Raman Anisotropy and Polarization-Sensitive Photodetection in 2D Bi$_2$O$_2$Se–WSe$_2$ Heterostructure

Lin Tao,† Sina Li,† Bin Yao, Mengjia Xia, Wei Gao, Yujue Yang,*, Xiaozhou Wang,*, and Nengjie Huo*  

ABSTRACT: Two-dimensional (2D) bismuth oxyselenide (Bi$_2$O$_2$Se) has attracted increasing attention due to its high mobility, tunable band gap, and air stability. The surface reconstruction of cleaved Bi$_2$O$_2$Se due to the electrostatic interlayer interactions can lead to the in-plane anisotropic structure and physics. In this work, we first discovered the strong anisotropy in phonon modes through the angle-resolved polarized Raman (ARP) spectra. Benefiting from the anisotropic feature, a high-performance polarization-sensitive photodetector has been achieved by constructing a heterostructure composed of the multilayer Bi$_2$O$_2$Se as polarized-light sensitizers and 2D WSe$_2$ as a photocarrier transport channel. The detectors exhibit broadband response spectra from 405 to 1064 nm along with high responsivity, fast speed, and high sensitivity owing to the photogating effect in this device architecture. More importantly, the photocurrent shows strong light polarization dependence with the maximum dichroism ratio of 4.9, and a reversal is observed for the angle-dependent photocurrent excited by polarized 405 and 635 nm light. This work provides new insight in terms of optical and photocurrent anisotropy of exfoliated Bi$_2$O$_2$Se and expands its applications in angle-resolved electronics and optoelectronics.

INTRODUCTION

For the two-dimensional (2D) materials with an in-plane anisotropic crystalline structure, the electronic and band structures show high dependence on orientations, leading to the strong anisotropy in effective mass, optical absorption, and electrical transport, giving rise to the unique feature of linear dichroism in these classes of materials. The linear dichroism endows them as promising platforms for angle-resolved optoelectronic applications such as polarization spectroscopy imaging, polarized photodetectors, and optical radar. In the past, the optical media with meta-surface structures have been widely utilized to manipulate the light phase and polarization, while the complex and costly manufacturing process is the limiting factor for practical applications. Due to the geometric anisotropy, the one-dimensional (1D) nanowires or nanobelts such as ZnO, InP, and Sb$_2$S$_3$ can also exhibit the linear dichroism effect and capability of polarization photodetection; however, the small aspect ratios hamper the dichroism ratio and limit the diversity of device fabrication.

Recently, the low-symmetric 2D materials have emerged as centers for polarization-dependent optical and electrical applications due to their intrinsic in-plane anisotropic properties. For example, the black phosphorus (b-P) with a puckered honeycomb structure has shown the distinct anisotropy in optical absorption, photoluminescence (PL), carrier mobility, and thermoelectric transport, realizing the polarization-sensitive photodetectors, field-effect transistors, etc. Inspired by the anisotropic feature of b-P, the black arsenic (b-As) from the same group V was also reported to exhibit in-plane optical and electrical anisotropy with a dichroism ratio of 2.68 in electron mobility. In addition, the germanium selenide (GeSe), germanium arsenic (GeAs), and low-symmetry transition-metal dichalcogenides (TMDs) such as T$_2$-WTe$_2$, 1T-MoTe$_2$, ReSe$_2$, and ReSe$_2$ have also been established as anisotropic material systems possessing strong linear dichroism. On the other hand, highly symmetric 2D materials such as graphene and 2H-TMDs with a hexagonal crystal structure have been regarded as in-plane isotropy lacking the potential in polarization-dependent applications.

As new emerging 2D ternary materials, layered bismuth oxyselenide (Bi$_2$O$_2$Se) has been rapidly developed with great success in electronic and optoelectronic applications including field-effect transistors, near-infrared photodetectors, thermal electronics, and topological quantum devices, benefitting from their ultrahigh mobility, outstanding stability, and tunable band gaps. The electron mobility can reach as high as 20 000 cm$^2$/V s at low temperature and 450 cm$^2$/V s at room temperature, enabling the detection of Shubnikov–de Haas quantum oscillations. The corresponding photodetectors exhibited broadband, highly sensitive, and ultrafast photo-detection performance from near-infrared to terahertz. Although a fascinating development, the linear dichroism and
polarized electronics based on Bi₂O₂Se have been rarely studied and remain elusive.

