Research article

Rui Cao^a, Ye Zhang^a, Huide Wang, Yonghong Zeng, Jinlai Zhao, Liyuan Zhang, Jianqing Li*, Fanxu Meng, Zhe Shi, Dianyuan Fan and Zhinan Guo*

Solar-blind deep-ultraviolet photodetectors based on solution-synthesized quasi-2D Te nanosheets

<https://doi.org/10.1515/nanoph-2019-0539>

Received December 23, 2019; revised January 6, 2020; accepted January 7, 2020

Abstract: Solar-blind deep ultraviolet (DUV) photodetectors with high responsivity (R) and fast response speed are crucial for practical applications in astrophysical analysis, environmental pollution monitoring, and communication. Recently, 2D tellurium has emerged as a potential optoelectronic material because of its excellent photoelectric properties. In this study, solar-blind DUV photodetectors are demonstrated based on solution-synthesized and air-stable quasi-2D Te nanosheets (Te NSs).

An R of 6.5×10^4 A/W at 261 nm and an external quantum efficiency (EQE) of higher than $2.26 \times 10^6\%$ were obtained, which are highest among most other 2D material-based solar-blind DUV photodetectors. Moreover, the photoelectric performance of the quasi-2D Te-based photodetector exhibited good stability even after ambient exposure for 90 days without any encapsulation. These results indicate that quasi-2D Te NSs provide a viable approach for developing solar-blind DUV photodetectors with ultrahigh R and EQE.

Keywords: quasi-2D Te nanosheets; photodetector; solar-blind deep ultraviolet; FET.

^a**Rui Cao and Ye Zhang:** These authors contributed equally to this work.

*Corresponding authors: Jianqing Li, Faculty of Information Technology Macau University of Science and Technology Avenida Wai Long, Taipa, Macau 999078, P.R. China, e-mail: jqli@must.edu.mo; and Zhinan Guo, Institute of Microscale Optoelectronics, International Collaborative Laboratory of 2D Materials for Optoelectronics Science and Technology, Key Laboratory of Optoelectronic Devices and Systems of Ministry of Education and Guangdong Province, College of Physics and Optoelectronic Engineering, Shenzhen Key Laboratory of Micro-Nano Photonic Information Technology, Guangdong Laboratory of Artificial Intelligence and Digital Economy (SZ), Shenzhen University, Shenzhen 518060, P.R. China, e-mail: guozhinan@szu.edu.cn. <https://orcid.org/0000-0002-6548-8516>

Rui Cao: Faculty of Information Technology Macau University of Science and Technology Avenida Wai Long, Taipa, Macau 999078, P.R. China; Institute of Microscale Optoelectronics, International Collaborative Laboratory of 2D Materials for Optoelectronics Science and Technology, Key Laboratory of Optoelectronic Devices and Systems of Ministry of Education and Guangdong Province, College of Physics and Optoelectronic Engineering, Shenzhen Key Laboratory of Micro-Nano Photonic Information Technology, Guangdong Laboratory of Artificial Intelligence and Digital Economy (SZ), Shenzhen University, Shenzhen 518060, P.R. China; and Institute for Quantum Science and Engineering and Department of Physics, Southern University of Science and Technology, Shenzhen 518055, P.R. China
Ye Zhang, Yonghong Zeng, Fanxu Meng, Zhe Shi and Dianyuan Fan: Institute of Microscale Optoelectronics, International Collaborative Laboratory of 2D Materials for Optoelectronics Science and

Technology, Key Laboratory of Optoelectronic Devices and Systems of Ministry of Education and Guangdong Province, College of Physics and Optoelectronic Engineering, Shenzhen Key Laboratory of Micro-Nano Photonic Information Technology, Guangdong Laboratory of Artificial Intelligence and Digital Economy (SZ), Shenzhen University, Shenzhen 518060, P.R. China

