Interface-Induced WSe₂ In-plane Homojunction for High-Performance Photodetection

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Abstract

2D transition metal dichalcogenides (TMDCs) have been extensively attractive for nano-electronics and nano-optoelectronics due to their unique properties. Especially, WSe₂, having bipolar carrier transport ability and sizable bandgap, is a promising candidate for future photodetectors. Here, we report an in-plane WSe₂ homojunction formed by the interface gate of the substrate. In this architecture, an insulated h-BN flake was used to make only part of WSe₂ flake contact substrate directly. Finally, the structures of WSe₂/substrate and WSe₂/h-BN/substrate construct an in-plane homojunction. Interestingly, the device can operate in both photovoltaic and photoconductive modes at different biases. As a result, a responsivity of 1.07 A W⁻¹ with a superior detectivity of over 10¹² jones and a fast response time of 106 μs are obtained simultaneously. Compared with previously reported methods adopted by chemical doping or electrostatic gating with extra bias voltages, our design provides a more facile and efficient way for the development of high-performance WSe₂-based photodetectors.

Keywords: Transition metal dichalcogenides, In-plane homojunction, Photodetection, Interface gate

Introduction

In recent decade, 2D transition metal dichalcogenides (TMDCs) have drawn great attention owing to their particular properties. High in-plane mobility, tunable bandgap, mechanical flexibility, strong light-matter interaction, and easy processing make them very competitive for future nano-optoelectronics devices [1–20]. Especially, tungsten diselenide (WSe₂), a bipolar semiconductor with facile carrier-type manipulation, allows remarkably potential applications in the junction-based photodetectors [21–28]. So far, the main strategies of constructing junction solely in WSe₂ include chemical doping and electrostatic gating. For example, recently, an intramolecular WSe₂ p-n junction was reported [26]. The n region and p region within WSe₂ were formed by polyethyleneimine chemical doping and back gate control, respectively. The p-n junction presented a responsivity of 80 mA W⁻¹ and 200 μs response time. Sun et al. doped WSe₂ by using cetyltrimethyl ammonium bromide to form intramolecular p-n junction, in which the responsivity and the response time are 30 A W⁻¹ and ~ 7 ms, respectively [27]. Baugher et al. demonstrate a lateral WSe₂ p-n junction achieved by electrostatic gating through applying two gate biases with opposite polarity. The responsivity of 210 mA W⁻¹ has been obtained [28]. However, due to the inevitable chemical impurities and the necessary multiple bias settings, these methods make the fabrication and application of junction-based devices complex and difficult. Assembling various 2D materials to build vertical van der Waals heterostructures like WSe₂/MoS₂ junction [29] has become popular for the development of novel photodetectors. But, in this configuration, the process of carrier transport between different layered materials suffers from the interface defects, which restricts the device response speed. For the Schottky junction formed between metals and 2D materials, the Schottky barrier height is usually...
determined by Fermi-level pinning, which is uncontrollable and has a great impact on the responsivity of the devices. Additionally, the reported works cannot seem to possess both high responsivity and fast response speed.

Here, we demonstrate a facile and more efficient way to realize an in-plane WSe$_2$ homojunction. In the architecture, part of WSe$_2$ channel is on the Si/SiO$_2$ substrate and the other part is on the h-BN flake. This scheme is common in floating/semi-floating gate memories, in which the h-BN is adopted as gate dielectric layer [30, 31]. The charges stored on one side of h-BN layer can regulate the conductivity of the material on the other side. In our work, however, the h-BN flake as a perfect isolator is used to eliminate the interface gating effect on the WSe$_2$ channel. The polarity of WSe$_2$, which part is only on the Si/SiO$_2$ substrate, can be modulated by interface gate. As a result, the devices operate in photovoltaic (PV) mode well at zero bias. Meanwhile, it exhibits photoconductive (PC) characteristics at high bias. A responsivity of $1.07 \ A \ W^{-1}$ with a superior detectivity of over $10^{12}$ jones and a fast response time of $106 \ \mu s$ are obtained simultaneously without the intricate device design and the risk of introducing additional chemical impurities.

