Band alignment of type-I $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ and type-II $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ van der Waals heterostructures for highly enhanced photoelectric responses

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ABSTRACT Heterostructures based on new advanced materials offer a cornerstone for future optoelectronic devices with improved photoelectric performance. Band alignment is crucial for understanding the mechanism of charge carrier transportation and interface dynamics in heterostructures. Herein, we grew $\text{SnS}_2/\text{Bi}_2\text{X}_3$ ($\text{X} = \text{Se}, \text{Te}$) van der Waals heterostructures by combining physical vapor deposition with chemical vapor deposition. The band alignment, measured by high-resolution X-ray photoelectron spectroscopy, suggested the successful design of type-I $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ and type-II $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ heterostructures. The $\text{SnS}_2/\text{Bi}_2\text{X}_3$ heterostructure greatly improved the photoelectric response of a photoelectrochemical-type photodetector. The photocurrent densities in the type-I $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ and type-II $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ heterostructure-based devices were more than one order of magnitude higher than those of SnS_2 , Bi_2Se_3 , and Bi_2Te_3 . The improved photoelectric properties of the $\text{SnS}_2/\text{Bi}_2\text{X}_3$ heterostructures can be explained as follows: (i) the photoexcited electrons and holes are effectively separated in the heterostructures; (ii) the charge-transfer efficiency and carrier density at the interface between the $\text{SnS}_2/\text{Bi}_2\text{X}_3$ heterostructures and the electrolyte are greatly improved; (iii) the formed heterostructures expand the light absorption range. The photoelectric performance was further enhanced by efficient light trapping in the upright SnS_2 . The photoelectric response is higher in the type-I $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ heterostructure than in the type-II $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ heterostructure due to more efficient charge transportation at the type-I $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ heterostructure/electrolyte interface. These results suggest that suitable type-I and type-II heterostructures can be developed for high-performance photodetectors and other optoelectronic devices.

Keywords: $\text{SnS}_2/\text{Bi}_2\text{Se}_3$, $\text{SnS}_2/\text{Bi}_2\text{Te}_3$, type-I heterostructure, type-II heterostructure, photoelectric response, photodetector

INTRODUCTION

The conversion of light into electrical signals is crucial for optical detection, providing many opportunities for developing technical applications such as solar cells, sensors, spectroscopy, and photodetectors [1–3]. Photoelectrochemical (PEC)-type photodetectors can output larger photocurrents under low-voltage conditions than traditional photodetectors and admit a simple manufacturing process. Furthermore, PEC-type photo-

detectors are inexpensive devices with high photoresponsivity, high photosensitivity, and fast photoresponse [4,5]. In recent years, wide-band-gap semiconductor TiO_2 has been widely used in PEC-type photodetectors [6,7]. However, the wide band gap, small specific surface area, and slow carrier transfer rate of TiO_2 reduce the photoresponsivity, which has hindered the applications of PEC-type photodetectors. In particular, TiO_2 absorbs only ultraviolet (UV) light [8] and demonstrates poor charge-transfer kinetics in PEC-type photodetectors. Unlike TiO_2 , two-dimensional (2D) materials such as metallic sulfides have a tunable band gap from the visible-to-infrared region, which can greatly improve the photoelectric conversion. Meanwhile, 2D metallic sulfides possess high carrier mobility, strong light-matter interaction, and large surface area [9,10], which improve the magnitude and stability of the photocarrier generation and transfer efficiency. Among the metallic sulfides, SnS_2 is a typical n-type semiconductor with a tunable band gap (2.0–2.4 eV). Owing to its cheapness, abundance, and environmental friendliness [11–13], along with stability in visible-light-driven photocatalysis [14,15], SnS_2 has been widely used in PEC-type devices. However, single-component SnS_2 is disadvantaged for relatively low solar absorption spectra and slow charge transfer at the SnS_2 /electrolyte interface. In early research, these disadvantages limited the photocurrent density of SnS_2 to the $\mu\text{A cm}^{-2}$ scale. Recently, these problems have been solved by strategies such as the fabrication of low-dimensional nanostructures, construction of multidimensional-edge structures, and design of heterostructures. For instance, Liu *et al.* [16] reported the direct syntheses of multidimensional-edge SnS_2 with a higher photocurrent density (1.73 mA cm^{-2}) than parallel nanosheets ($1.3 \mu\text{A cm}^{-2}$) because the active edges improved the light harvesting. Mu *et al.* [17] fabricated vertically oriented SnS_2 on TiO_2 nanotube arrays, which achieved a photocurrent density of 1.05 mA cm^{-2} due to highly efficient separation of electron-hole pairs. Thus, heterostructures formed by combining multidimensional edge SnS_2 can effectively improve the photoelectric performance of PEC-type photodetectors.

2D layered narrow-band-gap materials are outstanding heterogeneous components by virtue of their active edges, wide absorption range (up to infrared light), and high carrier mobility. For example, Bi_2Se_3 and Bi_2Te_3 show narrow band gaps (0.3–1.0 eV) [18,19], conductive surface states, and high specific surface areas. Furthermore, Bi_2Se_3 and Bi_2Te_3 are typical topologically insulator-layered materials [20,21] with an outer spin-momentum-locked Dirac cone and an internal insulating band

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gap [22]. These topologically protected and massless Dirac-type surface states are considered superior electrodes [23,24]. Especially, Bi_2X_3 ($\text{X} = \text{Se}, \text{Te}$) materials can be easily synthesized by physical vapor deposition (PVD) adopting a van der Waals (vdW) approach. The resulting 2D materials are high-quality and have large areas [18,19]. Unlike traditional heterostructures, 2D vdW heterostructures can be easily constructed without the limitations of lattice matching. The vdW technique greatly promotes the heterostructure construction between SnS_2 and Bi_2X_3 ($\text{X} = \text{Se}, \text{Te}$). VdW heterostructures based on 2D materials also exhibit synergistic effects such as interlayer excitons [25] and interlayer charge transfer [26,27], which cannot be achieved in single-component structures. Several 2D materials, such as black phosphorus (BP) [28] and InSe [29], have been synthesized by liquid-phase exfoliation and incorporated into successful PEC-type photodetectors. However, the photoresponsivity of these PEC-type photodetectors is lower than desired. The vdW heterostructure is among the most promising solutions for photodetectors with high photoresponsivity [30].