As we know, Bi₂O₂Se belongs to a body-centered tetragonal phase (I4/mmm) group with strong anisotropy, consisting of positively charged [Bi₂O₂]ⁿ⁺⁺ layers that are alternately sandwiched with the negatively charged [Se]ⁿ⁻⁻, as shown in Figure 1a. Different from other van der Waals (vdW) layer materials, the interaction between [Bi₂O₂]ⁿ⁺⁺ and [Se]ⁿ⁻⁻ is the electrostatic force instead of vdW force,²⁸ making it hard to be mechanically exfoliated. Currently, the chemical vapor deposition (CVD) method is the most common approach to obtain the thin and large-area Bi₂O₂Se with the lateral size of up to hundreds of micrometers.²⁵,²⁹,₃₀ We note that the CVD-grown samples have atomically smooth surfaces; in contrast, the Bi₂O₂Se samples obtained through the cleavage method show a complicated surface reconstruction due to the existence of interlayer electrostatic interactions, which led to the difference in surface morphology and band structure.³¹ When the crystal is mechanically cleaved, 50% of the Se atoms are attached to each Bi plane because of the electroneutrality requirement.³² Through the scanning tunneling spectroscopy, the interlinked weave pattern of Se vacancies and morphology of steps have been observed on the Bi₂O₂Se surface,³₂ which can offer an opportunity for exploring unique physical properties and device functionality. For example, the strong surface reconstruction due to the interlayer electrostatic force can result in a remarkable spontaneous in-plane anisotropy and electric polarization.³³

In this work, we prepared the multilayer Bi₂O₂Se using the mechanically exfoliated method. Through the angle-resolved polarized Raman spectroscopy (ARPR), we first discovered the significant anisotropic Raman modes of the exfoliated Bi₂O₂Se. The intensities of Raman modes show a marked periodic feature (180°) with a two-lobed shape. Furthermore, Bi₂O₂Se as a photosensitive layer has been integrated with WSe₂ layers acting as a photocarrier channel, the constructed heterostructures exhibit high polarization-sensitive photodetection performance. The dichroism ratio of photocurrent for 405 and 635 nm light can reach 2.2 and 4.9, respectively. It is interesting that the orientations at which the photocurrent under 405 and 635 nm polarized light reach the maximum are 0 and 90°, respectively, implying the optical reversal of linear dichroism when switching light from 405 to 635 nm. This is consistent with the predicted polarization-resolved absorption spectra where the linear dichroism reversal also occurs.³³ Due to the photogating effect at the interface and a suitable band gap of Bi₂O₂Se, the devices also exhibit broadband photoresponse ranging from 405 to 1064 nm with a high responsivity of 44 A/W, fast speed of less than 20 ms, and high detectivity of up to 3 × 10¹⁵ Jones. The first observation of Raman anisotropy and high-performance polarized-light photodetection can make layered Bi₂O₂Se promising candidates for angle-dependent optoelectronic applications.

### RESULTS AND DISCUSSION

The multilayer Bi₂O₂Se was exfoliated on the Si/SiO₂ substrate and then transferred on top of the WSe₂ layers (Figure 1b). The clear diffraction selected area electron diffraction (SAED) pattern is observed (Figure S1), demonstrating the high crystalline quality of the Bi₂O₂Se nanosheets. The detailed process can be seen in the Experimental Section. The purpose of constructing the heterostructure is to form the out-of-plane built-in field at the interface, inducing the photogating effect for highly efficient photodetection, which will be discussed.
later. Figure 1c shows the Raman spectra of Bi$_2$O$_2$Se, WSe$_2$, and their heterostructures. The Raman peaks located at 158.8 and 252 cm$^{-1}$ are ascribed to the A$_{1g}$ mode of Bi$_2$O$_2$Se and WSe$_2$, respectively, which is consistent with previous reports.34,35 The PL spectrum was obtained under the excitation of a 532 nm laser, showing a strong PL peak at 920 nm (Figure 1d), corresponding to an indirect optical band gap of multilayer WSe$_2$, while the PL is absent in Bi$_2$O$_2$Se layers. In the heterostructures, the thickness of the Bi$_2$O$_2$Se and WSe$_2$ layers is 36.6 and 68.2 nm from AFM images as shown in Figure 1e,f, respectively.

