Ultrathin 2D ternary $\text{Bi}_2\text{Te}_2\text{Se}$ flakes for fast-response photodetectors with gate-tunable responsivity

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ABSTRACT Two-dimensional (2D) ternary materials have sprung up in a broad variety of optoelectronic applications due to their robust degree of freedom to design the physical properties of the materials through adjusting the stoichiometric ratio. However, the controlled growth of high-quality 2D ternary materials with good chemical stoichiometry remains challenging, which severely impedes their further development and future device applications. Herein, we synthesize ternary $\text{Bi}_2\text{Te}_2\text{Se}$ (BTS) flakes with a thickness down to 4 nm and a lateral dimension about 60 μm by an atmospheric-pressure solid source thermal evaporation method on a mica substrate. The phonon vibration and electrical transportation of 2D BTS are respectively investigated by temperature-dependent Raman spectrum and conductivity measurements. Furthermore, the photodetector based on 2D BTS exhibits excellent performance with a high light on/off ratio of 1300 (365 nm), a wide spectral response range from 365 to 980 nm, and an ultra-fast response speed up to 2 μs . In addition, its electrical and photoelectric properties can be modulated by the gate voltage, offering an improved infrared responsivity to 2.74 A W^{-1} and an on/off ratio of 2266 under 980 nm. This work introduces an effective approach to obtain 2D BTS flakes and demonstrates their excellent prospects in optoelectronics.

Keywords: 2D materials, ternary materials, $\text{Bi}_2\text{Te}_2\text{Se}$, photodetectors, field-effect transistors

INTRODUCTION

The unique physical properties and ultrathin nature of two-dimensional (2D) materials have opened up a new world to meet the highly desired miniaturization, func-

tionalization and flexibility of future electronic and optoelectronic devices [1–5]. With much more new 2D materials being excavated, there is a rapid growing trend in the development of 2D materials from single-element materials to multi-element systems [6–8]. Recently, theoretical and experimental investigations on 2D ternary materials are on the rise for their additional freedom by stoichiometry modulation [9–11]. The relatively diversiform combinations of elements and ratios not only generate a variety of crystal structures, but also bring about many novel characteristics for fascinating applications [12–14]. Therefore, it is significant and interesting work to develop new 2D ternary materials and study their unique electronic and optoelectronic properties.

$\text{Bi}_2\text{Te}_2\text{Se}$ (BTS), as an important member of 2D ternary Bi-based materials, has drawn increasing attention recently [15–17]. BTS has a similar crystal structure with Bi_2Se_3 and Bi_2Te_3 but different physical properties for the special atomic arrangement as shown in Fig. 1a [18,19]. The ordered stacking sequence of Te-Bi-Se-Bi-Te has the following three features [20–22]: (i) the Se atomic layer is sandwiched in the middle of the stacking, rather than exposing to the outermost, which could avoid the Se vacancy defects caused by evaporation; (ii) the Bi atoms prefer to bond with the Se atoms due to the stronger chemical interaction, which could suppress the anti-site defects coming from the Bi-Te bonding; (iii) the determined stoichiometric ratio and atomic occupancy minimize the other disorder defects resulting from Te/Se randomness. Hence, BTS is expected to have much fewer defects, in a sharp contrast to Bi_2Se_3 , Bi_2Te_3 , and $\text{Bi}_2\text{Te}_{3-x}\text{Se}$ ($0 < x < 3$, $x \neq 1$), resulting in a larger resistivity

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[23,24]. What is more, 2D BTS was theoretically predicted to have promising potentials for optoelectronic applications due to the good thermal and dynamical stability, suitable band gap, broad spectral absorption and high electron mobility [25–28]. However, there are few reports on optoelectronic properties of 2D BTS because of the absence of high-quality ternary BTS flakes confused by equivocal chemical stoichiometry, hybrid phases and lattice defects [9,29–31].

Here, 2D BTS flakes are successfully synthesized by an atmospheric-pressure solid source thermal evaporation method on a mica substrate. Through optimizing the thermal evaporation conditions of the bulk crystals of BTS source, we obtain the high-quality 2D BTS flakes with a thickness down to 4 nm and investigate the optoelectronic properties systematically. The 2D BTS photodetectors demonstrate excellent performance with a high light on/off ratio of 1300 (365 nm), broadband response from 365 to 980 nm, and fast response speed up to 2 μ s. In addition, photodetection performance could be flexibly modulated in the BTS field-effect transistors (FETs), in which the infrared response is further increased to 2.74 A W⁻¹ under 980 nm. Our work opens an avenue for new 2D ternary materials based on BTS flakes with outstanding performance and promising potentials for optoelectronic applications.