Based on their band offset parameters, heterostructures are broadly divided into type-I, type-II, and type-III heterostructures. A combined structure of Bi_2X_3 ($\text{X} = \text{Se}, \text{Te}$) and vertical SnS_2 nanosheets can enhance the photon-capturing ability and accelerate charge transportation at the heterostructure interface. Type-I heterostructures, in which the hole-and-electron transfer favors the semiconductor with the narrower band gap, are widely used in transistors [31]. Type-II heterostructures, which improve the PEC efficiency by reducing the electron-hole pair recombination, are widely used in photocatalytic water splitting [32]. Type-III heterostructures are characterized by efficient carrier band-to-band tunneling [33], a wide response range, and high photogenerated carrier separation efficiency [34], which are desired in transistors and light-emitting diodes [35]. In all these applications, band alignment is vital for understanding the fundamentals of carrier transportation and interfacial recombination during photoelectric conversion. However, few band-alignment experiments have been performed on vdW heterostructures based on 2D materials.

In this work, $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ and $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ heterostructures were fabricated by combining PVD and chemical vapor deposition (CVD) methods. The morphologies of SnS_2 , Bi_2X_3 ($\text{X} = \text{Se}, \text{Te}$), and $\text{SnS}_2/\text{Bi}_2\text{X}_3$ ($\text{X} = \text{Se}, \text{Te}$) were studied by scanning

electron microscopy (SEM), and the chemical compositions of the samples were revealed by Raman spectroscopy and X-ray photoelectron spectroscopy (XPS). Through UV-Vis absorption spectroscopy and high-resolution XPS analyses, we determined that $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ and $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ are type-I and type-II heterostructures, respectively. Meanwhile, PEC-type photodetector measurements revealed that both type-I and type-II heterostructures achieve much higher photoelectric performance than pure SnS_2 or Bi_2X_3 . The band alignment of the heterostructure promotes the separation of photogenerated carriers, thereby enhancing the photoelectric performance. These results suggest that constructing narrow-band-gap semiconductors into heterostructures can effectively improve the photoelectric response of photodetectors.

EXPERIMENTAL SECTION

Fabrication of the $\text{SnS}_2/\text{Bi}_2\text{X}_3$ ($\text{X} = \text{Te}, \text{Se}$) heterostructure photodetectors

The $\text{SnS}_2/\text{Bi}_2\text{X}_3$ heterostructures were grown by a combined CVD and PVD method. The growth setup consists of a quartz tube (of diameter 6 cm) in a tube furnace with two temperature zones. Following the flow direction, the first and second temperature zones are close to the gas inlet and air outlet, respectively, as shown in Fig. 1.

The $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ and $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ heterostructures were grown on indium-tin-oxide (ITO) substrates by a two-step vapor phase epitaxy method. In the first step, 5 mg Bi_2X_3 powder was placed in the center of the second temperature zone, and Bi_2X_3 (Bi_2Se_3 , Alfa Aesar, 99.99%; Bi_2Te_3 , Alfa Aesar, 99.98%) films were successfully deposited on ITO substrate at approximately 10 cm downstream of the center of the second temperature zone. Before the growth process, the air in the tube was exhausted by flowing argon at 200 sccm (standard cubic centimeter per minute) (Ar , 99.999%). Under a low pressure (500 Pa), the Bi_2X_3 vapor in the second temperature zone (500°C) was carried downstream by 30 sccm Ar gas and physically adsorbed on the ITO substrate surface to form thin films.

In the second step, upright SnS_2 was grown on the Bi_2X_3 films by the CVD method. One gram of $\text{SnCl}_4 \cdot 5\text{H}_2\text{O}$ (Aladdin, 99.99%) and 100 mg of sulfur (S) powder were placed at the centers of the second and first temperature zones, respectively.

Figure 1 Schematic of the $\text{SnS}_2/\text{Bi}_2\text{X}_3$ ($\text{X} = \text{Se}, \text{Te}$) heterostructure growth.

The as-grown Bi_2X_3 films were placed approximately 12 cm downstream of the center of the second temperature zone. Next, the first and second temperature zones were heated to 180 and 450°C, respectively, in 35 min. Under continuous Ar gas (60 sccm), the growth temperature was maintained for 15 min. After the growth process, the $\text{SnS}_2/\text{Bi}_2\text{X}_3$ heterostructures on the ITO substrate were formed by gradually cooling the quartz tube to room temperature.

RESULTS AND DISCUSSION

Characterization of SnS_2 , Bi_2X_3 ($\text{X} = \text{Te}, \text{Se}$) and $\text{SnS}_2/\text{Bi}_2\text{X}_3$ ($\text{X} = \text{Te}, \text{Se}$) heterostructures

The $\text{SnS}_2/\text{Bi}_2\text{X}_3$ heterostructures were prepared by a two-step vapor phase epitaxy method. First, uniform centimeter-scaled Bi_2X_3 films were successfully grown on the ITO substrates. Next, flower-like SnS_2 structures were formed on the nanosheets. This special structure expanded the exposed surface of the SnS_2 nanosheets. Simultaneously, this vertically grown SnS_2 promoted the internal reflection of light, improved the light capture, and facilitated the production of electron-hole pairs [16,17]. SEM images (Thermo Scientific, Apreo S, USA) of the formed $\text{SnS}_2/\text{Bi}_2\text{X}_3$ films are shown in Fig. 2a, b. The nanoflowers were determined as 600–650 nm wide and 795.7 nm thick (Fig. 2a), and the $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ sheet was 706.1 nm thick (Fig. 2b). Both the SnS_2 nanosheets and Bi_2X_3 ($\text{X} = \text{Se}, \text{Te}$) thin films were isotropic and elicited no polarization response. This isotropic response to incident light was corroborated by the SEM images, which revealed randomly stacked polycrystallites. The element mapping images (Fig. 2c, d) of the Sn, S, Bi, Se, and Te elements confirmed the uniform growth of the heterostructures on the ITO substrate. This combined SnS_2 and Bi_2X_3 films can greatly improve the photoelectric performance by enhancing the light trapping capacity and enabling fast separation of the photo-generated carriers.