Angle-resolved polarized Raman spectroscopy (ARPR) has been regarded as a facile technique to identify the anisotropic crystal structure. To further investigate the crystal structure symmetry and the electron–phonon interactions on the surface of Bi$_2$O$_2$Se, we performed the ARPR measurement with both parallel and cross-polarization configurations. To realize this, we inserted a linear polarizer in front of the Raman detection system and detected the scattered light along the parallel or perpendicular to the incident light polarization. The ARPR was measured by rotating the sample with 30° steps. The rotation angle $\theta$ is defined as the angle between the a-axis and laser polarization direction, and Figure S2 shows the optical microscopy images of the Bi$_2$O$_2$Se sample under each rotation angle from 0 to 330°.

Figure 2a,b shows the Raman spectra for Bi$_2$O$_2$Se at different rotation angles under the parallel and cross-polarized configuration, respectively. Figure 2c,d shows the polarized Raman mapping at different rotation angles from 0 to 330° under parallel and cross-polarization configuration, respectively.

Figure 3a Schematic diagram of Bi$_2$O$_2$Se/WSe$_2$ heterostructure devices. (b) KPFM of the heterostructure at the interface. (c, d) Band diagram of the heterostructure before and after contact, respectively.

Figure 3. (a) Schematic diagram of Bi$_2$O$_2$Se/WSe$_2$ heterostructure devices. (b) KPFM of the heterostructure at the interface. (c, d) Band diagram of the heterostructure before and after contact, respectively.
one pronounced Raman peak at 159.7 cm$^{-1}$ is observed, while two Raman peaks at 159.73 and 158.07 cm$^{-1}$ appear under cross configuration. In both cases, we found that the intensities of these $A_{1g}$ modes present a strong correlation with rotation angles, indicating the in-plane anisotropic phonon vibration and lattice structure. The Raman intensities were then extracted to be plotted in polar coordinates as shown in Figure 2e,f. The data were well fitted using the formula

$$b(\theta) = b_{\text{min}} \sin^2(\theta + \varphi) + b_{\text{max}} \cos^2(\theta + \varphi)$$

where $\theta$ is the angle of the linear polarization laser. $b_{\text{min}}$ and $b_{\text{max}}$ are the minimum and maximum fitting parameters, respectively. The Raman intensities of $A_{1g}$ mode show a period of 180° with a two-lobed shape under both configurations. The dichroism ratios defined as the ratio of maximum intensity at 0° divided by the minimum value at 90° are 3.6 and 3.2 for parallel or cross-polarized configuration, respectively.

To further investigate the potential application of the novel linear dichroism feature, we then assembled the Bi$_2$O$_2$Se nanoflakes with multilayer WSe$_2$ and fabricated the heterostructure-based photodetectors as shown in Figure 1b. The architecture of this device is shown in Figure 3a, the underlying WSe$_2$ can act as a photocarrier transport layer and top Bi$_2$O$_2$Se acts as polarization-sensitive layers. We note that the photoconductor based on individual exfoliated Bi$_2$O$_2$Se has poor photoresponse due to the extremely high dark current, which can hamper the study of the polarized light detection. Thus, the purpose of constructing heterostructure structure is to introduce the photogating effect for highly efficient photodetection. Under light illumination, the photons are absorbed by Bi$_2$O$_2$Se and the excited electron−hole pairs are separated under the built-in electric field (Figure 3d). The holes are transferred into the WSe$_2$ channel layers and the electrons reside in top Bi$_2$O$_2$Se, resulting in the photogating effect. Within the lifetime, the holes can recirculate multiple times in the channel before recombining with electrons, leading to a large photo gain. A similar scheme is also reported in 2D/0D hybrids and 2D MoS$_2$ with an out-of-plane homojunction.

We then performed the photodetection measurement using the lasers with different wavelength and power densities at room temperature and ambient environment. Figure 4a−c shows the dynamic photoresponse of the device under laser irradiation with wavelengths of 405, 635, and 808 nm, respectively. (d, e) Time-dependent photoresponse as a function of light power density under 405 and 635 nm light, respectively. (f) Photocurrent as a function of light power density. The solid curves are the power-law fitting.
as $I_{\text{light}}/I_{\text{dark}}$ can reach $10^3$ and $10^4$ for 405 and 635 nm light, respectively, as a result of low dark current, implying a high sensitivity. The device can also respond to the near-infrared laser with wavelength of 980 and 1064 nm as shown in Figure S4 (Supporting Information) due to the small band gap of Bi$_2$O$_2$Se layers, indicating a broad spectral coverage from 405 to 1064 nm. In addition, the photocurrent mapping of the photodetector is also measured (Figure S5), showing the strong photocurrent at the area between drain electrodes and the Bi$_2$O$_2$Se layer.