Huide Wang: Institute of Microscale Optoelectronics, International Collaborative Laboratory of 2D Materials for Optoelectronics Science and Technology, Key Laboratory of Optoelectronic Devices and Systems of Ministry of Education and Guangdong Province, College of Physics and Optoelectronic Engineering, Shenzhen Key Laboratory of Micro-Nano Photonic Information Technology, Guangdong Laboratory of Artificial Intelligence and Digital Economy (SZ), Shenzhen University, Shenzhen 518060, P.R. China; and Institute for Quantum Science and Engineering and Department of Physics, Southern University of Science and Technology, Shenzhen 518055, P.R. China

Jinlai Zhao: Faculty of Information Technology Macau University of Science and Technology Avenida Wai Long, Taipa, Macau 999078, P.R. China; and Institute of Microscale Optoelectronics, International Collaborative Laboratory of 2D Materials for Optoelectronics Science and Technology, Key Laboratory of Optoelectronic Devices and Systems of Ministry of Education and Guangdong Province, College of Physics and Optoelectronic Engineering, Shenzhen Key Laboratory of Micro-Nano Photonic Information Technology, Guangdong Laboratory of Artificial Intelligence and Digital Economy (SZ), Shenzhen University, Shenzhen 518060, P.R. China

Liyuan Zhang: Institute for Quantum Science and Engineering and Department of Physics, Southern University of Science and Technology, Shenzhen 518055, P.R. China

1 Introduction

The discovery of graphene, the first 2D material, in 2004 [1], led to 2D materials attracting widespread attention because of their unique photoelectric properties, such as strong light absorption [2–4], high light sensitivity [5, 6], fast light response speed [7–9], and wide light response range [10, 11]. Recently, tellurium, a new 2D material, which is a member of the chalcogen element family and a well-known p-type semiconductor with a narrow band gap energy of 0.35 eV at room temperature exhibiting intriguing properties, has attracted the attention of scientists [12–16]. Ye et al. demonstrated that solution synthesized air-stable quasi-2D Te nanosheets (Te NSs) can be applied as the basic materials for field-effect transistors (FETs) [17]. The prepared FETs exhibited air-stable performance at room temperature for more than 2 months, on/off ratios in the order of 10^6 , and field-effect mobilities of approximately $700 \text{ cm}^2/\text{V s}$. Then, Wang et al. reported a high photoresponsivity and flexible photodetector based on van der Waals epitaxy synthesized 2D hexagonal Te nanoplates on a flexible mica substrate for the first time; the fabricated photodetector exhibited excellent stability and photoresponsivity that reached 389.5 A/W [17]. Amani et al. exhibited short-wave infrared photodetectors based on solution-synthesized environmentally stable quasi-2D Te nanofilms, the peak photoresponsivity of which can be adjusted from $1.4 \mu\text{m}$ (13 A/W) to $2.4 \mu\text{m}$ (8 A/W), and up to $3.4 \mu\text{m}$ [18]. Recently, Xie et al. demonstrated a high photoresponse electrochemical photodetector based on liquid phase exfoliation synthesized 2D nonlayered Te NSs for ultraviolet (UV) (350 nm) and visible light (475 nm) [19]. This indicates that despite the band gap of Te NSs being 0.35 eV, it can obtain UV light response.

Further, UV radiation of wavelength shorter than $\sim 280 \text{ nm}$ from sunlight cannot penetrate the atmosphere and reach the surface of the earth; $200\text{--}280 \text{ nm}$ is typically referred to as the solar-blind spectrum region. Benefiting from advances in the semiconductor industry in the past few decades [20, 21], UV light detection, specifically solar-blind deep-ultraviolet (DUV) photodetection, has become an important subject in recent years because of its significant applications in various fields, including remote control, chemical analysis, flame detection, missile warning system, and secure space-to-space communication [22–26]. Recently, the optical absorption coefficients of bulk $\beta\text{-Te}$ and few-layer $\beta\text{-tellurenes}$ were systematically calculated by Wu et al. [27]. Moreover, layer-dependent absorption of layered $\beta\text{-tellurenes}$ has been obtained, and it has been found that absorption of few-layer $\beta\text{-tellurenes}$ begins at 175 nm to the visible region. In particular, the peak of absorptivity occurs in blue-violet visible regions.