The Raman spectra of the samples were measured using a SmartRaman confocal-micro-Raman module (Institute of Semiconductors, Chinese Academy of Sciences). Fig. 2e shows the Raman spectra of Bi_2Se_3 , SnS_2 , and their heterostructures. The characteristic peaks of Bi_2Se_3 near 129 and 174 cm^{-1} accord with the E_g and A_{1g} vibration modes of Bi_2Se_3 , respectively [18]. The single peak near 313 cm^{-1} in the spectrum of SnS_2 is consistent with the A_{1g} vibration mode of SnS_2 . Three vibration modes were evident in the spectrum of the formed $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ heterostructure. The peaks at 126 and 173 cm^{-1} corresponded to the E_g and A_{1g} vibration modes of Bi_2Se_3 , respectively, while that at 314 cm^{-1} was the A_{1g} vibration mode of SnS_2 . Similarly, Fig. 2f shows the Raman spectra of Bi_2Te_3 , SnS_2 , and their heterostructures. The characteristic peaks of Bi_2Te_3 near 100 and 138 cm^{-1} corresponded to the E_g and A_{1g} vibration modes of Bi_2Te_3 , respectively [19]. The spectrum of the $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ heterostructure exhibited three characteristic peaks at 99, 139, and 311 cm^{-1} . The first and second of these peaks corresponded to the E_g and A_{1g} vibration modes of Bi_2Te_3 , respectively, and the third was the A_{1g} vibration mode of SnS_2 . It is worth mentioning that the E_g and A_{1g} peaks of Bi_2Se_3 in $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ were red-shifted and blue-shifted from those of pure Bi_2Se_3 , respectively. Similarly, the E_g and A_{1g} peaks of Bi_2Te_3 in $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ were red-shifted and blue-shifted, respectively, from those of pure Bi_2Te_3 . Meanwhile, the A_{1g} peaks of SnS_2 in $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ and $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ were red-shifted and blue-shifted, respectively, from that of pure

SnS_2 . These Raman mode shifts provide clear evidence of vdW heterostructures with interlayer coupling and charge redistribution at the interface [36].

The elemental compositions and bonding configurations of the heterostructures were evaluated by high-resolution XPS (VG ESCA Lab220I-XL, province, country). The whole XPS spectra confirmed the stoichiometries and chemical states of the heterostructure films (see Fig. 3a, b). The Sn and S peaks from SnS_2 and the Bi and Se peaks from Bi_2Se_3 were clearly observed in the spectrum of the $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ heterostructure. The additional peak at 531.1 eV corresponded to O element from the ITO substrate. Similarly, the peaks of Sn, S, Bi, Te, and O elements appeared in the spectrum of the $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ heterostructure. These results further confirm the successful synthesis of the $\text{SnS}_2/\text{Bi}_2\text{X}_3$ heterostructures.

To accurately determine the binding state of the elements in the samples, the Sn 3d spectra in the $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ heterostructure and in SnS_2 were fitted by Gaussian and Lorentz functions (see Fig. 3c). The peaks at 487.05 and 495.43 eV in the Sn 3d spectrum of SnS_2 belonged to Sn 3d_{5/2} and Sn 3d_{3/2}, respectively, and were contributed by Sn^{4+} species. In the $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ heterostructure, these two peaks were located at 486.97 and 495.39 eV, respectively. Two additional small peaks at 485.90 and 494.30 eV were caused by a small amount of SnS generated by SnO_2 during the thermal decomposition of $\text{SnCl}_4 \cdot 5\text{H}_2\text{O}$ in the vulcanization process [37]. Meanwhile, the Bi 4f orbitals were fitted with three peaks belonging to Bi 4f_{7/2} (157.21 eV), Bi 4f (164.00 eV) and Bi 4f_{5/2} (162.50 eV) of Bi_2Se_3 (see Fig. 3d). The additional small peak at 158.70 eV was caused by the precipitation of a small amount of metallic bismuth during the preparation process. In the spectrum of the $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ heterostructure, the Bi 4f_{5/2} and Bi 4f_{7/2} peaks were located at 162.47 and 157.16 eV, respectively. The peak at 161.10 eV belonged to S 2p_{3/2} orbitals arising from vulcanization induction. Obviously from Fig. 3c, d, the binding energies of Bi and Sn in the $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ heterostructure slightly deviated from those of pure Bi_2Se_3 and SnS_2 . The Bi binding energy in the $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ heterostructure was 0.05 eV smaller than in the pure Bi_2Se_3 , and the Sn binding energy in the $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ heterostructure was 0.01 eV larger than in the pure SnS_2 . These shifts can be explained by charge redistribution between SnS_2 and Bi_2Se_3 during the formation of the heterostructure. Specifically, the charge is transferred from SnS_2 to Bi_2Se_3 at the interface of the $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ heterostructure.