EXPERIMENTAL SECTION

Growth of bulk BTS crystals

Bulk BTS crystals were prepared by a modified Bridgman method [21,23,28]. The high-purity (Alfa Aesar, 99.999%) Bi powder, Te powder and Se powder with a molar ratio of 2:2:1 were mixed intensively and vacuum sealed into a clean quartz tube under a pressure of 10⁻² bar (1 bar = 10⁵ Pa). Then the quartz tube was heated in a muffle furnace with a two-stage heating program. The temperature was first set to 850°C with a ramping time and holding time of 5 and 24 h, respectively, to ensure the mixture in a molten state. Then the temperature was lowered to 550°C slowly and kept at this temperature for a week to anneal the BTS crystal before natural cooling down to room temperature. It is worth noting that the slow cooling rate and annealing procedures are the keys to the minimization defects of Se vacancies for the high-quality BTS crystal [23].

Growth and characterizations of 2D BTS flakes

The as-prepared bulk BTS was used as the evaporation source and put in the center of a quartz tube (diameter

1 inch). The fresh cleaved mica substrates were placed on a quartz plate at the downstream (11–15 cm) of the tube. Before the heating, repeat evacuation and flush were first carried out with high-purity Ar (99.99%) to exhaust air of the quartz tube. Then, the furnace was set to 650°C with the ramping time and holding time of 25 and 30 min, respectively, and finally cooled down to room temperature naturally. During the growth, the whole system was under an atmospheric pressure with 50 sccm Ar (99.99%) as carrier gas.

The as-grown BTS flakes were evaluated by optical microscope (BX53M, OLYMPUS), atomic force microscope (AFM, Dimension Icon, Bruker), X-ray diffraction (XRD, D2 phaser, Bruker), transmission electron microscope (TEM, Technai G2 F30, FEI), field emission scanning electron microscope (SEM, Quanta 650 FEG, FEI) and confocal Raman spectroscopy (Alpha 300RS+, WI-Tec) equipped with cryogenic control console.

Transfer process of 2D BTS flakes

The BTS samples on mica were firstly spin-coated with polymethyl methacrylate (PMMA) solution at 500 r min⁻¹ for 5 s and 4000 r min⁻¹ for 60 s, then baked at 150°C for 5 min. In order to separate the BTS flakes from the mica, the whole substrate was immersed in a dilute HF solution (~2%) and heated at 60°C for 1 h. Next, the PMMA film carrying BTS flakes was slowly peeled off from mica, rinsed in deionized water several times, and carefully transferred onto a SiO₂/Si substrate to avoid the folds and bubbles. Then the whole substrate was dried at 100°C for 1 h to enhance the adhesion with the BTS flakes, and finally the PMMA was removed by immersing in acetone.

Device fabrication and measurement

After the BTS was transferred from the mica to SiO₂/Si substrate, the contact electrodes were patterned by a standard electron-beam lithography (EBL) (Quantum FEG 650, FEI, and Elphy Plus, Raith) and underwent deposition of Cr/Au (10/90 nm) by electron-beam evaporation on a Nexdep platform (Angstrom Engineering). The electronic and photoelectronic measurements were carried out in a probe station (CRX-6.5K, Lakeshore) with a semiconductor system (4200-SCS, Keithley). Lasers of different wavelengths (365, 532, 680, 808, 980 nm) with tunable power intensity were used as light source after being calibrated by a powermeter (FieldMaxll-TO, Coherent).

RESULTS AND DISCUSSION

Ternary BTS has a layered rhombohedral structure, in

which units of quintuple layers (QL) stack continuously through weak van der Waals interactions [24,25]. And the stacking sequence of each QL is Te-Bi-Se-Bi-Te with strong covalent bonding, as shown in Fig. 1a [27,32]. The special atomic arrangement, in which Se atoms are sandwiched in the center and Te atoms are exposed outside, portends its unique properties compared with binary Bi_2X_3 ($\text{X} = \text{Se}, \text{Te}$) [20,33]. In order to obtain the high-quality 2D ternary BTS flakes and avoid the defects from element segregation, we used an improved atmospheric-pressure thermal evaporation method with BTS bulk crystals as the evaporation source [27,34]. Therefore, the stoichiometric BTS bulk crystal was firstly prepared and confirmed by theoretical XRD pattern (Fig. S1), and then placed in the hot center of the quartz tube as source materials (Fig. 1b). The freshly cleaved fluorophlogopite mica [$\text{KMg}_3(\text{AlSi}_3\text{O}_{10})\text{F}_2$] with an atomic flat surface was used as the grown substrate [14,35]. With the help of the carrier gas (high-purity Ar), uniformly distributed large-area triangular BTS flakes were successfully obtained (Fig. 1c) and the largest lateral size could reach up to