**Results and Discussion**

Figure 1a shows a schematic of the in-plane WSe$_2$ homojunction. It can be seen that part of WSe$_2$ flake is placed on h-BN flake (WSe$_2$-h) and the other part contacts the Si/SiO$_2$ substrate directly (WSe$_2$-S). The function of h-BN is to isolate the interface gate (IG) of the Si/SiO$_2$ substrate on the WSe$_2$-h. So, the formation of homojunction between WSe$_2$-h and WSe$_2$-S mainly relies on the IG modulating the polarity of WSe$_2$-S. The
IG is produced by the trapped charges at the SiO₂ surface. This will be discussed below in detail. Figure 1b presents the optical picture of the device. Four electrodes (E1-E4, TiAu) were prepared by electron-beam lithography, metallization, and the lift-off process. The thickness of materials is characterized by atomic force microscope (AFM) (see Fig. 1c). The height of WSe₂ (h-BN) flake in direct contact with the Si/SiO₂ substrate (white dotted lines) was measured as 65 (23) nm (see Fig. 1d, e). It can be seen that there is a slope instead of sharp step in the height profile between the WSe₂ (h-BN) and the Si/SiO₂ substrate. This may be due to the residual photoresist at the edge of the material. Figure 1f shows the Raman spectra of WSe₂ and h-BN flakes. For the WSe₂, the first order E₂g and A₁g Raman modes are clearly distinguished at ~ 1370 cm⁻¹, suggesting that the WSe₂ has a multilayer morphology [32, 33]. For the h-BN, the Raman peak of E₂g mode at ~ 1370 cm⁻¹ is observed. Due to the large bandgap of h-BN, the Raman signal is weak compared with that in WSe₂ [34].

To explore the effect of substrate on WSe₂, transfer characteristics of WSe₂-S and WSe₂-h were studied separately. As shown in Fig. 2a, both transfer curves exhibit bipolar behavior and an obvious hysteresis can be observed in the curve of WSe₂-S (black) compared with that of WSe₂-h (red). The current of WSe₂-h is higher than that of WSe₂-S. The steep slope in the curve of WSe₂-h indicates a relatively large transconductance, which is proportional to carrier mobility. For WSe₂-S, the hysteresis is attributed to the charge trapping at the SiO₂ surface [35–38]. When V₉ was swept from −30 to 0 V, the negative V₉ makes the WSe₂ populated with holes and drives some holes into the SiO₂ (see Fig. 2b). The trapped holes in SiO₂ generate a positive local gate, i.e., IG, to modulate the WSe₂ conductance in return (weak depletion effect). Therefore, the charge neutrality point of V₉ appears around ~ 5 V. Similarly, when V₉ was swept from 30 to 0 V, the positive V₉ makes the WSe₂ populated with electrons and also drives some electrons into the SiO₂ (see Fig. 2c). The trapped electrons in SiO₂ generate a negative IG to modulate the WSe₂ conductance in return (the same weak depletion effect). So, the charge neutrality point of V₉ appears around 5 V. For WSe₂-h, the h-BN flake inhibits the carrier transfer between WSe₂ and SiO₂ under V₉ modulation. This is the reason for the non-obvious hysteresis in the WSe₂-h curve. Therefore, an in-plane homojunction can be formed simply by taking advantage of the IG.

Figure 3a shows the I₉–V₉ curves of the device under dark and light conditions at V₉ = 0 V. The source-drain voltage is applied on electrodes E2 and E3 (see the inset). It can be seen that the short-circuit currents (at V₉ = 0 V) increase with the incident power, indicating a PV effect. Interestingly, the curves also present PC characteristics at V₉ = ± 1 V. For the former, the photocurrents are attributed to the homojunction. As shown in Fig. 3b, although V₉ and V₉ were set at 0 V, a few already trapped holes in SiO₂ form a small positive IG to modulate the WSe₂-S. So, the n-type WSe₂-S and intrinsic WSe₂-h (without the effect of IG due to the isolation by h-BN flake) constitute an in-plane homojunction. Under illumination, the photoexcited electron-hole pairs will be separated by built-in field of the homojunction. Although I₉–V₉ curves present PV characteristic well at zero bias, the homojunction did not show a rectifying behavior maybe due to the relatively weak built-in field compared with the externally applied V₉. For the latter, the whole WSe₂ flake as a photoconductor responds the light signal at high bias. The photoexcited carriers will be driven to the electrodes by V₉. Therefore, the photoresponse in Fig. 3a is the result of synergistic effect of PV and PC modes. The responsivities as a function of the light power for different V₉ are summarized in Fig. 3c, given by R = I₉/P, where I₉ is the photocurrent, P is the power intensity, and A is the effective photosensitive area of the detector [39, 40]. During the calculation, the effective photosensitive area, i.e., the WSe₂ part between E2 and E3, is 115.75 μm². The responsivities of 1.07 A W⁻¹ and 2.96 A W⁻¹ are obtained for V₉ of 0 V.