The fitting results in Fig. 3e suggest the existence of two Sn 3d peaks in the spectrum of SnS_2 : an Sn 3d_{5/2} peak at 486.97 eV and an Sn 3d_{3/2} peak at 495.39 eV. Both peaks belong to the Sn^{4+} category. In the $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ heterostructure, these two peaks belonging to Sn species were located at 487.01 and 495.45 eV, respectively. According to the fitting results in Fig. 3f, the peaks attributable to the three Bi 4f orbitals in Bi_2Te_3 can be divided into Bi 4f_{5/2} (162.36 eV), Bi 4f (163.60 eV), and Bi 4f_{7/2} (157.12 eV), all contributed by Bi^{3+} species. In the spectrum of the $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ heterostructure, the corresponding Bi 4f_{5/2}, Bi 4f, and Bi 4f_{7/2} peaks were located at 162.49, 164.00, and 157.19 eV, respectively. The additional peak near 158.70 eV was caused by the precipitation of a small amount of metal during the growing process of Bi_2Te_3 . The binding energies of Bi and Sn in the $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ heterostructure also slightly deviated from those of pure Bi_2Te_3 and SnS_2 (see Fig. 3e, f). In the $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ heterostructure, the Bi binding energy was 0.13 eV larger than in the pure Bi_2Te_3 , whereas the Sn binding energy was 0.06 eV smaller

Figure 2 SEM images of (a) $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ and (b) $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ heterostructures on the ITO substrate; (c) Sn, S, Bi, and Se element mappings; (d) Sn, S, Bi, and Te element mappings; Raman spectra of (e) Bi_2Se_3 , SnS_2 and $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ and (f) Bi_2Te_3 , SnS_2 and $\text{SnS}_2/\text{Bi}_2\text{Te}_3$.

than in the pure SnS_2 . This shift can be explained by charge redistribution of Bi_2Te_3 and SnS_2 during the formation of the heterostructure; specifically, the charge is transferred from Bi_2Te_3 to SnS_2 at the interface of the $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ heterostructure.

Band alignment is essential for analyzing charge transportation and carrier recombination in PEC-type photodetectors. To understand the band alignment at the interface, the valence band spectra of Bi_2Se_3 , Bi_2Te_3 , and SnS_2 were obtained by XPS. As

Figure 3 (a, b) XPS full spectra of the $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ and $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ heterostructures, respectively; (c) XPS spectra of Sn 3d in the $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ heterostructure and SnS_2 ; (d) XPS spectra of Bi 4f in the $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ heterostructure and Bi_2Se_3 ; (e) XPS spectra of Sn 3d in the $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ heterostructure and SnS_2 ; (f) XPS spectra of Bi 4f in the $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ heterostructure and Bi_2Te_3 .

indicated in Fig. 4a–c, the maximum valence bands (VBMs) of Bi_2Se_3 , Bi_2Te_3 , and SnS_2 appeared at 0.51, −0.10, and 1.67 eV, respectively. The energy difference between the Bi 4f core level and the VBM of Bi_2Se_3 was 156.59 eV. In the $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ heterostructure, the energy difference between the Sn 3d and Bi 4f core levels was 338.30 eV. Meanwhile, the energy difference between Bi 4f and the VBM of Bi_2Te_3 was 157.20 eV, and that

between the Sn 3d and Bi 4f core levels was 338.30 eV after the formation of the $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ heterostructure. The band offset parameters (ΔE_v) were calculated as follows [38–40]:

$$\Delta E_{v1} = \left(E_{\text{Bi } 4f_{7/2}}^{\text{Bi}_2\text{Se}_3} - E_{\text{VBM}}^{\text{Bi}_2\text{Se}_3} \right) + \left(E_{\text{Sn } 3d_{3/2}}^{\text{SnS}_2/\text{Bi}_2\text{Se}_3} - E_{\text{Bi } 4f_{7/2}}^{\text{SnS}_2/\text{Bi}_2\text{Se}_3} \right) - \left(E_{\text{Sn } 3d_{3/2}}^{\text{SnS}_2} - E_{\text{VBM}}^{\text{SnS}_2} \right), \quad (1)$$

Figure 4 (a–c) Valence band spectra of Bi₂Se₃, Bi₂Te₃ and SnS₂, respectively; (d–f) Tauc plots $((\alpha h\nu)^{1/2}$ versus $h\nu$) giving the band gaps of Bi₂Se₃, Bi₂Te₃, and SnS₂. Here, α , h , and ν denote the absorbance coefficient, Planck constant, and frequency, respectively. (g, h) Schematics of the band alignment in the SnS₂/Bi₂Se₃ and SnS₂/Bi₂Te₃ heterostructures, respectively.

$$\Delta E_{v_2} = (E_{\text{Bi } 4f_{7/2}}^{\text{Bi}_2\text{Te}_3} - E_{\text{VBM}}^{\text{Bi}_2\text{Te}_3}) + (E_{\text{Sn } 3d_{3/2}}^{\text{SnS}_2/\text{Bi}_2\text{Te}_3} - E_{\text{Bi } 4f_{7/2}}^{\text{SnS}_2/\text{Bi}_2\text{Te}_3}) - (E_{\text{Sn } 3d_{3/2}}^{\text{SnS}_2} - E_{\text{VBM}}^{\text{SnS}_2}). \quad (2)$$

The first and third terms in Equation (1) (Equation (2)) are the VBM energies of the nuclear level positions of the pure Bi₂Se₃ and SnS₂ (pure Bi₂Te₃ and SnS₂), respectively. The second term in both expressions is the energy difference between Sn 3d_{3/2} and Bi 4f_{7/2}. From experimental data, the ΔE_v of the SnS₂/Bi₂Se₃ and SnS₂/Bi₂Te₃ heterostructures were confirmed as 1.16 and 1.77 eV, respectively. The band gaps of Bi₂Se₃, Bi₂Te₃, and SnS₂ were determined in Tauc plots derived from the absorption spectra (Fig. 4d, f). The band gaps of the Bi₂Se₃, Bi₂Te₃, and SnS₂ samples were 0.72, 0.87, and 2.22 eV, respectively. The conduction band offsets in the SnS₂/Bi₂Se₃ and SnS₂/Bi₂Te₃ heterostructures were respectively calculated as follows:

$$\Delta E_{c_1} = E_g^{\text{Bi}_2\text{Se}_3} + \Delta E_{v_1} - E_g^{\text{SnS}_2}, \quad (3)$$

$$\Delta E_{c_2} = E_g^{\text{Bi}_2\text{Te}_3} + \Delta E_{v_2} - E_g^{\text{SnS}_2}. \quad (4)$$

From experimental data, the ΔE_c of the SnS₂/Bi₂Se₃ and SnS₂/Bi₂Te₃ heterostructures were determined as -0.36 and 0.42 eV, respectively. The band-alignment diagrams in Fig. 4g, h suggest

that SnS₂/Bi₂Se₃ is a type-I heterostructure, while SnS₂/Bi₂Te₃ is a type-II heterostructure.