All these results indicate that layered $\beta\text{-Te}$ is suitable for DUV light detection.

In this study, the optical and optoelectronic properties of solution-synthesized quasi-2D Te NSs are experimentally studied. Both the absorption and the photoresponse results confirm that quasi-2D Te NSs are solar-blind DUV sensitive materials. The experimental results demonstrate that the Te NS-based FETs exhibit an ultrahigh responsivity (R) of $6.5 \times 10^4 \text{ A/W}$, a remarkable external quantum efficiency (EQE) of $2.26 \times 10^6\%$, and a high detectivity (D^*) of $3.73 \times 10^8 \text{ Jones}$ in the solar-blind band (261 nm), which indicate the great potential of Te NSs for high-performance solar-blind DUV photodetectors.

2 Experimental section

2.1 Synthesis of quasi-2D Te nanosheets

Following a typical synthesis procedure, Na_2TeO_3 of 96 mg and polyvinyl pyrrolidone of 1 g ($M_w \sim 30,000$) were first dissolved in 75 ml deionized water, which was then subjected to magnetic stirring for 30 min to form a homogeneous solution. Then, 10 ml of ammonium hydroxide (25%, wt/wt%) solution and 5 ml of hydrazine monohydrate (80%, wt/wt%) were added to the obtained homogeneous solution, and stirring was prolonged for another 10 min. Subsequently, the mixture was transferred to a 100 ml Teflon-lined autoclave and placed in an oven at 160°C for 24 h. After the autoclave cooled to the room temperature, the obtained product (of silver-gray color) was washed with deionized water three times by centrifugation at 2000 rpm for 20 min. The final product was placed in a vacuum oven at 80°C overnight for the next procedure.

2.2 Characterization

The morphologies and dimensions of the synthesized Te NSs were identified using SEM (SU8010; Hitachi, Tokyo, Japan) and TEM (FEI Tecnai G2 F30, Hillsboro, OR, USA). The AFM measurements were performed using Dimension Icon (Bruker Dimension Ico, Karlsruhe, Germany) under the tapping mode under ambient conditions. The UV-Vis-NIR absorption spectra were obtained using a UV-Vis-NIR absorbance spectrometer (Cary 60; Agilent, Santa Clara, CA, USA). The Raman data were obtained using the Horiba Jobin-Yvon LabRAM HR-VIS high-resolution confocal Raman microscope (Horiba Instruments, Beijing, China) equipped with a 633 nm laser as the illumination source and an XYZ motorized sample stage controlled by

the LabSpec software. The laser spot size on the surface of the sample was about 1 μm after focusing through a $50\times$ objective lens with a numerical aperture of 0.90. The XRD analysis was performed using the X'Pert Pro-MPD diffractometer (Malvern, UK) with a $\text{Cu } K_\alpha$ ($\lambda = 1.7903 \text{ \AA}$) radiation source at room temperature.

2.3 Electrical and optoelectronic measurements

The electrical properties of the Te FET were evaluated using the Keithley 4200 Semiconductor characteristic analyzer system (Keithley 4200 SCS, Cleveland, OH, USA) along with a probe station in ambient environment. A standard three-probe method was used to measure the optoelectronic properties of the device. The light source was a fixed wavelength semiconductor laser, and the continuous laser was a separately fixed frequency discontinuous laser with a chopper (time interval: 10 s). The source and drain poles were connected to two electrodes, and the other probe was connected to silicon to provide the back gate. The source and drain voltages were in the range of -1 V to 1 V , back gate was 3 V , and the photocurrent was finally read using Keithley 4200 SCS.