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**Fig. 2** Transfer characteristics. a) I₉–V₉ curves of WSe₂-S (black line) and WSe₂-h (red line). The sweep direction of V₉ is indicated by the arrows. b) Physical explanation for the hysteresis phenomenon. The arrows indicate the direction of electric field induced by V₉. The red and blue spheres represent holes and electrons, respectively.
and 1 V, respectively. The specific detectivity ($D^*$) as an important parameter determines the capability of a photodetector to respond to a weak light signal. Assuming that the shot noise from the dark current is the major contribution, $D^*$ can be defined as $D^* = RA^{1/2}/(2eI_{\text{dark}})^{1/2}$, where $R$ is the responsivity, $A$ is the effective photosensitive area, $e$ is the electron charge, and $I_{\text{dark}}$ is the dark current [41, 42]. Benefitting from the extremely low $I_{\text{dark}}$, $D^*$ of $3.3 \times 10^{12}$ and $1.78 \times 10^{11}$ jones are achieved for $V_d$ of 0 V and 1 V, respectively.

Moreover, response time as a key figure of merit has been studied. As shown in Fig. 3d, a high and a low current state acquired at $V_d = 0$ V have been obtained with the light modulation. The transient photoresponse exhibits highly stable and reproducible characteristics. Figure 3e gives a single modulation cycle of temporal response. The rising time ($t_r$), defined as the time necessary for the current to increase from 10% $I_{\text{peak}}$ to 90% $I_{\text{peak}}$, was found to be $\sim 106 \mu$s, and the falling time ($t_f$), defined analogously, was found to be $\sim 91 \mu$s. Figure S1 shows temporal response of the device acquired at $V_d = 0$ V for 637 nm illumination. An oscilloscope was used to monitor the time dependence of the current.

Table 1 Optoelectronic characteristics of WSe$_2$ homojunction formed by different methods

| WSe$_2$ homojunction formed by | Wavelength (nm) | Responsivity (A W$^{-1}$) | Detectivity (jones) | Time (ms) | References |
|--------------------------------|----------------|---------------------------|---------------------|----------|------------|
| h-BN/two gates                 | 532            | $7 \times 10^{-4}$        | -                   | 10 ms    | 24         |
| SiN/two gates                  | 500–900        | 0.016                     | -                   | -        | 25         |
| Polyethylene imine chemical doping | 520         | 0.08                      | $10^{11}$           | 200 $\mu$s | 26         |
| Cetyltrimethyl ammonium bromide chemical doping | 450          | 30                        | $10^{11}$           | 7.8 ms   | 27         |
| HfO$_2$/two gates              | 532            | 0.21                      | -                   | -        | 28         |
| h-BN/interface gate            | 637            | 1.07                      | $10^{12}$           | 106 $\mu$s | This work  |

Fig. 3 Photoresponse performance of the homojunction acquired between E2 and E3. a Drain current as a function of source-drain voltage applied on electrodes E2 and E3 (see the inset) with variable light power intensity (637 nm). b Formation mechanism of the homojunction at $V_g = 0$ V and $V_d = 0$ V. c Responsivity as a function of light power. d, e Temporal response of the device acquired at $V_d = 0$ V for 637 nm illumination. An oscilloscope was used to monitor the time dependence of the current.
WSe₂-h and WSe₂-S exhibit PC property, and there is no photocurrent at zero bias. In fact, Ti/WSe₂/Ti should be supposed to form a metal/semiconductor/metal structure which contains two Schottky junctions with opposite built-in field. So, the $I_d$-$V_d$ curves should cross the zero-point and exhibit PC behavior. In our case, due to the different work functions of WSe₂-h and WSe₂-S, there are two asymmetric Schottky contacts, i.e., E2/WSe₂-S and E3/WSe₂-h, as shown in Fig. 4c. At zero bias, the direction of net photocurrents originated from the Schottky junctions is opposite to that in the homojunction, and the experiment result shown in Fig. 3a is consistent with the latter. Therefore, the homojunction formed between WSe₂-h and WSe₂-S is the reason for the short-circuit photocurrents.