The photoexcited holes and electrons in type-I heterostructures tend to transfer to the semiconductor with the narrower band gap. Such heterostructures are widely used in photodiodes and photodetectors [41]. In the type-I SnS₂/Bi₂Se₃ heterostructure, the photogenerated electrons and holes probably transferred from SnS₂ to Bi₂Se₃. The transfer phenomenon promotes the intensity of photogenerated carriers, thereby enhancing the overall charge-transfer dynamics of the system [41,42]. The SnS₂/Bi₂Se₃ heterostructure should also achieve faster charge separation and better carrier recombination suppression than the pure SnS₂ and Bi₂Se₃. Meanwhile, type-II heterostructures can effectively reduce the recombination of photoexcited electron-hole pairs [32,43]. In the SnS₂/Bi₂Te₃ heterostructure, the excited electrons transferred from Bi₂Te₃ to SnS₂, while the photogenerated holes transferred from SnS₂ to Bi₂Te₃. This phenomenon also promotes the separation of photogenerated carriers, reduces carrier recombination, and enhances the overall charge-transfer dynamics of the system, thereby improving the photoelectric performance [44,45]. The ΔE_c and ΔE_v were both smaller in the SnS₂/Bi₂Se₃ heterostructure than in the SnS₂/Bi₂Te₃ heterostructure, suggesting a lower

energy barrier at the interface (and consequently, faster transport of the photoexcited electron–holes) in the $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ heterostructure.

Photoelectric properties of SnS_2 , Bi_2X_3 ($\text{X} = \text{Te, Se}$) and $\text{SnS}_2/\text{Bi}_2\text{X}_3$ ($\text{X} = \text{Te, Se}$)

Fig. 5a shows the electrochemical workstation (CHI660e, Shanghai Chenhua, Shanghai, China) and the three-electrode PEC system illuminated by a xenon lamp (GLORIA-X150, Zolix, Beijing, China) used in the PEC measurements. SnS_2 , Bi_2X_3 , and their heterostructures were used as the working electrodes, platinum (Pt) was used as the counter electrode, and silver chloride (Ag/AgCl) electrodes were used as the reference electrodes. All experiments were carried out in $0.2 \text{ mol L}^{-1} \text{ Na}_2\text{SO}_3$ solution electrolyte at room temperature.

The photoelectric properties of the samples were measured in a three-electrode system with a weak alkaline solution electrolyte ($0.2 \text{ mol L}^{-1} \text{ Na}_2\text{SO}_3$). The measurement device was a PEC-type photodetector. Fig. 5b shows the voltammogram (J – V curve) acquired by linear sweep voltammetry at a sweep rate of 10 mV s^{-1} . The photocurrent density J increased with bias voltage V . Evidently, the photocurrent density was higher in the $\text{SnS}_2/\text{Bi}_2\text{X}_3$ heterostructures than in SnS_2 and Bi_2X_3 . Comparing the heterostructure performances, $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ demonstrated a higher photocurrent density than $\text{SnS}_2/\text{Bi}_2\text{Te}_3$. The transient photocurrent response (J – t curve) was measured with an on/off duration of 5 s under a bias voltage of -0.1 V (see Fig. 5c). The photocurrent response of the $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ heterostructure was approximately $170 \mu\text{A cm}^{-2}$, about 21 times that of SnS_2 and 14 times that of Bi_2Se_3 . The photocurrent response of the $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ heterostructure was also approximately 14 times that of SnS_2 and 12 times that of Bi_2Te_3 . These photoelectric responses exceeded those of recently reported PEC-type photodetectors [30,46]. The photodetection performance was assessed by two widely used indices: the photocurrent density (I_{ph}) and photoresponsivity (R_{ph}), which are respectively calculated as [4]

$$I_{\text{ph}} = (I_{\text{light}} - I_{\text{dark}}) / S, \quad (5)$$

$$R_{\text{ph}} = I_{\text{ph}} / P_{\lambda}. \quad (6)$$

Here, I_{light} and I_{dark} are the currents in the light and dark states, respectively, P_{λ} is the incident power density of the photodetector, and S is the effective illumination area on the photodetector. As shown in Table 1, Bi_2X_3 and SnS_2 demonstrated higher photocurrent responses than recently reported photodetectors based on BP [28], InSe [29], Bi_2S_3 [47], and WSe_2 [44]. The enhancements (up to dozens of times) can be attributed to the uniformity, high quality, high stability, and high carrier mobility of Bi_2X_3 and SnS_2 synthesized by the combined CVD and PVD method. In the $\text{SnS}_2/\text{Bi}_2\text{X}_3$ heterostructures, the separation of photogenerated carriers was accelerated while the recombination of electrons and holes was reduced, resulting in a greatly improved photoelectric performance. The photocurrent density was 14–20 times larger in our type-I and type-II heterostructures than in the pure SnS_2 and Bi_2X_3 . The photocurrent density and responsivity in the $\text{SnS}_2/\text{Bi}_2\text{X}_3$ heterostructures also exceeded those of SnS_2 -Pt [48], $\text{SnS}_2/\text{TiO}_2$ [49], and Te@Se [30] heterostructures (see Table 1). The minimum detectable power of the illumination, which decides the threshold of the photodetector, was quantified by the detectivity $D^* = R_{\text{ph}} \times S^{1/2} / (2q \times I_{\text{dark}})^{1/2}$, where q is the electron charge ($1.60 \times 10^{-19} \text{ C}$). The

