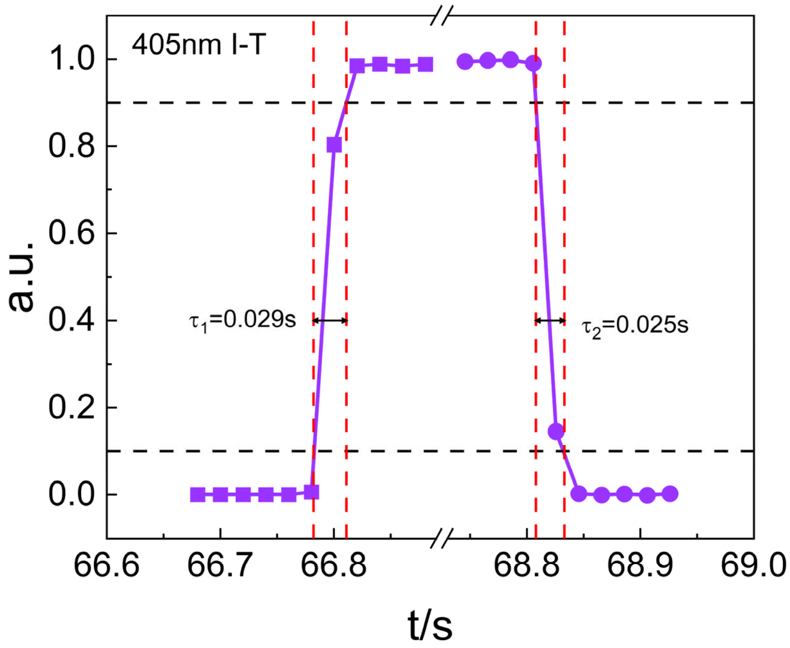

Figure 4. Response time of WTe_2/WS_2 photodetector at different maximum optical powers at wavelength of 405 nm.

We have plotted histograms of the above three parameters at wavelength of 405 nm, as shown in Figures 3 (a) -3 (d). The heterojunction of this device is sensitive to a light wavelength of 405 nm, with a maximum photoresponsivity R, quantum efficiency EQE, and detectivity D^* of 0.177 A/W, 54.37%, and 1.67×10^{11} Jones, respectively. In addition, we calculated the photo-dark current ratio (PDCR) of the device according to the formula, which is defined as the ratio of the net photocurrent to the dark current of the photodetector, reaching up to 0.8×10^4.

$$PDCR = \frac{I_{ph}}{I_{dark}}$$

At the same time, we measured the time-resolved optical response and tested the I-t curves of 405 nm wavelength at their respective maximum optical power densities. Under 405 nm illumination, the rising time τ_1 is around 29 ms and decay time τ_2 is about 25 ms, as shown in Figure 4, which indicates that our device has fast and stable dynamic response.

3. Conclusion

This work developed a high performance photodetectors based on the heterojunction composing of 2D semimetal T_d-WTe_2 and semiconductor 2H-WS_2. The device was characterized and the photoelectric characteristics were tested, and the experimental phenomena were analyzed. The fast response time of around 25 ms is achieved and the specific D* can reach about 10^{11} Jones. We have demonstrated through experiments that the device exhibits good response to incident light with a wavelength of 405 nm, showing a great potential in photodetector applications.

4. Experimental Section

4.1. Device fabrication

Firstly, the block shaped crystal materials T_d-WTe_2 and 2H-WS_2 are peeled off into multiple layers of two-dimensional materials using adhesive tape. Then, PDMS (polydimethylsiloxane) is mechanically peeled off into multiple layers of nanosheets and subjected to dry transfer. T_d-WTe_2 is first transferred onto a silicon substrate containing 300 nm SiO_2 using a high-precision three-dimensional transfer platform, and then 2H-WS_2 is transferred to one side of the T_d-WTe_2 layer using the same method to form a heterostructure. Afterwards, UV lithography technology was used to perform lithography treatment on the device. After development, Cr (10nm) / Au (50nm) were prepared on both sides of T_d-WTe_2/2H-WS_2 using electron beam deposition technology as electrodes. Finally, the lift off process was used to remove the gold and prepare the device.

4.2. Characterization

We use optical microscopy to characterize the optical images of the device. After the device preparation was completed, we measured its photoelectric characteristics at room temperature using a probe station equipped with a Keithley 2636B semiconductor device analyzer and a four channel laser.

Acknowledgements

This work was financially supported by the Guangzhou Basic and Applied Basic Research Foundation (No. 2023A04J1710).

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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