2.4 Stability measurements

The photodetectors were stored in a clean room (the humidity was 49% and temperature was 22°C), and the stability measurements of the photodetectors were taken on day 22, day 66, and day 90, respectively.

3 Results and discussion

Quasi-2D Te NSs, with a thickness of approximately 20 nm, were synthesized (with a small modification) via the facile hydrothermal method based on a former report by Ye et al., the details of which can be found in the Experimental section [17]. The crystal structure of Te, as shown in Figure 1A and B, is highly anisotropic, and the chains of Te are oriented along the c -axis and band together by strong van der Waals forces. Each Te atom shares covalent bonds with its nearest atoms with a systematic arrangement in a helical chain [28]. Figure 1B shows the 3D structure of Te, viewed along the $[001]$ direction; in addition, zigzag layers can be seen, which are banded via weak van der Waals forces. The scanning electron microscopy (SEM) image of Te NSs reveals irregular shapes of lengths in the order

of tens of micrometers and widths of a few micrometers (Figure 1C). Figure 1D shows the transmission electron microscopy (TEM) image of a section of Te NSs, and the corresponding high-resolution TEM (Figure 1E) image shows the continuous crystal lattice of the synthesized Te NSs with a lattice constant of 0.196 nm, which can be assigned to the (003) plane of Te. The inset in Figure 1E shows the selected area electron diffraction (SAED) pattern of the Te NS, and the typical bright diffraction spots correspond to the (001), (110), and (013) planes of Te, which verify that the synthesized Te NS has a single-crystalline structure. Figure 1F shows the atomic force microscopy (AFM) image of a Te NS of thickness 18.9 nm. An obvious absorption peak located at 278 nm can be detected in the ultraviolet-visible (UV-Vis) spectrum (Figure 1G), which can be attributed to the direct transition from band to band. In addition, four vibrational modes at 92 cm^{-1} , 105 cm^{-1} , 121 cm^{-1} , and 141 cm^{-1} can be found in the Raman spectrum (Figure 1H), which correspond to the E_1 -TO, E_1 -LO, A_1 , and E_2 modes of Te NSs, respectively, and are consistent with previous reports [29, 30]. The X-ray diffraction (XRD) pattern in Figure 1I shows the characteristic peaks of the synthesized Te NSs, which are similar to those in the simulated reference (PDF No# 36-1452) [31]. The UV-Vis absorption and the Raman and XRD results confirm the successful synthesis of quasi-2D Te NSs.

Figure 2A shows a 3D schematic of the Te NS photodetector. In this image, the source/drain electrodes are in direct contact with the Te NSs, and the current is generated by the bias voltage (V_d) applied across the two electrodes, which flows through the Te NS channel and is modulated by the back-gate voltage (V_g) applied to the p^+ -doped Si substrate. The surface morphology of the Te NSs was measured by AFM. As shown in Figure 2B, the thickness of the few-layered quasi-2D Te NSs is approximately 20 nm. The $I_{ds}-V_{ds}$ curves of the device in the dark condition were measured at various V_g values from -5 to 5 V (Figure 2C), indicating that the device current can be tuned using the back-gate voltage. The representative transfer curves (I_d-V_g) of the device at $V_d = 1 \text{ V}$ are shown in Figure 2D, which indicate a carrier mobility of approximately $100 \text{ cm}^2/\text{V s}$ and an on/off ratio of 10 in the Te NS-based transistor.