calculated D^* values of the $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ and $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ heterostructures were 1.28×10^9 and 5.67×10^8 Jones, respectively, demonstrating a weak generated dark current and the strong advantages of the $\text{SnS}_2/\text{Bi}_2\text{X}_3$ heterostructures. Together, these results indicate a high photoresponsivity of the $\text{SnS}_2/\text{Bi}_2\text{X}_3$ heterostructures and the potential applicability of the heterostructures as PEC-type photodetectors.

The excellent PEC-type photodetector performances of the heterostructures are mainly conferred by the following factors: (i) an appropriate band gap allowing the sample to expand its light absorption range (Fig. 4d–f); (ii) band alignment of the heterostructure, which accelerates the carrier separation and transportation and prolongs the recombination of electron–hole pairs (Fig. 4g, h); and (iii) fast interface kinetics at the sample/solution interface, which slows both the surface charge accumulation and the recombination of electron–hole pairs [50]. The enhanced photoelectric response was further confirmed in open circuit potential (V_{OC}) measurements. The results are shown in Fig. 5d. The V_{OC} values of Bi_2Se_3 , Bi_2Te_3 , and SnS_2 were obtained as -0.211 , -0.192 , and -0.085 V , respectively. The V_{OC} raised in the heterostructures, and the maximum value was -0.316 V in $\text{SnS}_2/\text{Bi}_2\text{Se}_3$. Under light irradiation, photoexcited electrons are transferred and accumulated in the conduction band of the material, causing the Fermi level to drop to a negative potential. In the absence of excitation, these accumulated electrons bind to the receptor and inhibit the decline of V_{OC} . The results show that the generation, accumulation, and recombination behaviors of the light-excited electron–hole pairs were greatly improved in the heterostructures.

The fast interface kinetics in the heterostructures was further confirmed by the electrochemical impedance spectroscopy (EIS) within the frequency range of 0.01 Hz to 100 kHz . Fig. 5e shows the Nyquist plots of the samples under an open circuit voltage without light. The diameter of the semicircle represents the resistance of the charge crossing the electrode/electrolyte interface. In general, the smaller the diameter, the lower the interface resistance is [51]. The interface resistance can be revealed by constructing a complete equivalent circuit (Fig. 5e, inset). Here, R_{ct} , R_s , and CPE represent the charge-transfer resistance, the resistance of the electrolyte, and the double-layer capacitance at the electrode/electrolyte interface, respectively. The semicircle is related to R_{ct} and CPE at the electrode/electrolyte interface, where R_{ct} can be directly inferred from the semicircle diameter. The R_{ct} of the $\text{SnS}_2/\text{Bi}_2\text{X}_3$ heterostructures was smaller than those of SnS_2 and Bi_2X_3 , indicating lower resistance and higher charge-transfer efficiency between the $\text{SnS}_2/\text{Bi}_2\text{X}_3$ heterostructures and the electrolyte than between the single-component electrodes and electrolyte. The electron lifetime (τ_e) at the interface can be calculated as $\tau_e = 1 / (2\pi f_{\text{max}})$ [36,52]. Here, f_{max} is the characteristic peak frequency, which can be obtained from the Bode phase diagram presented in Fig. 5f. The peak frequencies of SnS_2 , Bi_2Se_3 , and Bi_2Te_3 were determined as 14.83, 8.25, and 10.05 Hz, respectively. The peak frequencies were considerably reduced in the $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ and $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ heterostructures, to 4.83 and 6.81 Hz, respectively. This result indicates a longer electron lifetime in the heterostructures than in SnS_2 , Bi_2Se_3 , and Bi_2Te_3 , thus confirming a lower electron–hole pair recombination rate at the photoelectrode/electrolyte interface in the heterostructures. Meanwhile, the properties of the photodetectors can be understood through the Mott–Schottky plot in Fig. 5g. The positive slope of the Mott–Schottky curve implies that these

Figure 5 (a) Schematic of the PEC measurement setup; (b) PEC linear scan voltammograms of different working electrodes based on SnS_2 , Bi_2X_3 , and the $\text{SnS}_2/\text{Bi}_2\text{X}_3$ heterostructures; (c) $J-t$ cycles of the different samples at a bias voltage of -0.1 V (relative to Ag/AgCl); (d) open circuit potentials of the different samples; (e) Nyquist plots of different samples and the equivalent circuit model (diagram); (f) Bode phase plots and (g) Mott-Schottky curves of different samples.

samples were n-type semiconductors. In addition, the x -intercept of the tangent to the Mott-Schottky curve gives the flat band potential (V_{FB}) of the sample. The V_{FB} of the $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ and $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ heterostructures were thus estimated as -1.03

and -0.97 V (vs. Ag/AgCl), respectively. The absolute values of these V_{FB} were larger than those of Bi_2Se_3 (-0.92 V), Bi_2Te_3 (-0.88 V), and SnS_2 (-0.86 V). These results suggest a large interface potential in the heterostructure, which promotes the

Table 1 Comparison of photocurrent densities and photoresponsivities of different materials

