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Controllable Growth of Monolayer and Bilayer WSe₂ by Liquid-Phase Precursor via Chemical Vapor Deposition for Photodetection

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Abstract: Two-dimensional WSe₂ nanosheets have received increasing attention due to their excellent optoelectronic properties. Solid precursors, such as WO₃ and Se powders, have been extensively employed to grow WSe₂ nanosheets by the chemical vapor deposition (CVD) method. However, the high melting point of WO₃ results in heterogeneous nucleation sites and nonuniform growth of the WSe₂ nanosheet. By dissolving WO₃ powder in a NaOH solution, we report a facile and uniform growth of monolayer and bilayer WSe₂ nanosheets on a SiO₂/Si substrate at a large scale using liquid precursor by the CVD method. The size and thickness of the WSe₂ nanosheets were controlled by modulating the precursor concentration and growth temperature. The as-prepared monolayer and bilayer WSe₂ nanosheets were well characterized by optical microscopy, atomic force microscopy, and Raman and photoluminescence spectroscopy. With the increase in precursor concentration, the size of the monolayer WSe₂ increased up to 120 μm. Bilayer WSe₂ nanosheets were grown at higher temperatures. The photosensitivity of the bilayer WSe₂ was one order of magnitude higher than that of the monolayer WSe₂. The carrier mobility, specific detectivity, photoresponsivity, and external quantum efficiency of the bilayer WSe₂ were about two orders of magnitude higher than those of the monolayer WSe₂. Our method opens up a new avenue to grow monolayer and bilayer WSe₂ for optoelectronic applications.



Citation: Wang, S.; Wang, P.; Tang, H.; Yu, S.; Ye, H.; Fang, X.; Ding, J.; Yang, Y.; Li, H. Controllable Growth of Monolayer and Bilayer WSe₂ by Liquid-Phase Precursor via Chemical Vapor Deposition for Photodetection. *Nanomaterials* **2024**, *14*, 2021. <https://doi.org/10.3390/nano14242021>

Academic Editor: Christian Mitterer

Received: 15 November 2024

Revised: 12 December 2024

Accepted: 13 December 2024

Published: 16 December 2024



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Keywords: monolayer WSe₂; bilayer WSe₂; liquid precursor; optoelectronic performance; chemical vapor deposition

1. Introduction

As an important two-dimensional (2D) semiconductor material, WSe₂ has gained tremendous attention due to its unique optical and electrical properties. Similar to other transition metal dichalcogenides (TMDCs; e.g., MoS₂, WS₂, and MoSe₂), WSe₂ also shows a thickness-dependent band gap as well as excellent optoelectronic performance. The band structure of WSe₂ exhibits an indirect-to-direct transition as the thickness decreases from bilayer (2L) to monolayer (1L) [1,2], which greatly enhances the photoelectronic conversion efficiency. The monolayer WSe₂ also exhibits quite high photoluminescence (PL) and high photo gain and specific detectivity [3]. While different from other TMDCs, WSe₂ exhibits promising ambipolar behavior by modulating the interface and metal contact electrode [4–8]. In addition, a self-powered photovoltaic photodetector with fast photoresponse can be achieved by contacting the WSe₂ nanosheet with TiN/Ti metal electrodes [9]. Interestingly, the WSe₂ nanosheet also shows the lowest thermal conductivity among the layered TMDC materials [10]. It also has extensive applications in hydrogen evolution reactions [11], light-emitting diodes [12], photodetectors [13], and field-effect transistors [14]. To date, researchers have developed various methods to prepare WSe₂ nanosheets, including mechanical exfoliation (ME) [1], physical vapor deposition (PVD) [15,16], chemical vapor deposition (CVD) [5,7,17–20], and liquid

exfoliation [21–23]. Among them, CVD is a widely used method because of its advantages of low cost, high-quality growth, good uniformity, and high controllability of thickness [24–27].

It is well known that the successful CVD growth of WSe₂ nanosheets is highly dependent on the type of transition metal and selenium precursors. Solid precursors such as transition metal oxides (e.g., WO₃) and selenium powders have been extensively employed to grow WSe₂ nanosheets on a substrate during the CVD process. However, the high melting point of WO₃ powder (~1475 °C) hinders its uniform vapor phase distribution in the tube furnace [28–30], leading to nonuniform nucleation sites on the substrate. Therefore, heterogeneous WSe₂ nanosheets with mixed layer numbers can be obtained. Various solutions have been proposed to grow uniform WSe₂ nanosheets on substrates in large sizes, such as introducing halide salts to reduce the melting point of WO₃ [31,32], adding Te powder as a growth promoter [33], and optimizing the growth temperature as well as the distance between substrate and precursor [28,29]. However, it is still a challenge to grow large WSe₂ nanosheets with homogeneous morphology, large domain size, and low density of defects by using a solid precursor, which, in turn, influences the electrical and optoelectronic properties of the as-grown WSe₂ nanosheets.