The measured time-dependent photoresponse as a function of light power density under 405 and 635 nm light is shown in Figure 4d,e, respectively, demonstrating gradually decreased photocurrent with decreasing light power. The photocurrent is then extracted and plotted in Figure 4f. The curves are fitted by the power-law equation of $I_{\text{ph}} \sim P^\varphi$, where $P$ is the laser power and $\varphi$ is the fitting exponent. We can see that the exponents $\varphi$ are fitted to be $\sim0.66$ and $\sim0.75$ for 405 and 635 nm light, respectively, indicating a highly efficient conversion efficiency from incident photons to collected electron–hole pairs.

As key figures of merit for photodetectors, the responsivity ($R$), external quantum efficiency (EQE), and detectivity ($D^*$) are also evaluated as follows

$$R = I_{\text{ph}}/P \times S$$

$$\text{EQE} = \frac{h \times R \times C}{e \times \lambda}$$

![Figure 5](image-url) (a) Responsivity, (b) EQE, and (c) detectivity as functions of light power density for 405 and 635 nm light.

![Figure 6](image-url) (a, b) Photocurrent as a function of polarization angles for the 405 and 635 nm light. (c) Same as (a, b) but in polar coordinates. (e, f) Mapping plot of $I$–$V$ curves at 405 and 635 nm light with varying light polarization angles.
where  is the photocurrent,  is the effective area of the detector,  is the optical power density,  is the Planck constant,  is the unit charge,  is the incident wavelength,  is the speed of light, and  is the dark current.

Figure 5a shows  as a function of light power densities for 450 and 635 nm light. In both cases,  increases with increased light power owing to the gradual saturation of the photosensing states in the heterostructure. The  can reach up to 43 and 44 A/W for 405 and 635 nm, respectively, at weak light illumination. The EQE as a function of light power density is shown in Figure 5b, the maximum EQE up to 1.3 × 10^4 and 8.6 × 10^3% can be achieved for 405 and 635 nm, respectively. The high responsivity results from the huge photogain due to the existence of the photogating effect in the heterostructure as discussed above. The detectivity  is a common figure of merit to characterize the sensitivity of a detector with the unit of cm Hz^{1/2}/W or Jones. The  of the device at 405 and 635 nm light is shown in Figure 5c, which can reach up to 6.2 × 10^{12} Jones at 405 nm light and 3.1 × 10^{13} Jones at 635 nm light, exceeding the sensitivity of most photodetectors based on 2D materials. The  and  for the light wavelength of 808, 980, and 1064 nm as a function of light power have also been performed as shown in Figure 5d, demonstrating moderate performance.

From the angle-resolved polarized Raman, Bi2O2Se has an anisotropic in-plane crystal structure, the polarization absorption spectrum has also been measured, indicating that exfoliated Bi2O2Se flakes have the linear dichroism in the visible light (Figure S7), which can enable a polarization-sensitive photodetection. To investigate the polarization sensitivity of the heterostructure device under the polarized light illumination, we performed the measurement using the 405 and 635 nm polarized light achieved through a polarizer. The polarization angle was varied by rotating the polarizer with 30° steps. Figure 6a,b shows photocurrent as a function of polarization angles at V_{DS} of 1 V for the 405 and 635 nm light, exhibiting the periodic variations with varying polarization angles. However, the angle-varied photocurrent exhibits different phases with a difference of about 90° for the 405 and 635 nm light. Based on the data, the angle-dependent photocurrent is plotted in polar coordinates (Figure 6c,d), showing a two-lobed shape with a period of 180°, which is consistent with the periodicity of Raman modes. It is interesting that the angle at which the photocurrent reaches the maximum is 0° for 635 nm and 90° for 405 nm, which may be attributed to the reversal of linear dichroism of Bi2O2Se. To further confirm the reversal of polarized photocurrent, we prepared other heterostructures with thicker Bi2O2Se. The angle-dependent photocurrents for 405 and 635 nm light are shown in Figure S8 (Supporting Information), also demonstrating polarization-sensitive photocurrent and reverse phenomenon. A similar phenomenon of reversal in optical absorption and anisotropic photocurrent has also been observed in GeAs-based polarized photodetectors. The dichroism ratio of photocurrent, defined as the value of maximum photocurrent divided by the minimum photocurrent, is calculated to be 2.2 and 4.9 for 405 and 635 nm light, respectively, which implies a high polarization-sensitive performance and is at par with that of other 2D low-symmetric materials. Figure 6e,f shows the mapping plot of I–V curves at 405 and 635 nm light with varying light polarization angles, also depicting strong anisotropic photocurrent.