The characteristics of the Te NS-based photodetectors were further studied by examining the photoconductivity effect under various illumination wavelengths of 261–405 nm. The performance of the UV photodetection of the Te NS-based photodetectors can be evaluated by the output current under illumination at different powers. Figure 3 shows the I - V curves of the Te NS photodetectors under different light excitation powers of 261 nm (0.08 nW, 0.12 nW, and 0.14 nW in the dark). Figure 3A shows that the photocurrent increases gradually

Figure 1: Crystal structure of Te viewed from the (A) x-axis and (B) z-axis. (C) SEM and (D) TEM images of Te NSs. (E) HR-TEM image and the corresponding SAED pattern of Te NSs. (F) AFM image of a typical Te NS of thickness 18.9 nm. (G–I) UV-Vis absorption, and Raman and XRD spectra of Te NSs.

with increasing illumination power density, which can be attributed to the increase in the number of photons from the incident light. Under intense illumination, more photogenerated electron-hole pairs are generated in Te, which are driven to the electrodes in different directions guided by the drain-source electric field, resulting

in a larger channel current. The laser power-dependent photocurrent curves are shown in Figure 3B. The photocurrent displays a positively related dependence on the applied V_{ds} , implying that a larger photocurrent can be readily obtained by increasing V_{ds} . Figure 3C–E show the R, EQE, and D^* curves of Te NS photodetectors under

Figure 2: The structure and electronic characterization of the Te NS FET.

(A) Schematic of the Te FET. (B) AFM image of the Te NSs photodetector (scale bar: 5 μm). (C) I_{ds} - V_{ds} curves of the device in the dark measured at various V_g from -5 to 5 V by applying a voltage on Si. (D) I_{ds} - V_{gs} curves of the device in the dark measured at $V_d = 1$ V.

Figure 3: Optoelectronic characterization of the Te NS photodetector by illumination at 261 nm.

(A) I_{ds} - V_{ds} curves of the Te NS photodetector obtained in dark and with illumination at various excitation intensities (0.08 nW, 0.12 nW, and 0.14 nW) at $V_g = 3$ V. (B) I_p - V_{ds} curves of the Te NS photodetectors for different excitation powers with illuminations of 0.08 nW, 0.12 nW, and 0.14 nW, which exhibit a linear dependence on the bias ($V_g = 3$ V). (C) Responsivity of the Te NS photodetector vs. light illumination power. (D) EQE of Te NS photodetector vs. light illumination power. (E) D^* of the Te NS photodetector vs. light illumination power. (F) I - t response curve under an illumination of 261 nm, $P = 0.14$ nW, and $V_{ds} = 1$ V. Inset: dynamic response of the Te NS photodetector during on/off of the incident light with a temporal resolution.

different illumination powers, which can be calculated using the equations provided in the equation section in Supporting Information. Furthermore, R is an important parameter to evaluate the performance of photodetectors. Figure 3C shows that R decreases with the increase in illumination power. Remarkably, the responsivity of the Te NS photodetectors reached up to $\sim 6.5 \times 10^4$ A/W with an illumination power of 0.08 nW at 261 nm. The EQE reflects the ratio of the number of photon-excited charge carriers and incident photons per unit time. The Te NSs based on photodetectors of EQE for DUV illumination (261 nm) on the incident illumination power density are presented in Figure 3D, which reveals that the photodetector exhibits an EQE of $2.26 \times 10^6\%$, when $P = 0.08$ nW and $V_{ds} = 3$ V. The high EQE of the Te NS photodetectors, which exceeds 100%, can be attributed to the additional gain inside the quasi-2D Te NSs. The carrier transit time in Te was calculated to be 1.36 ns, using the formula $\tau = L^2/(\mu V_{ds})$, where L is the distance between source-drain separation ($L = 3.7$ μm , $\mu = 100$ $\text{cm}^2/\text{V s}$, $V_{ds} = 1$ V), which is significantly less than the carrier lifetime of Te, according to the time-dependent photocurrent, as shown in Figure 3F (on the order of seconds). Therefore, a large internal gain exists in the Te NS photodetector, resulting in $\text{EQE} > 100\%$. In

addition to R and EQE, D^* is another key factor for a photodetector that describes the detection limit for a weak illumination signal. Figure 3E presents the relationship of D^* with V_d of a Te NS photodetector under different illumination powers. When the power of a 261 nm light is 0.08 nW ($V_{ds} = 3$ V), D^* is 3.73×10^8 Jones. It can thus be concluded that the R and EQE of the Te photodetector in the solar-blind DUV band are highest among those of the previously reported similar detectors, as shown in Table S1; however, D^* is relatively low.