Recently, a liquid-phase precursor instead of solid powder has been developed to grow TMDC nanosheets uniformly at wafer scale [34–37]. Compared to with the solid precursor, the precursor concentration can be well controlled by dissolving the precursor salt in a certain solvent, which is suitable for making the mixture of different salts grow a heterostructure nanosheet. In addition, the liquid precursor can be uniformly distributed on the substrate by the spin coating method. Thus, the nucleation density can be precisely modulated by depositing a tiny amount of precursor solution on a substrate. As a consequence, monolayer TMDC nanosheets can be grown effectively by avoiding the supersaturation state of the precursor vapor in the solid precursor method [38,39]. Moreover, the precursor salt can be easily converted into the molten state due to its lower melting point (650–850 °C). Uniform and high-quality TMDC nanosheets, such as monolayer MoS₂ and WS₂ as well as hetero-bilayer MoS₂/WS₂, have been successfully grown by using the liquid precursor method [36,40]. However, the growth of 1L and 2L WSe₂ nanosheets using the liquid precursor remains poorly explored. Therefore, it is desirable to develop a liquid-phase precursor to achieve controllable growth of 1L and 2L WSe₂.

Herein, we report the uniform growth of 1L and 2L WSe₂ nanosheets on a SiO₂/Si substrate in at a large scale with the CVD method using a liquid-phase precursor. The liquid precursor is firstly obtained by dissolving WO₃ powder in NaOH solution and then depositing it on the SiO₂/Si substrate with a controlled concentration. By optimizing the precursor concentration and growth temperature, the size and thickness of the WSe₂ nanosheets were well regulated. The as-prepared 1L and 2L WSe₂ nanosheets were characterized by optical microscopy (OM), atomic force microscopy (AFM), and Raman and PL spectroscopy. Compared with 1L WSe₂, the 2L WSe₂ shows one order of magnitude improvement in terms of photosensitivity. In addition, the photoresponsivity, external quantum efficiency (EQE), carrier mobility, and specific detectivity of 2L WSe₂ are two orders of magnitude higher than those of 1L WSe₂, indicating that the 2L WSe₂ could be promising candidate for optoelectronic devices.

2. Materials and Methods

2.1. Growth of Monolayer and Bilayer WSe₂ Nanosheets by Chemical Vapor Deposition

The CVD process was performed in a single-heating-zone tube furnace under ambient pressure. In order to dissolve the WO₃ powder (99.9%, Aladdin, Riverside, CA, USA) completely, 0.2 g of WO₃ powder was added to NaOH solution (10 mL, 10 mg/mL) in water bath at 80 °C to form WO₃ precursor solution with concentration of 20 mg/mL. The as-prepared WO₃ precursor solution was diluted to 5, 10, and 15 mg/mL, respectively. The 300 nm SiO₂/Si substrate was first immersed in a mixture of concentrated sulfuric acid and hydrogen peroxide at 120 °C for 30 min, and then washed by deionized water and dried by N₂. The as-cleaned SiO₂/Si substrate was soaked in a mixture of WO₃ precursor solution

and sodium cholate (1 mg/mL, 98%, Aladdin) with a volume ratio of 5:1 for 1 min. The sodium cholate was used as promoter to accelerate the growth of WSe₂ [38,41,42]. Due to the hydrophilicity of the SiO₂/Si substrate, the precursor was uniformly deposited on the substrate. The precursor-coated SiO₂/Si substrate was slowly dried by N₂ and then put face-down on a quartz boat in the center of a tube furnace. Another quartz boat with 0.15 g Se powder (99%, Alfa Aesar, Ward Hill, MA, USA) was placed upstream of the tube. For the growth of 1L WSe₂ nanosheet, the temperature was controlled at 800 °C, and the growth time was kept for 5 min with 20 sccm N₂ and 10 sccm H₂ used as carrier gas. The growth of 2L WSe₂ nanosheet was the same as that of 1L WSe₂ nanosheet, except the temperature was controlled at 900 °C.