As control experiments, we also measured the angle-dependent photocurrent of individual WSe2 devices. The photocurrent as a function of angles is shown in polar coordinates, presenting no polarization angle dependence (Figure S9). This indicates that the WSe2 component is in-plane isotropic materials, thus the anisotropic- and polarization-sensitive photocurrent of the heterostructures can be contributed from the Bi2O2Se component.

**CONCLUSIONS**

In summary, we prepared multilayer Bi2O2Se using the mechanically exfoliated method. The intensities of phonon vibration modes show significant angle dependence with a period of 180° through the angle-resolved polarized Raman spectra, this indicates that the surface reconstruction led to the anisotropic crystal structure. We then assembled Bi2O2Se, which acted as a polarized light sensitizer with 2D WSe2 layers as a photocarrier transport channel. Due to the p-type and n-type features of WSe2 and Bi2O2Se, respectively, an out-of-plane p–n heterojunction can be formed, resulting in an out-of-plane built-in field that can facilitate the separation of photoexcited electron–hole pairs. As a result, superior photodetection performance in terms of high responsivity, fast speed, and high detectivity has been achieved. The detectors exhibit a broadband spectral coverage from 405 to 1064 nm. More importantly, the photoresponse of the device is also polarization-sensitive due to the linear dichroism character of the Bi2O2Se layers. The dichroism ratio for photocurrent can reach as high as 2.2 and 4.9 for 405 and 635 nm, respectively. In addition, the photodetection performance is much superior compared to that of other reported polarization-sensitive photodetectors (Tables S1 and S2). We discovered the linear dichroism characters of exfoliated Bi2O2Se through the ARPR and polarization absorption measurement, which is successfully utilized for polarization-sensitive photodetector applications. This work expands the family of low-symmetry 2D materials and offers a new opportunity for the development of angle-resolved electronics and optoelectronics.

**EXPERIMENTAL SECTION**

**Device Fabrication of Bi2O2Se/WSe2 Heterostructure.** Multilayer Bi2O2Se and WSe2 were achieved by the mechanical exfoliation method from the bulk crystal (purchased from Shanghai OnWay Technology Co., Ltd.) on the 300 nm SiO2/Si substrate. The details of the exfoliation process can be found in the Supporting Information (Figure S10). Then, the Bi2O2Se layer was stacked on top of the WSe2 layer using the poly(vinyl alcohol) (PVA)/poly(dimethylsiloxane) (PDMS) assisted dry-transfer method. Briefly, the PVA solution was injected on top of the PDMS placed on the glass, then the solid PVA/PDMS film was obtained by heating at 50 °C for 10 minutes. The film was stacked on Bi2O2Se. After heating at 90 °C for 5 min, the PDMS attached with Bi2O2Se was separated from the PVA by tweezers. Then the PDMS/PVA/Bi2O2Se film was stacked on the target WSe2. Finally, the PVA can be removed by soaking in water. The contact electrodes of Ti/Au (10/60 nm) were fabricated by an ultraviolet maskless photolithography machine (TuoTuo Technology Co., Ltd.).
Characterization. Raman spectra were obtained using a confocal microscope spectrometer (Nost Technology Co., Ltd., a laser excitation of 532 nm). The thickness and surface potential differences were measured by AFM and KPFM (Dimension FastScan from Bruker Co., Ltd.). The electrical and optical characteristics were measured using a probe stage equipped with a semiconductor device analyzer (Keithley 2636B) and a four-channel laser. All of the measurements were performed in ambient conditions.

ASSOCIATED CONTENT

Supporting Information
The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.1c05246.