60 μm (Fig. 1d). The thickness of a typical flake was determined at about 4 nm (~ 4 QL) by AFM as shown in Fig. 1e. The XRD spectrum (Fig. 1f) of the flakes transferred from the mica to SiO_2/Si substrate is matched well with the standard BTS pattern (PDF #29-0248) [21], which verifies the as-grown samples. The consistent plane orientation (0001) indicated the prior orientation along the c -axis. Furthermore, high-resolution TEM (HRTEM) and the selected-area electron diffraction (SAED) (Fig. 1g) confirm the high crystallinity of BTS flake with the exact lattice spacing (0.214 nm for (11 $\bar{2}$ 0)) in the equilateral triangle, which is between that of Bi_2Te_3 (0.221 nm) [36] and Bi_2Se_3 (0.207 nm) [19]. The uniform element distribution was also proved by the element mapping in Fig. 1h. Therefore, high-quality ultrathin BTS flakes were obtained by our atmospheric-pressure solid source thermal evaporation method, which is critical for subsequently studying the physical properties and photoelectric performance.

Raman spectroscopy is an effective tool to investigate the materials' characteristics including crystal structure,

Figure 1 Characterization of 2D BTS flakes. (a) Crystal structure of layered BTS. (b) Schematic of the growth of BTS flakes with the bulk BTS as the source. (c, d) Optical microscopy images. (e) AFM image of the as-grown BTS flake on mica. (f) XRD pattern of the transferred BTS flakes on the SiO_2/Si substrate. (g) HRTEM image and the corresponding SAED pattern and (h) the element mappings (Bi, Te, Se) of a BTS flake.

lattice symmetry, molecular vibration mode and relative interaction between layers [37–39]. The ternary BTS demonstrates similar vibration modes (A_{1g}^1 , E_g^2 , A_{1g}^2) as binary Bi_2X_3 [19,35,40,41] with three observable peaks as shown in Fig. 2a. With the addition of Te, all phonon peaks shift to higher energy in agreement with the transition from Bi_2Se_2 to Bi_2Te_3 due to the heavier Te atoms compared with Se atoms [21,40]. Under the scanning of 532-nm laser, the clear and uniform mapping result based on the peak intensity of A_{1g}^1 (Fig. 2b) indicates the homogeneity distribution of stoichiometric BTS flakes. It should be noted that the BTS flake could display hexagonal or truncated triangle morphology for the different growth rate of each facet caused by the local growth environment [30,42]. The Raman and SEM measurements of the flake with hexagonal morphology are shown in Fig. S2, which confirm the hexagonal morphology samples are

high-quality BTS flakes, too.

Furthermore, we carried out the temperature-dependent Raman investigation of BTS flakes from 80 to 300 K. With decreasing temperature, absence of additional peaks indicates that the crystal structure is stable over the test temperature range, which is beneficial to the practical application of 2D BTS at low temperatures. On the other hand, both the E_g and A_g peaks demonstrated obvious blue-shift (stiffen) as the temperature decreased to 80 K (Fig. 2c). In fact, the variation of phonon frequency was influenced by the anharmonicity of the phonon modes and change of crystal volume under different temperatures [43,44]. When the temperature decreased, the anharmonicity vibration weakened and the crystal lattice shrunk, resulting in the blue-shift of the peak positions in Raman spectroscopy [19]. Then we extracted the Raman peak positions (ω) at different temperatures (T) and plotted them in Fig. 2d. We linearly fitted the ω with the

Figure 2 Raman investigation of BTS flakes. (a) Raman spectrum and the corresponding atomic vibrational patterns of BTS flake at room temperature. (b) Raman mapping of A_{1g}^1 phonon mode. (c) Temperature-dependent Raman spectra and (d) the corresponding peak position evolution under different temperatures.