2.2. Characterizations

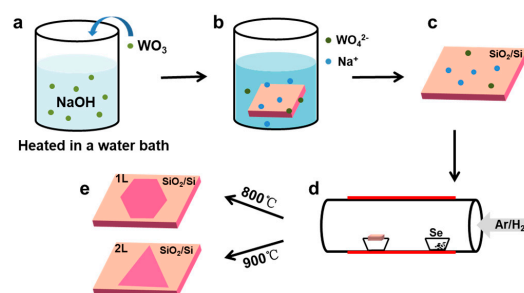
An optical microscope (ECLIPSE LV100ND, Nikon, Tokyo, Japan) was used for a preliminary check on the location, shape, and thickness of the as-grown samples. An atomic force microscope (Dimension ICON with Nanoscope V controller, Bruker, Billerica, MA, USA) was used to characterize the thickness of 1L and 2L WSe₂ nanosheets. The Raman and photoluminescence (PL) spectra of 1L and 2L WSe₂ nanosheets were collected on a LabRAM HR Evolution Raman spectrometer (Horiba Jobin Yvon, Longjumeau, France) with a 532 nm laser focused through a 100 × objective lens at room temperature. The electrical performance was measured by a Keithley 4200 semiconductor device parameter analyzer (Keithley 4200-SCS, Tektronix, Beaverton, OR, USA).

2.3. Device Fabrication and Photodetection

A 300-mesh TEM mesh was used as mask in thermal evaporator. Then, 3 nm thick chromium and 50 nm thick gold films were deposited on 1L and 2L WSe₂ nanosheets to obtain the device for measuring optoelectronic and electrical performance. The Keithley 4200 semiconductor characterization system was used to monitor the real-time current change in the WSe₂ devices. The optoelectronic performance test was recorded under blue (405 nm), green (532 nm), and red (633 nm) lasers.

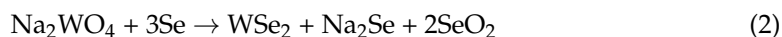
3. Results

The growth of the WSe₂ nanosheet is shown in Scheme 1. Firstly, WO₃ powder was dissolved in NaOH solution at a certain concentration. In order to accelerate the dissolution of WO₃, the NaOH solution was then immersed into a water bath at 80 °C (Scheme 1a). The dissolution of WO₃ in the NaOH solution can be described by the following reaction.



Scheme 1. Schematic illustration of the CVD synthesis of WSe₂ nanosheets using a liquid-phase precursor. (a) Preparation of the liquid-phase Na₂WO₄ precursor by dissolving WO₃ powder in a NaOH solution. (b) Soaking the SiO₂/Si substrate in a Na₂WO₄ solution for 1 min. (c) The precursor was uniformly distributed on the SiO₂/Si substrate. (d) The growth of the WSe₂ nanosheet by CVD method with Ar/H₂ as carrier gas. (e) The growth of 1L and 2L WSe₂ nanosheets by CVD at 800 and 900 °C, respectively.

Thus, a Na_2WO_4 solution was obtained after WO_3 was completely reacted with NaOH . A freshly cleaned SiO_2/Si substrate was then immersed into the Na_2WO_4 solution for some time to obtain a Na_2WO_4 -coated substrate (Scheme 1b,c). The CVD process was performed by putting Se powder upstream of the Na_2WO_4 -coated SiO_2/Si substrate in a single-heating-zone tube furnace with Ar/H_2 as the carrier gas (Scheme 1d). By controlling the growth temperature, 1L and 2L WSe_2 nanosheets were grown at 800 and 900 °C (Scheme 1e), respectively. The growth of a WSe_2 nanosheet by CVD can be described as the following chemical reaction.