Materials	Preparation method	Measurement conditions	Photocurrent density	R_{ph}	Ref.
Bi_2Se_3	PVD	$0.2 \text{ mol L}^{-1} \text{ Na}_2\text{SO}_3$, -0.1 V	$12 \mu\text{A cm}^{-2}$	$170 \mu\text{A W}^{-1}$	This work
Bi_2Te_3	PVD	$0.2 \text{ mol L}^{-1} \text{ Na}_2\text{SO}_3$, -0.1 V	$9 \mu\text{A cm}^{-2}$	$130 \mu\text{A W}^{-1}$	This work
SnS_2	CVD	$0.2 \text{ mol L}^{-1} \text{ Na}_2\text{SO}_3$, -0.1 V	$10 \mu\text{A cm}^{-2}$	$140 \mu\text{A W}^{-1}$	This work
BP	Liquid-phase exfoliation	$0.2 \text{ mol L}^{-1} \text{ Na}_2\text{SO}_3$, -0.1 V	$0.64 \mu\text{A cm}^{-2}$	$2.2 \mu\text{A W}^{-1}$	[28]
InSe	Liquid-phase exfoliation	$0.2 \text{ mol L}^{-1} \text{ KOH}$, 1.0 V	$0.3 \mu\text{A cm}^{-2}$	$4.9 \mu\text{A W}^{-1}$	[29]
Bi_2S_3	Liquid-phase exfoliation	$1 \text{ mol L}^{-1} \text{ Na}_2\text{SO}_4$, 0.5 V	$0.6 \mu\text{A cm}^{-2}$	-	[47]
WSe_2	Liquid-phase exfoliation	$1 \text{ mol L}^{-1} \text{ Na}_2\text{SO}_4$, 0.8 V	$0.2 \mu\text{A cm}^{-2}$	-	[44]
$\text{SnS}_2/\text{Bi}_2\text{Te}_3$	PVD and CVD	$0.2 \text{ mol L}^{-1} \text{ Na}_2\text{SO}_3$, -0.1 V	$100 \mu\text{A cm}^{-2}$	$1430 \mu\text{A W}^{-1}$	This work
$\text{SnS}_2/\text{Bi}_2\text{Se}_3$	PVD and CVD	$0.2 \text{ mol L}^{-1} \text{ Na}_2\text{SO}_3$, -0.1 V	$170 \mu\text{A cm}^{-2}$	$2430 \mu\text{A W}^{-1}$	This work
$\text{SnS}_2/\text{TiO}_2$	In-situ synthesis	$0.5 \text{ mol L}^{-1} \text{ Na}_2\text{SO}_4$, 0 V	$10 \mu\text{A cm}^{-2}$	-	[49]
SnS_2 -Pt Nanoplates	Hot-injection	$0.5 \text{ mol L}^{-1} \text{ Na}_2\text{SO}_4$, 1.23 V	$112 \mu\text{A cm}^{-2}$	-	[48]
Te@Se	Epitaxial growth	$0.5 \text{ mol L}^{-1} \text{ KOH}$, 0.6 V	$11.6 \mu\text{A cm}^{-2}$	$98.8 \mu\text{A W}^{-1}$	[30]

effective charge-transfer process at the interface. The charge carrier density (N_D) of the photodetectors is given by [53]

$$N_D = \frac{2}{e\epsilon_0\epsilon_r} \left[\frac{dE}{d\left(\frac{1}{C^2}\right)} \right] \quad (7)$$

where $e = 1.6 \times 10^{-19} \text{ C}$ is the electron charge, ϵ_0 is the vacuum dielectric constant ($8.85 \times 10^{-14} \text{ F cm}^{-1}$), and ϵ_r is the relative permittivity of Bi_2X_3 , SnS_2 , or $\text{SnS}_2/\text{Bi}_2\text{X}_3$ [54,55]. The quantity $dE/d\left(\frac{1}{C^2}\right)$ can be calculated from the Mott-Schottky curves.

The calculated carrier densities of $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ ($\sim 5 \times 10^{24} \text{ cm}^{-3}$) and $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ ($\sim 3 \times 10^{24} \text{ cm}^{-3}$) were larger than those of Bi_2Se_3 ($\sim 1.8 \times 10^{24} \text{ cm}^{-3}$) and Bi_2Te_3 ($\sim 1.2 \times 10^{24} \text{ cm}^{-3}$). The Mott-Schottky measurements indicate that both the charge-transfer efficiency of carriers at the electrode/electrolyte interface and the carrier density were much higher in the heterostructures than in the single-component electrodes.

To explore the relationship between the photoresponsivity of the $\text{SnS}_2/\text{Bi}_2\text{X}_3$ heterostructures and the light wavelength, we measured the J - t curves at different wavelengths (420, 450, 475, 500, 520, 550, 600, and 650 nm). The wavelengths were changed by placing a filter in front of the light source. The light intensity was fixed at 10 mW cm^{-2} . The resulting J - t curves are plotted in Fig. 6a, b. The photocurrent density was much smaller under the individual wavelengths than under the whole light spectrum (Fig. 5c) because the irradiation intensity was weakened. To quantitatively analyze the wavelength-dependent photoresponsivity, the photocurrent density and photoresponsivity at each light wavelength were calculated by Equations (5) and (6), respectively, and the results are plotted in Fig. 6c, d. Both $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ and $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ were sensitive to 450 and 475 nm and achieved their highest light-response rate at 475 nm (2.60 and $1.67 \mu\text{A mW}^{-1}$, respectively). This result is attributable to the photon energy (2.6 eV@ 475 nm) being higher than the band gap energies of SnS_2 (2.22 eV), Bi_2Se_3 (0.72 eV), and Bi_2Te_3 (0.87 eV) (Fig. 4d-f). Therefore, 475 nm light can be readily absorbed by both SnS_2 and Bi_2X_3 . Importantly, as shown in the inserts of Fig. 6c, d, the $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ and $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ heterostructures also absorbed most strongly under 475 nm light. Therefore, the $\text{SnS}_2/\text{Bi}_2\text{X}_3$ heterostructures show great potential

in the photodetection of 475 nm light. The I_{ph} and R_{ph} were of the scale of $10 \mu\text{A cm}^{-2}$ and $10^3 \mu\text{A W}^{-1}$, respectively, larger than in other 2D materials such as GeP [4], Te@Se [30], and Bi/Te [56]. These improvements were related to the enhanced absorption.