formulate [43]:

$$\omega(T) = \omega_0 + \chi T, \quad (1)$$

where the longitudinal intercept ω_0 equals to the Raman peak position at 0 K, the slope χ is the first-order temperature coefficient and related to the interlayer interaction of layered materials [45]. The χ of A_{1g}^1 , E_g^2 , A_{1g}^2 were about -0.01687 , -0.01935 and $-0.00996 \text{ cm}^{-1} \text{ K}^{-1}$, respectively, which are bigger than those of MoS_2 (-0.0136 of E_g^2) [43] and Bi_2Se_3 (-0.00538 of A_{1g}^1 , -0.01089 of E_g^2 , -0.00544 of A_{1g}^2) [19] due to the stronger van der Waals interaction of BTS compared with that of MoS_2 and Bi_2Se_3 .

To explore the electrical transport mechanism, we conducted the temperature-dependent electrical measurement with the BTS flake. The optical microscopy image of the tested device on the SiO_2/Si substrate is shown in Fig. S3a. A standard EBL and electron-beam evaporation technology were used to prepare the Cr/Au (10/90 nm) electrodes. The thickness of the transferred

BTS was about 8 nm (Fig. S3b). Fig. 3a demonstrates the temperature-dependent I - V curves from 80 to 300 K. The slopes of the curves raised monotonically with increasing temperature, which agreed with the typical semiconductor behavior. We plotted the extracted conductivity (σ) as a function of temperature ($1000/T$) in Fig. 3b to study the temperature-dependent conductance in the vacuum [46] and found that the conductivity could be well fitted with a double exponential Arrhenius equation as following [47]:

$$\sigma = \sigma_1 \exp\left(-\frac{E_1}{K_B T}\right) + \sigma_2 \exp\left(-\frac{E_2}{K_B T}\right), \quad (2)$$

where K_B , σ_1 and σ_2 refer to Boltzmann constant and conductivity pre-factors under different situations, respectively. The relevant activation energies E_1 and E_2 were calculated to be 210.3 and 21.8 meV, which indicates two different activation mechanisms in the thermal activation process [48]. According to the relationship between conductivity and temperature, we excluded the transport contribution of the strong phonon scattering, in which

Figure 3 Electrical characteristics of BTS flakes. (a) Temperature-dependent I - V curves of an individual flake and (b) the corresponding conductivity under different temperatures. (c) $\ln(\sigma T)$ - T^{-1} plot by optical hopping fitting. (d) $\ln(\sigma)$ - $T^{-0.25}$ plot with variable-range hopping fitting.

the current tended to decrease with the rise of temperature [46]. Considering the optical phonon excitation theory of small-polaron hopping, the change of conductivity with temperature follows the following formula [48]:

$$\sigma = \left(\frac{v_0 e^2 c (1-c)}{K_B T r} \right) \exp \left(\frac{-\Delta E}{K_B T} - 2mr \right), \quad (3)$$

where v_0 , e , c , m and r refer to the longitudinal optical phonon frequency, elementary charge, the fraction of sites occupied by electrons, the average hopping distance and the rate of wave-function decay, respectively. By fitting the points of Fig. 3c, the activation energies ΔE is about 98.5 meV in the range from 200 to 300 K. However, when the temperature below 200 K, the energy of optical phonons is too low to promote the carrier hopping. Therefore, Davis and Mott [48] proposed a variable-range hopping mechanism to supplement the electrical transmission at low temperatures. As shown in Fig. 3d, the conductivity at $T < 200$ K demonstrates close fitting

by the corresponding equation [48]:

$$\sigma = \sigma_0 \exp \left(- \left(\frac{T_0}{T} \right)^{1/4} \right), \quad (4)$$

where σ_0 and T_0 are both constants. Hence, the conduction mechanism of 2D BTS is dominated by optical phonon excitation of small-polaron hopping at room temperature. It may introduce photogate current in the 2D BTS photodetector by the trapping effect of the small polaron [49]. And the relatively small ΔE (98.5 meV) indicates the small fluctuation of conductivity with various temperatures and favors the practical application of 2D BTS-based photodetector in a broad temperature range [46,50].