At first, the influence of WO_3 concentration on the growth of the WSe_2 nanosheet was investigated. Figure 1a–d show the optical microscopy (OM) images of 1L WSe_2 nanosheets grown at 800 °C by dissolving WO_3 in NaOH solutions with concentrations of 5, 10, 15, and 20 mg/mL, respectively. With the increased concentration of WO_3 , the size and density of the WSe_2 nanosheets also increased quickly. When WO_3 with concentration of 5 mg/mL was used as precursor, symmetric six-pointed WSe_2 stars with sizes of $34.7 \pm 4.7 \mu\text{m}$ were obtained (Figure 1a). As the concentration of WO_3 increased to 10 mg/mL, the as-grown WSe_2 nanosheets showed hexagonal shapes with sizes of $51.0 \pm 3.6 \mu\text{m}$ (Figure 1b). The size of the WSe_2 nanosheets gradually increased to 56.0 ± 5.3 and $155.0 \pm 5.0 \mu\text{m}$ as the concentration of WO_3 increased to 15 and 20 mg/mL, respectively (Figure 1c,d). Meanwhile, the densities of the WSe_2 nanosheets also increased with the increasing concentrations of WO_3 . In order to measure the percentage of the surface area of the SiO_2/Si substrate covered by WSe_2 nanosheets, ImageJ software was used for statistical measurement (Figure S1 in Supporting Information (SI)). When 5 mg/mL of WO_3 was used as the precursor, only $17.9 \pm 2.6\%$ area of the SiO_2/Si substrate was covered by WSe_2 nanosheets. The density of the WSe_2 nanosheets further increased to $50.7 \pm 4.0\%$ as 10 mg/mL WO_3 was used. It slightly increased to $55.8 \pm 4.8\%$ when the concentration of WO_3 increased to 15 mg/mL, while the density of the WSe_2 nanosheets largely increased to $84.7 \pm 6.4\%$ as the concentration of WO_3 increased to 20 mg/mL. These results indicated that the size and density of WSe_2 nanosheets are highly dependent on the concentration of WO_3 dissolved in the NaOH solution, as indicated in Figure 1e. At a low concentration of WO_3 solution (5 mg/mL), the nucleation density is also low, and the as-grown WSe_2 nanosheets are small and sparsely distributed on the substrate. With the increasing concentration of WO_3 (10 and 15 mg/mL), the amount of Na_2WO_4 is also increased, which results in the increased size of the WSe_2 nanosheets. A higher concentration of WO_3 solution (20 mg/mL) can provide a sufficient amount of Na_2WO_4 precursor for growing larger WSe_2 nanosheets. In addition to the concentration of WO_3 , the distance between the Se powder and Na_2WO_4 -coated SiO_2/Si substrate also affects the growth of the WSe_2 nanosheet (Figure S2 in SI). As shown in Figure S2a in SI, the precursor-coated SiO_2/Si substrate is placed at the center of the tube furnace, where the temperature is the highest. The Se powder in the ceramic boat is placed at the left end of the furnace, a certain distance away from the SiO_2/Si substrate. Since there is a temperature gradient in the tube furnace, the temperature of the Se boat decreases with the increasing distance. Therefore, the Se powder is evaporated quickly when the distance is 15.5 cm, resulting in oversaturation of Se vapor near the SiO_2/Si substrate, while insufficient Se vapor is provided for the growth of the WSe_2 nanosheet when the distance is set to 17 cm because of the lower temperature. As shown in Figure S2b in SI, large monolayer WSe_2 nanosheets and thick flakes are grown when the distance is 15.5 cm, while very small monolayer WSe_2 nanosheets are grown at a distance of 17 cm (Figure S2e in SI), confirming the important influence of distance on the growth of WSe_2 nanosheets. The size of the monolayer WSe_2 nanosheet increases as the distance decreases from 17 cm to 16.5 cm (Figure S2d in SI). As shown in Figure S2c in SI, the large monolayer WSe_2 nanosheets with clean surfaces are grown when the distance is 16 cm, indicating it is the optimal distance.