To test the sensitivity and photoresponsivity of the photodetectors to different wavelength bands, we collected the J - t measurements in the wavelength bands $\geq 400 \text{ nm}$ and $\geq 700 \text{ nm}$ (changed by adding a bandpass filter). In the visible-to-infrared range of $\geq 400 \text{ nm}$ (Fig. 6e), the photocurrent density was higher in $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ ($134.1 \mu\text{A cm}^{-2}$) than in $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ ($78.2 \mu\text{A cm}^{-2}$), SnS_2 ($7.8 \mu\text{A cm}^{-2}$), Bi_2Se_3 ($9.9 \mu\text{A cm}^{-2}$), and Bi_2Te_3 ($12.1 \mu\text{A cm}^{-2}$). The R_{ph} of $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ and $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ were 2.48 and $1.44 \mu\text{A mW}^{-1}$, respectively, much larger than in SnS_2 ($0.14 \mu\text{A mW}^{-1}$), Bi_2Se_3 ($0.22 \mu\text{A mW}^{-1}$), and Bi_2Te_3 ($0.18 \mu\text{A mW}^{-1}$). These results confirm the superior photoelectric performances of the heterostructures. The higher R_{ph} in Bi_2Se_3 and Bi_2Te_3 is attributable to the larger number of photons that can be absorbed due to the lower band gap of Bi_2X_3 than that of SnS_2 . The higher R_{ph} of $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ and $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ than those of the pure components implies a wide absorption range and efficient electron-hole separation and transportation. In the visible-to-infrared range ($\geq 700 \text{ nm}$) (Fig. 6f), the photocurrent density remained higher in $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ ($20.0 \mu\text{A cm}^{-2}$) than in $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ ($12.6 \mu\text{A cm}^{-2}$), SnS_2 ($0.2 \mu\text{A cm}^{-2}$), Bi_2Se_3 ($1.9 \mu\text{A cm}^{-2}$), and Bi_2Te_3 ($1.7 \mu\text{A cm}^{-2}$). The calculated R_{ph} of $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ and $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ were 1.18 and $0.74 \mu\text{A mW}^{-1}$, respectively, much larger than those of Bi_2Se_3 ($0.11 \mu\text{A mW}^{-1}$) and Bi_2Te_3 ($0.10 \mu\text{A mW}^{-1}$). SnS_2 elicited almost no photoelectric response because it does not absorb in this wavelength range.

CONCLUSION

Type-I and type-II $\text{SnS}_2/\text{Bi}_2\text{X}_3$ heterostructures were successfully prepared by a combined CVD and PVD method and verified by high-resolution XPS. The photocurrent densities and photoresponsivities of the $\text{SnS}_2/\text{Bi}_2\text{X}_3$ heterostructures were at least one order of magnitude larger than those of SnS_2 and Bi_2X_3 over the whole solar region. This enhancement is due to the effective separation of electron-hole pairs and strong charge transportation performance at the heterostructure/electrolyte interface. EIS

Figure 6 (a, b) Transient photocurrent response curves of the $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ and $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ heterostructures under different wavelengths of light; (c, d) wavelength dependences of the photocurrent density (red) and photoresponsivity (blue) of the $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ and $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ heterostructures (insets show the absorption spectra of the heterostructures); (e, f) transient photocurrent response curves of the $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ and $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ heterostructures in different wavelength ranges.

and Mott–Schottky measurements confirmed that the charge transport efficiency at the photoelectrode/electrolyte interface was enhanced in the heterostructures. Moreover, the photoelectric performance was higher in the type-I $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ heterostructure than in the type-II $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ heterostructure, mainly due to the lower interface resistance and higher charge-transfer efficiency in the former. A PEC-type photodetector based on the vdW heterostructure showed high photoelectric performance, demonstrating the great potential of $\text{SnS}_2/\text{Bi}_2\text{X}_3$ heterostructures as photoelectric devices.

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构建I型 $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ 和II型 $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ 范德瓦尔斯异质结构提升其光电性能

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摘要 基于新型先进材料的异质结构为提高光电器件的光电性能奠定了基石。能带排列是理解异质结构中载流子输运机理和界面动力学的关键。本文利用物理气相沉积法和化学气相沉积法制备了 $\text{SnS}_2/\text{Bi}_2\text{X}_3$ ($\text{X}=\text{Se}, \text{Te}$)范德华异质结构。通过高分辨率X射线光电子能谱测量的能带排列证实了I型 $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ 和II型 $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ 异质结构的成功制备。基于 $\text{SnS}_2/\text{Bi}_2\text{X}_3$ 异质结构的光电化学型光电探测器的光电响应得到了极大的提高。I型 $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ 和II型 $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ 异质结构的光电流密度均比 SnS_2 、 Bi_2Se_3 和 Bi_2Te_3 的光电流密度高一个数量级以上。 $\text{SnS}_2/\text{Bi}_2\text{X}_3$ 异质结构光电性能的显著提高主要是由于: (i) 异质结构中光激发电子和空穴的有效分离; (ii) $\text{SnS}_2/\text{Bi}_2\text{X}_3$ 异质结构与电解质界面具有更高的电荷转移效率和载流子密度; (iii) 异质结构的构建拓宽了光的吸收范围。此外, 直立的 SnS_2 还可以有效地捕获光子以提高其光电性能。I型 $\text{SnS}_2/\text{Bi}_2\text{Se}_3$ 异质结构的光电性能优于II型 $\text{SnS}_2/\text{Bi}_2\text{Te}_3$ 异质结构, 这主要源于异质结构/电解质界面上更高效的电荷传输能力。实验研究结果表明, I型和II型异质结构的构建为开发高性能光电探测器及其他光电器件提供了新思路。