After discussing the electrical transport mechanism, we further explored the photoelectrical properties of the 2D BTS flakes. Considering the narrow band gap of BTS based on theoretical reports [25], we firstly studied its broadband photodetection under various wavelengths of light with similar intensity as shown in Fig. 4a. The I - V

Figure 4 Photoresponse characteristics of BTS flakes. (a) Schematic illustration of the BTS photodetector on SiO_2/Si . (b) I - V curves and (c) the corresponding photoresponse under light with different wavelengths from 365 to 980 nm at $V_{\text{ds}} = 5$ V (the inset: band diagram of BTS photodetector under illumination). (d) Photoresponse to the on/off laser irradiation of 980 nm. (e) I - V curves and (f) the corresponding photoresponse under 365-nm illumination with varying light intensities. (g) The dependence of photodetector photocurrent and (h) responsivity and on/off ratio on light intensity under 365-nm illumination. (i) Rise and decay curve of the device under 365 nm.

curves under 365 to 980 nm (Fig. 4b) demonstrate obvious photoresponse compared with dark current. The corresponding time-resolved photocurrent is illustrated in Fig. 4c, which confirms the ability of broadband detection and stability of the dynamic response. When the BTS photodetector is excited by the light ($E_{hv} > E_{g, \text{BTS}}$), a large number of photogenerated electron-hole pairs move towards the opposite electrodes and contribute additional channel current which is dominated by the photoconductive effect. On the other hand, a small part of minority carriers (hole in BTS) trapped in the defects of BTS would act as local gates and increase the electron concentration of channel (photogate effect), as shown in the inset of Fig. 4c [14]. The best photodetection performance on the ultraviolet band (365 nm) is attributed to the high photogenerated-carrier concentration under high light energy E_{hv} . On the other hand, the BTS device also demonstrates the competitive performance on the infrared light detection. Fig. 4d shows the time-resolved photoresponse behavior under 980-nm illumination with periodically repeated on/off operation, which indicates the good reproducibility and stability of the BTS photodetector at infrared wavelengths.

Next, we chose the detection results based on the 365-nm laser to discuss the photoresponse performance in detail. The I - V curves and the corresponding photoresponse at 365 nm under varied light intensities are shown in Fig. 4e and f. It is clear that the channel current gradually increases as the light power varies from 1.83 to 12.47 mW cm⁻² due to the increase of photogenerated carriers. The extracted power-dependent photocurrent (I_{ph}) is plotted in Fig. 4g and fitted with formula [51]: $I_{ph} = \alpha P^\theta$. The exponential factor θ was calculated to be 0.49, which also indicated that the photocurrent generation mechanism of our BTS photodetector included photoconductive and photogate effect [14]. And the trapping sites may come from the impurities at the interface between BTS flakes and substrate, or the charge impurity states inside the transported flakes [46,52]. What is more, we calculated the responsivity (R) of the BTS photodetector according to the formula [51]: $R = I_{ph}/PS$, where S is the effective channel area estimated to be 44 μm^2 as shown in Fig. S3. Together with the light on/off ratio, we plotted these results in Fig. 4h. The highest responsivity was 8.53 A W⁻¹ achieved at the low light intensity (1.83 mW cm⁻²) and the light on/off ratio could reach up to 1300 when the $P = 12.47$ mW cm⁻². To accurately evaluate the photoresponse speed of the BTS device, the dynamic response was demonstrated in Fig. 4i with the laser switching frequency of 10 kHz. As shown in the

result, a fast rise and decay speed about 2 μs were achieved, which is much faster than most 2D photodetectors [19,34,53–55]. What is more, the BTS detector also demonstrated high-performance photoresponse with similar fast response speed under 532 to 980 nm illumination (Fig. S4). The responsivity and on/off ratio of BTS flake under 980 nm illumination with different light intensities were calculated in Fig. S5, in which the light on/off ratio and responsivity could reach to 1658 and 0.058 A W⁻¹ without gate voltage (V_g).

As an important cornerstone of integrated electronic devices, FET is considered to be a potential application field of emerging 2D materials [56]. The gate voltage provides an effective method for the modulation of electronic and optoelectronic characteristics, which could be used for our BTS device as shown in the inset of Fig. 5a. From the transfer curves, a typical n -type conductivity behavior was demonstrated in the BTS flake (Fig. 5a) with an on/off ratio of about 10³. The corresponding output curves (Fig. 5b) clearly present the regulation effect, in which the current gradually increased when the V_g varied along a positive direction, resulting in the accumulation of the electrons. In order to evaluate the field-effect mobility of the 2D BTS flakes, we also measured the transfer curve of BTS flake at a low temperature (80 K) as shown in Fig. S6. When the V_g was swept from -50 to 50 V, the mobility (μ) of BTS flake was calculated by the equation [14]:

$$\mu = \frac{L}{CW} \times \frac{dI_{ds}}{dV_g} \times \frac{1}{V_{ds}}, \quad (5)$$

where L and W are the length and width of the device, C is the capacitance of 300 nm SiO₂ equal to 11.57 nF cm⁻¹ [14]. The field-effect mobility of BTS flake was calculated to be 0.736 cm² V⁻¹ s⁻¹, which was relatively smaller than that of Bi₂Se₃ [19] and Bi₂Te₃ [57] due to the low carrier concentration and high resistivity of the 2D BTS flake and the defects introduced in the growing and wet transfer process [52,58].