Based on the dynamic response of the device to the on/off condition of laser (Figure 3F and inset), the rising and falling times were measured as ~ 2 s and ~ 5 s, respectively. Moreover, the photodetection performance of the Te NS photodetector under the UV bands of 360 nm and 405 nm was further investigated, and the results are shown respectively in Figures S1 and S2. The results indicate that the device exhibits good power-dependent photoelectric response to lasers of 360 nm and 405 nm, as well as high R and EQE.

The results of power-dependent photocurrent are summarized in Figure 4 to further investigate the performance of the Te NS photodetector. As shown in Figure 4A, under an illumination of 261 nm, the photocurrent at $V_d = 3$

Figure 4: Photoresponse of the Te NS photodetector at 261 nm.

(A) Power dependence of photocurrent. (B) Responsivity vs. laser illumination power with an excitation wavelength of 261 nm. (C) EQE vs. laser illumination power with an excitation wavelength of 261 nm, which indicates the high sensitivity of the device. (D) D^* vs. laser illumination power with an excitation wavelength of 261 nm.

Figure 5: Aging characterization of the Te NS photodetector under ambient conditions.

Photodetection of the Te NS photodetector at 261 nm. (A) Responsivity of the Te NS photodetector at $V_g = 3$ V. (B) EQE of the Te NS photodetector at $V_g = 3$ V. (C) D^* with the measured bias at $V_g = 3$ V.

V increases monotonically with the increase in illumination power from 0.08 nW to 0.14 nW. Moreover, R decreases from 6.5×10^4 A/W to 3.9×10^4 A/W, EQE decreases from $2.2 \times 10^6\%$ to $1.3 \times 10^6\%$, and D^* decreases from 3.7×10^8 Jones to 2.2×10^8 Jones with the increase in illumination power from 0.08 nW to 0.14 nW. The decrease in R , EQE, and D^* with the increase in light power could be attributed to hole-trapping saturation. The corresponding parameters of the device under light illuminations of 360 nm and 405 nm are shown in Figures S3 and S4, respectively. The R , EQE, and D^* of the Te NS photodetector as functions of illumination power decrease linearly, and their trends are consistent with those at 261 nm.

The long-term stability of photodetectors under ambient conditions is another important property for evaluating these devices [32–35]. To evaluate the stability of the device under ambient conditions, the photoelectric performance of the Te NS photodetector at different intervals was investigated. Optoelectronic measurement results were obtained from devices that had been exposed to air with a relative humidity of 90% at 22°C. The R , EQE, and D^* values of the Te NS photodetector are shown in Figure 5A–C. Although a small decline in photoresponse performance is observed initially for a few days, the R , EQE, and D^* remain almost constant at 2.19×10^4 A/W, $7.55 \times 10^5\%$, and 1.24×10^8 Jones, respectively, for as long as 90 days. Furthermore, these values are higher than those of most other 2D material-based DUV photodetectors, as shown in Table S1. These results indicate that the Te photodetectors can maintain long-term and stable high-performance under ambient conditions.

4 Conclusions

In this study, a UV photoconductive detector was fabricated based on quasi-2D Te NSs on a SiO_2/Si substrate

with high responsivity over a broad UV spectral range of 261–405 nm. A responsivity of 6.5×10^4 A/W at a solar-blind DUV band, an EQE of more than $2.26 \times 10^6\%$, and a high detectivity of 3.73×10^8 Jones were obtained, which are highest among those of other 2D material-based solar-blind DUV photodetectors. Moreover, the Te NS DUV photodetector was found to be stable for a long time (as long as 90 days), when exposed to air with a relative humidity of 90% at 22°C without any encapsulation. The findings of this study indicate that quasi-2D Te NSs can provide a viable approach for future ultrahigh-responsivity and ultrahigh-EQE solar-blind DUV photodetectors.