Transfer curves of WS2- and Bi2O2Se-based transistors, photoresponse of Bi2O2Se and WS2 at 980 and 1064 nm light, the R, EQE, and D* of the device at the wavelengths of 808, 980, and 1064 nm, and polar plots of photocurrent of the thicker Bi2O2Se and individual WSe2 (PDF).

AUTHOR INFORMATION

Corresponding Authors
Bin Yao – State Key Lab of Superhard Material, and College of Physics, Jilin University, Changchun 130012, China; Key Laboratory of Physics and Technology for Advanced Batteries (Ministry of Education), College of Physics, Jilin University, Changchun 130012, China; orcid.org/0000-0003-0748-3220; Email: binyao@jlu.edu.cn

Yujuang Yang – School of Physics and Optoelectronic Engineering, Guangdong University of Technology, Guangzhou 510006, China; Email: yujuange@mail.ustc.edu.cn

Xiaozhou Wang – Institute of Semiconductors, South China Normal University, Guangzhou 510631, China; Email: wzxzanu@outlook.com

Nengjie Huo – Institute of Semiconductors, South China Normal University, Guangzhou 510631, China; Guangdong Key Lab of Chip and Integration Technology, Guangzhou 510631, China; orcid.org/0000-0003-2520-6243; Email: njhuo@m.scnu.edu.cn

Authors
Lin Tao – State Key Lab of Superhard Material, and College of Physics, Jilin University, Changchun 130012, China; Key Laboratory of Physics and Technology for Advanced Batteries (Ministry of Education), College of Physics, Jilin University, Changchun 130012, China

Sina Li – Institute of Semiconductors, South China Normal University, Guangzhou 510631, China

Mengjia Xia – Institute of Semiconductors, South China Normal University, Guangzhou 510631, China

Wei Gao – Institute of Semiconductors, South China Normal University, Guangzhou 510631, China; orcid.org/0000-0002-6491-6128

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.1c05246

Author Contributions
*L.T. and S.L. contributed equally to this work.

Notes
The authors declare no competing financial interest.

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

ACKNOWLEDGMENTS

This work is supported by the National Natural Science Foundation of China (Nos. 11904108 and 61805045) and the “The Pearl River Talent Recruitment Program” (2019ZT08X639).

REFERENCES

(1) Li, L.; Han, W.; Pi, L.; Niu, P.; Han, J.; Wang, C.; Su, B.; Li, H.; Xiong, J.; Bando, Y.; Zhai, T. Emerging in-plane anisotropic two-dimensional materials. InfoMat 2019, 1, 54–73.

(2) Xia, F.; Wang, H.; Jia, Y. Rediscovering black phosphorus as an anisotropic layered material for optoelectronics and electronics. Nat. Commun. 2014, 5, No. 4488.

(3) Ribeiro, H. B.; Pimenta, M. A.; de Matos, C. J. S.; et al. Unusual angular dependence of the Raman response in black phosphorus. ACS Nano 2015, 9, 4270–4276.

(4) Kim, J.; Lee, J. U.; Lee, J.; et al. Anomalous polarization dependence of raman scattering and crystallographic orientation of black phosphorus. Nanoscale 2015, 7, 18708–18715.

(5) Shen, W.; Hu, C.; Tao, J.; et al. Resolving the optical anisotropy of low-symmetry 2D materials. Nanoscale 2018, 10, 8329–8337.

(6) Qiao, J.; Kong, X.; Hu, Z. X.; Yang, F.; Ji, W. High-mobility transport anisotropy and linear dichroism in few-layer black phosphorus. Nat. Commun. 2014, 5, No. 4475.

(7) Peng, L.; Wells, S. A.; Ryder, C. R.; Hersam, M. C.; Grayson, M. All-electrical determination of crystal orientation in anisotropic two-dimensional materials. Phys. Rev. Lett. 2018, 120, No. 086801.

(8) Zhang, E.; Wang, P.; Li, Z.; Wang, H.; Song, C.; Huang, C.; Chen, Z.; Yang, L.; Zhang, K.; Lu, S.; Wang, W.; Liu, S.; Fang, H.; Zhou, X.; Yan, H.; Zhou, J.; Wang, X.; Zhou, P.; Hu, W.; Xiu, F. Tunable Ambipolar Polarization-Sensitive Photodetectors Based on High-Anisotropy ReSe2 Nanosheets. ACS Nano 2016, 10, 8067–8077.