Finally, we took the near-infrared light (980 nm) as an example to study the gate modulation effect to the performance of BTS photodetector. Fig. 5c shows the transfer curves of FET under different light intensities at 980 nm. Under the test range of V_g , the device still kept excellent photoresponse and demonstrated significant improvement when V_g turned to positive value. With the modulation of back gate, the light on/off ratio of BTS flake could be further improved to 2266 (Fig. S7). We extracted the photocurrent and responsivity under different light intensities with the help of the gate modula-

Figure 5 Gate-tunable electrical and photoresponse characteristics of the BTS flakes. (a) Transfer curves of the BTS transistor under different V_{ds} . The inset is the schematic structure of an FET device. (b) Output curves of the device. (c) Transfer curves of the FET under different light intensities at 980 nm. (d) The light intensity-dependent photocurrent and responsivity at 980 nm with $V_g = 50$ V and $V_{ds} = 5$ V.

tion ($V_g = 50$ V) in Fig. 5d. The photocurrent and responsivity would reach up to 31.67 nA and 2.74 A W^{-1} , respectively. The comparison of infrared photoresponse performance between our BTS and other 2D materials is summarized in Table S1. The competitive values in both light on/off ratio, responsivity and response time indicate the 2D BTS is a promising candidate material for high-performance photodetectors due to the special stacking sequence and low dark current.

CONCLUSIONS

In summary, we successfully synthesized high-quality 2D Bi-based ternary BTS flakes by an atmospheric-pressure solid source thermal evaporation method and investigated their optoelectronic properties. The temperature-dependent Raman spectrum and conductivity measurements indicate the strong interlayer interaction and good conductivity of 2D BTS flakes. Impressively, the 2D BTS-based photodetector demonstrated excellent photoresponse performance like high light on/off ratio (1300) at 365 nm, wide spectral response (365–980 nm),

and ultra-fast response speed (2 μs). What is more, the photoresponse performance could be further improved in the BTS transistors, in which the responsivity and on/off ratio under 980 nm could reach to 2.74 A W^{-1} and 2266, respectively. Our results display a new possibility of the 2D BTS flakes in the application of electronic and optoelectronic devices.

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Author contributions Luo P and Zhai T conceived the idea; Zhai T supervised the project; Luo P carried out materials synthesis, device fabrication and most of the measurements. Wang F and Feng X performed the AFM and Raman characterizations; Luo P wrote the paper; Zhai T revised the paper. All authors discussed the results and commented on the manuscript.

Conflict of interest The authors declare that they have no conflict of interest.

Supplementary information Experimental details and supporting data are available in the online version of the paper.

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超薄二维三元Bi₂Te₂Se纳米片用于响应度栅压可调的快速响应光电探测器

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摘要 二维(2D)三元材料近年来如雨后春笋般兴起, 由于其物理性质能够通过调整化学计量比来实现自由设计而被认为在光电子学中具有重要的应用前景. 然而, 具有良好化学计量比的高质量二维三元材料的可控制备仍然面临挑战, 严重阻碍了它们进一步的发展和在未来器件中的应用. 本文中, 我们通过一种常压固体源热蒸发法在云母衬底上制备了厚度薄至4 nm, 横向尺寸约为60 μm的三元Bi₂Te₂Se (BTS)薄片. 通过变温拉曼光谱和导电性测量研究了二维BTS的声子振动和电传输特性. 进一步地, 基于二维BTS的光电探测器表现出优异的光电响应特性, 其光开关比在365 nm光照下约为1300, 光谱响应范围宽至365–980 nm, 同时其响应速度快至2 μs. 此外, 栅极电压能够有效调控BTS的电输运和光电性能, 从而将980 nm下的红外响应度和光开关比提高至2.74 A W⁻¹和2266. 我们的工作介绍了一种有效获得二维BTS薄片的方法, 并展示了其在光电领域良好的应用前景.