Acknowledgments: This study was supported by the National Natural Science Foundation of China (61605131 and 61905157); Natural Science Foundation of Guangdong Province for Distinguished Young Scholars (2018B030306038); The Science and Technology Innovation Commission of Shenzhen (KQJSCX20180328095501798, JCYJ20180507182047316); The Postdoctoral Research Foundation of China (Grant No. 2019M653017); The Educational Commission of Guangdong Province (2016KCXTD006); and The Science and Technology Development Fund, Macao SAR, China (Nos. 007/2017/A1 and 132/2017/A3). Authors also acknowledge the support from Instrumental Analysis Center of Shenzhen University.

References

- [1] Novoselov KS, Geim AK, Morozov SV, et al. Electric field effect in atomically thin carbon films. *Science* 2004;306:666–9.
- [2] Wu L, Dong Y, Zhao J, et al. Kerr nonlinearity in 2D graphdiyne for passive photonic diodes. *Adv Mater* 2019;31:1807981.
- [3] Lu L, Tang X, Cao R, et al. Broadband nonlinear optical response in few-layer antimonene and antimonene quantum dots: a prom-

- ising optical Kerr media with enhanced stability. *Adv Opt Mater* 2017;5:1700301.
- [4] Song Y, Chen S, Zhang Q, et al. Vector soliton fiber laser passively mode locked by few layer black phosphorus-based optical saturable absorber. *Optics Exp* 2016;24:25933–42.
  - [5] Yang J, Yu W, Pan Z, et al. Ultra-broadband flexible photodetector based on topological crystalline insulator SnTe with high responsivity. *Small* 2018;14:1802598.
  - [6] Gan X, Shiue R-J, Gao Y, et al. Chip-integrated ultrafast graphene photodetector with high responsivity. *Nat Photon* 2013;7:883–7.
  - [7] Yin Y, Cao R, Guo J, et al. High-speed and high-responsivity hybrid silicon/black-phosphorus waveguide photodetectors at 2 μm . *Laser Photon Rev* 2019;13:1900032.
  - [8] Youngblood N, Li M. Ultrafast photocurrent measurements of a black phosphorus photodetector. *Appl Phys Lett* 2017;110:051102.
  - [9] Mueller T, Xia F, Avouris P. Graphene photodetectors for high-speed optical communications. *Nat Photon* 2010;4:297–301.
  - [10] Ye L, Li H, Chen Z, Xu J. Near-infrared photodetector based on MoS_2 /black phosphorus heterojunction. *ACS Photon* 2016;3:692–9.
  - [11] Jiang Y, Miao L, Jiang G, et al. Broadband and enhanced non-linear optical response of MoS_2 /graphene nanocomposites for ultrafast photonics applications. *Sci Rep* 2015;5:16372.
  - [12] Coker A, Lee T, Das TP. Investigation of the electronic properties of tellurium – energy-band structure. *Phys Rev B* 1980;22:2968–75.
  - [13] Bottom VE. The hall effect and electrical resistivity of tellurium. *Science* 1952;115:570–1.
  - [14] Liu J, Zhu J, Zhang C, Liang H, Yu S-O. Mesostuctured assemblies of ultrathin superlong tellurium nanowires and their photoconductivity. *J Am Chem Soc* 2010;132:8945–52.
  - [15] Lee TI, Lee S, Lee E, et al. High-power density piezoelectric energy harvesting using radially strained ultrathin trigonal tellurium nanowire assembly. *Adv Mater* 2013;25:2920–5.
  - [16] Huang W, Zhang Y, You Q, et al. Photodetectors: enhanced photodetection properties of tellurium@selenium roll-to-roll nanotube heterojunctions (*Small* 23/2019). *Small* (Weinheim an der Bergstrasse, Germany) 2019;15:e1900902.