(9) Yang, H.; Jussila, H.; Autere, A.; Komsa, H.; Ye, G.; Chen, X.; Hasan, T.; Sun, Z. Optical Waveplates Based on Birefringence of Anisotropic Two-Dimensional Layered Materials. ACS Photonics 2017, 4, 3023–3030.

(10) Chen, Y.; Chen, C.; Kealhofer, R.; Liu, H.; Yuan, Z.; Jiang, L.; Suh, J.; Park, J.; Ko, C.; Zhong, M.; Wei, Z.; Li, J.; Li, S.; Gao, H.; Liu, Y.; Analytis, J.; Xia, Q.; Asensio, M.; Wu, J.; Choe, H. S.; Avila, J. Black Arsenic: A Layered Semiconductor with Extreme In-Plane Optical and Electrical Anisotropy. Adv. Mater. 2018, 30, No. 1800754.

(11) He, Q.; Sun, S.; Xiao, S.; Zhou, L. High-Efficiency Metasurfaces: Principles, Realizations, and Applications. Adv. Opt. Mater. 2018, 6, No. 1800415.

(12) Soci, C.; Zhang, A.; Xiang, B.; Dayeh, S. A.; Aplin, D.; Park, J.; et al. Zno nanowire UV photodetectors with high internal gain. Nano Lett. 2007, 7, 1003–1009.

(13) Wang, J.; Gudiksen, M.; Duan, X.; Cui, Y.; Lieber, C. Highly Polarized Photoluminescence and Photodetection from Single Indium Phosphide Nanowires. Science 2001, 293, 1455–1457.

(14) Zhong, M.; Wang, X.; Liu, S.; Li, B.; Huang, L.; Cui, Y.; Li, J.; Wei, Z. High-performance photodetectors based on NbS2 nanowires: wavelength dependence and wide temperature range utilization. Nanoscale 2017, 9, 12364–12371.

(15) Akahama, Y.; Endo, S.; Narita, S. Electrical Properties of Black Phosphorus Single Crystals. J. Phys. Soc. Jpn. 1983, 52, 2148–2155.

(16) Lee, S.; Yang, F.; Suh, J.; et al. Anisotropic in-plane thermal conductivity of black phosphorus nanoribbons at temperatures higher than 100 K. Nat. Commun. 2015, 6, No. 8573.

(17) Zhong, M.; Meng, H.; Liu, S.; Yang, H.; Shen, W.; Hu, C.; Yang, J.; Ren, Z.; Li, B.; Liu, Y.; He, J.; Xia, Q.; Li, J.; Wei, Z. In-Plane Optical and Electrical Anisotropy of 2D Black Arsenic. ACS Nano 2021, 15, 1701–1709.
(18) Wang, X.; Li, Y.; Huang, L.; Jiang, X. W.; Jiang, L.; Dong, H.; Wei, Z.; Li, J.; Hu, W. Short-wave near-infrared linear dichroism of two-dimensional germanium selenide. J. Am. Chem. Soc. 2017, 139, 14976–14982.

(19) Zhou, Z.; Long, M.; Pan, L.; Wang, X.; Zhong, M.; Blei, M.; Wang, J.; Fang, J.; Tongay, S.; Hu, W.; Li, J.; Wei, Z. Perpendicular optical reversal of the linear dichroism and polarized photodetection in 2D GeAs. ACS Nano 2018, 12, 12416–12423.

(20) Song, Q.; Fan, X.; Wang, H.; et al. The in-plane anisotropy of WTe2 investigated by angle-dependent and polarized Raman spectroscopy. Sci. Rep. 2016, 6, No. 29254.

(21) Beams, R.; Cançado, L. G.; Krylyuk, S.; et al. Characterization of Few-Layer 1T’ MoTe2 by Polarization-Resolved Second Harmonic Generation and Raman Scattering. ACS Nano 2016, 10, 9626–9636.

(22) Chenet, D. A.; Aslan, O. B.; Huang, P. Y.; et al. In-plane anisotropy in mono- and few-layer ReS2 probed by Raman spectroscopy and scanning transmission electron microscopy. Nano Lett. 2015, 15, 5667–5672.

(23) Wovlerston, D.; Crampin, S.; Kazemi, A. S.; Ilie, A.; Bending, S. J. Raman spectra of monolayer, few-layer, and bulk ReSe2: an anisotropic layered semiconductor. ACS Nano 2014, 8, 11154–11164.