To further demonstrate that the photoresponse at zero bias is attributed to the homojunction, the output properties were investigated through measuring the $I_d$-$V_d$ curves of the device with the source-drain voltage applied on electrodes E1 and E4. As shown in Figure S3a, the curves, same as the situation in Fig. 3a, also exhibit the PV and PC characteristics. As discussed above, for the former, the photocurrents are attributed to the built-in field of in-plane homojunction formed between WSe₂-S and WSe₂-h. For the latter, the photocurrents are attributed to the collection of photoexcited carriers by the externally applied $V_d$. The responsivities as a function of the light power for different $V_d$ are summarized in Figure S3b. The responsivities (detectivities) of 0.51 A W⁻¹ (2.21 × 10¹² jones) and 3.55 A W⁻¹ (5.54 × 10¹² jones) are obtained for $V_d$ of 0 V and 1 V, respectively. During the calculation, the WSe₂ part between E1 and E4, is 519.4 μm². The response time measured at zero bias is shown in Figure S3c and 3d, in which the rising time is 289 μs and the falling time is 281 μs. For the $V_d$ of 1 V (Figure S3e and 3f), the rising and falling time are 278 μs and 250 μs, respectively. The response speed is a little slower than that measured between electrodes E2 and E3, because the relatively long conductive channel increases the photocarrier transmission distance and the probability for the interaction between photocarriers and defects.

Conclusion

In summary, we have demonstrated an in-plane WSe₂ homojunction by electrically tuning partial WSe₂ flake through interface gate. Compared with existing approaches like chemical doping and electrostatic gating by taking advantage of two gate biases, this design gives a more facile rout to realize WSe₂ homojunction. With light illumination, the device produces distinct short-circuit photocurrents with a detectivity of 3.3 × 10¹² jones. At high bias, the device presents photoconductive characteristic and generates photocurrents with a detectivity of 1.78 × 10¹¹ jones. A response time as fast as 106 μs is also obtained simultaneously. Our study provides an efficient and reliable way for the development of high-performance WSe₂-based photodetectors.

Methods

Both WSe₂ and h-BN bulk materials were purchased from Shanghai Onway Technology Co., Ltd. First, the h-BN and WSe₂ flakes were mechanically exfoliated onto a p⁺-Si/SiO₂ (300 nm) substrate and a poly-dimethyl siloxane (PDMS) layer, respectively. Then, a micromanipulator was used to put the WSe₂ flake, which is adhered to PDMS, onto the target h-BN flake through the microscope to locate the position. Part of WSe₂ flake overlaps the h-BN flake. Finally, the WSe₂ flake was released from PDMS through heating the substrate. The electrodes (Ti/Au) were prepared by electron-beam lithography, metallization, and the lift-off process. Photoresponse measurements were conducted using Agilent B1500.
semiconductor parameter analyzer and laser diode with the wavelength of 637 nm.

Supplementary information
Supplementary information accompanies this paper at https://doi.org/10.1186/s11671-020-03342-9.

Additional file 1: Figure S1. Temporal response of the device acquired at V_0 = 1 V for 637 nm illumination. Figure S2. Photorepons of the other three devices under 637 nm illumination. Figure S3. Photoreponse performance of the homojunction acquired between E1 and E4.

Abbreviations
TMDCs: Transition metal dichalcogenides; PV: Photovoltaic; PC: Photoconductive; AFM: Atomic force microscope; IG: Interface gate; PDMS: Poly-dimethyl siloxane

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Authors’ Contributions
NG and LX contributed to the idea of the project. JWC and NG designed and carried out the experiments. YS and LX participated in the analyses of the results and discussion of this work. GHL helped to draft and revise the manuscript. The authors read and approved the final manuscript.

Availability of Data and Materials
The data that support the findings of this work are available from the corresponding author upon reasonable request.

Competing Interests
The authors declare that they have no competing interests.

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