  - [17] Wang Y, Qiu G, Wang R, et al. Field-effect transistors made from solution-grown two-dimensional tellurene. *Nat Electron* 2018;1:228–36.
  - [18] Amani M, Tan C, Zhang G, et al. Solution-synthesized high-mobility tellurium nanoflakes for short-wave infrared photodetectors. *ACS Nano* 2018;12:7253–63.
  - [19] Xie Z, Xing C, Huang W, et al. Ultrathin 2D nonlayered tellurium nanosheets: facile liquid-phase exfoliation, characterization, and photoresponse with high performance and enhanced stability. *Adv Funct Mater* 2018;28:1705833.
  - [20] Sang L, Liao M, Sumiya M. A comprehensive review of semiconductor ultraviolet photodetectors: from thin film to one-dimensional nanostructures. *Sensors* 2013;13:10482–518.
  - [21] Zeng LH, Wang MZ, Hu H, et al. Monolayer graphene/germanium Schottky junction as high-performance self-driven infrared light photodetector. *ACS Appl Mater Interf* 2013;5:9362–6.
  - [22] Razeghi M. Short-wavelength solar-blind detectors-status, prospects, and markets. *Proc IEEE* 2002;90:1006–14.
  - [23] Pearton SJ, Yang J, Cary PH, et al. A review of Ga_2O_3 materials, processing, and devices. *Appl Phys Rev* 2018;5:011301.
  - [24] Zhang ZX, Zeng LH, Tong XW, et al. Ultrafast, self-driven, and air-stable photodetectors based on multilayer PtSe_2 /Perovskite heterojunctions. *J Phys Chem Lett* 2018;9:1185–94.
  - [25] Razeghi M. III-Nitride optoelectronic devices: from ultraviolet toward terahertz. *IEEE Photon J* 2011;3:263–7.
  - [26] Liao M, Koide Y, Alvarez J, Imura M, Kleider J-P. Persistent positive and transient absolute negative photoconductivity observed in diamond photodetectors. *Phys Rev B* 2008;78:1098–121.
  - [27] Wu BZ, Liu XH, Yin JR, Lee H. Bulk $\beta\text{-Te}$ to few layered $\beta\text{-tellurenes}$: indirect to direct band-gap transitions showing semiconducting property. *Mater. Res. Express* 2017;4:095902.
  - [28] Doi T, Nakao K, Kamimura H. The valence band structure of tellurium. I. The $k \cdot p$ perturbation method. *J Phys Soc Japan* 1970;28:36.
  - [29] Pine AS, Dresselhaus G. Raman spectra and lattice dynamics of tellurium. *Phys Rev B* 1971;4:356–71.
  - [30] Wang Q, Safdar M, Xu K, Mirza M, Wang Z, He J. Van der Waals epitaxy and photoresponse of hexagonal tellurium nanoplates on flexible mica sheets. *ACS Nano* 2014;8:7497–505.
  - [31] Cherin P, Unger P. Two-dimensional refinement of the crystal structure of tellurium. *Acta Crystall* 1967;23:670–1.
  - [32] Guo Z, Chen S, Wang Z, et al. Metal-ion-modified black phosphorus with enhanced stability and transistor performance. *Adv Mater* 2017;29:201703811.
  - [33] Cao R, Wang HD, Guo ZN, et al. Black phosphorous/indium selenide photoconductive detector for visible and near-infrared light with high sensitivity. *Adv Opt Mater* 2019;7:1900020.
  - [34] Xing C, Jing G, Liang X, et al. Graphene oxide/black phosphorus nanoflake aerogels with robust thermo-stability and significantly enhanced photothermal properties in air. *Nanoscale* 2017;9:8096–101.
  - [35] Zhao J, Zhu J, Cao R, et al. Liquefaction of water on the surface of anisotropic two-dimensional atomic layered black phosphorus. *Nat Commun* 2019;10:1–7.

Supplementary Material: The online version of this article offers supplementary material (<https://doi.org/10.1515/nanoph-2019-0539>).