(24) Gao, W.; Zheng, Z.; Wen, P. T.; Huo, N. J.; Li, J. B. Novel two-dimensional monooelemental and ternary materials: growth, physics and application. Nanophotonics 2020, 9, 2147–2168.

(25) Wu, J.; Yuan, H.; Meng, M.; Chen, C.; Sun, Y.; Chen, Z.; Dang, W.; Tan, C.; Liu, Y.; Yin, J.; Zhou, Y.; Huang, S.; Xu, H. Q.; Cui, Y.; Hwang, H. Y.; Liu, Z.; Chen, Y.; Yan, B.; Peng, H. High electron mobility and quantum oscillations in non-encapsulated ultrathin semiconducting Bi2O2Se. Nat. Nanotechnol. 2017, 12, 530–534.

(26) Li, T.; Tu, T.; Sun, Y.; Hu, F.; Yu, J.; Xing, L.; Wang, Z.; Wang, H.; Jia, R.; Wu, J.; Tan, C.; Liang, Y.; Zhang, Y.; Zhang, C.; Dai, Y.; Qiu, C.; Li, M.; Huang, R.; Jiao, L.; Lai, K.; Yan, B.; Gao, P.; Peng, H. A native oxide high-k gate dielectric for two-dimensional electronics. Nat. Electron. 2020, 3, 473–478.

(27) Yin, J.; Tan, Z.; Hong, H.; Wu, J.; Yuan, H.; Liu, Y.; Chen, C.; Tan, C.; Yao, F.; Li, T.; Chen, Y.; Liu, Z.; Liu, K.; Peng, H. Ultrafast, highly-sensitive infrared photodetectors based on two-dimensional oxyselenide crystals. Nat. Commun. 2018, 9, No. 3311.

(28) Yang, T.; Li, X.; Wang, L.; Liu, Y.; Chen, K.; Yang, X.; Liao, L.; Dong, L.; Shan, C. Broadband photodetection of 2D Bi2O2Se–MoSe2 heterostructure. J. Mater. Sci. 2019, 54, 14742–14751.

(29) Khan, U.; Luo, Y.; Tang, L.; Teng, C.; Liu, J.; Liu, B.; Cheng, H. Controlled vapor-solid deposition of millimeter-size single crystal 2D Bi2O2Se for high-performance phototransistors. Adv. Funct. Mater. 2019, 29, No. 1807979.

(30) Sun, Y.; Zhang, J.; Ye, S.; Song, J.; Qu, J. Progress Report on Property, Preparation, and Application of Bi2O2Se. Adv. Funct. Mater. 2020, 30, No. 2004480.

(31) Eremin, S. V.; Koroteev, Y. M.; Chulkov, E. V. Surface electronic structure of bismuth oxychalcogenides. Phys. Rev. B 2019, 100, No. 115417.

(32) Cheng, C.; Wang, M.; Wu, J.; Fu, H.; Chen, Y. Electronic structures and unusually robust bandgap in an ultrahigh-mobility layered oxide semiconductor, Bi2O2Se. Sci. Adv. 2018, 4, No. eaat8355.

(33) Xiao, J.; Wang, Y.; Feng, X.; Legut, D.; Wang, T.; Fan, Y. Anisotropic Bi2O2Se(Te) Monolayer: Realizing Ultra-High Carrier Mobility and Giant Electric Polarization in Two-Dimension. 2019, arXiv:1911.11327. arXiv.org e-Print archive. https://arxiv.org/abs/1911.11327.

(34) Fu, Q.; Zhu, C.; Zhao, X.; Wang, X.; Chatertvedi, A.; Zhu, C.; Wang, X.; Zeng, Q.; Zhou, J.; Liu, F.; Tan, B.; Zhang, H.; Pennycook, S.; Liu, Z. Ultrasensitive 2D Bi2O2Se phototransistors on silicon substrates. Adv. Mater. 2018, 1, No. 1804945.

(35) Huang, N.; Tongay, S.; Guo, W.; Li, R.; Fan, C.; Lu, F.; Yang, J.; Li, B.; Li, Y.; Wei, Z. Novel optical and electrical transport properties in atomically thin WSe2/MoS2 p–n heterostructures. Adv. Electron. Mater. 2015, 1, No. 1400066.