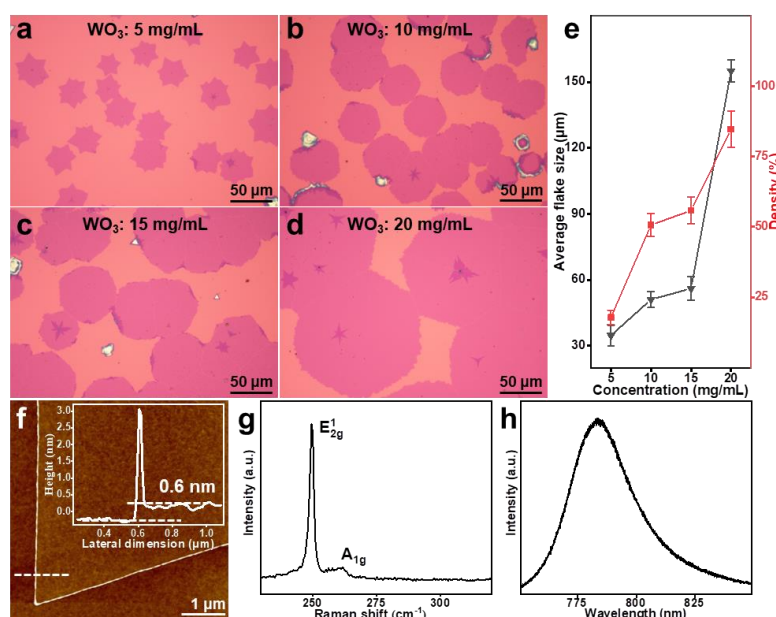


Figure 1. OM images of CVD-grown 1L WSe₂ nanosheets by dissolving WO₃ powder in NaOH solution at concentrations of (a) 5, (b) 10, (c) 15, and (d) 20 mg/mL, respectively. (e) The average flake size and density of 1L WSe₂ as a function of WO₃ concentration. (f) AFM image of the as-grown 1L WSe₂ nanosheet. Inset shows the height profile of the 1L WSe₂ nanosheet across the white dashed line. (g) Raman and (h) PL spectra of the 1L WSe₂ nanosheet.

Figure 1f–h shows the AFM image and Raman and PL spectra of a WSe₂ nanosheet grown at 800 °C by using 10 mg/mL of WO₃. The AFM image shown in Figure 1f indicates the smooth morphology of the WSe₂ nanosheet. The measured thickness of the WSe₂ nanosheet is 0.6 nm, indicating the monolayer structure. Raman and PL spectroscopy were then used to confirm the thickness and crystalline quality of the WSe₂ nanosheets shown in Figure 1a–d. There are two representative Raman peaks located at ~250 cm^{−1} (E_{2g}¹) and ~260 cm^{−1} (A_{1g}) (Figure 1g), indicating the good crystalline structure of the WSe₂ nanosheets. The absence of the B_{2g}¹ peak at ~308 cm^{−1} suggests the monolayer structure of the as-grown WSe₂ nanosheets. Moreover, a symmetric PL peak located at 783.1 nm further confirms the existence of 1L WSe₂ (Figure 1h) [1,5].

We found that the growth temperature also has an important effect on the growth of WSe₂ in addition to the precursor concentration and the distance between the substrate and Se powder. Figure 2a–c show OM images of WSe₂ nanosheets grown at 850, 900, and 950 °C, respectively. When the growth temperature was set to 850 °C, many WSe₂ nanosheets with darker contrast than the 1L WSe₂ nanosheet were observed (Figure 2a). AFM was used to measure the thickness of these WSe₂ nanosheets. As shown in Figure 2d, the thickness of the WSe₂ nanosheet was measured to be 1.3 nm, as expected for the 2L nanosheet [1]. Moreover, there are also some multilayer (ML) WSe₂ nanosheets shown in Figure 2a, as indicated by the yellow arrows. The size of the 2L and ML WSe₂ nanosheets grown at 850 °C was usually in the range of 10 to 20 μm. The number of 2L and ML WSe₂ nanosheets was then counted. It was found that more than 87.0 ± 3.6% of the WSe₂ nanosheets were 2L, as shown in Figure 2e. As the growth temperature increased to 900 °C, uniform 2L WSe₂ nanosheets with sizes larger than 20 μm were grown, and the surfaces of the WSe₂ nanosheets were cleaner than that of the WSe₂ nanosheet grown at 850 °C. In this case, the percentage of 2L WSe₂ nanosheets increased to 91.3 ± 3.1% (Figure 2e) while the percentage of 2L WSe₂ nanosheets decreased to 76.3 ± 2.5% as the temperature further increased to 950 °C. As indicated in Figure 2c, some ML WSe₂ nanosheets were observed. With the increase of in temperature, the longitudinal growth of WSe₂ nanosheets was promoted because of the increased concentration of selenium vapor, which accelerated

the reaction with Na_2WO_4 [38,43]. As the temperature increased from 850 to 950 °C, the size of the 2L WSe_2 nanosheets increased from 11.8 ± 0.6 to 21.2 ± 0.2 μm . Therefore, the optimal temperature for growing 2L WSe_2 nanosheets was set to 900 °C, which is higher than that of the 1L nanosheets. The reasons can be explained as follows. It is well known that the temperature gradients within the tube furnace play an important role in controlling the growth of 2D TMDC nanosheets in the CVD process. In our work, the temperature gradients also influenced the growth of the WSe_2 nanosheets. As shown in Figure S3 in SI, the Se powders were placed in a boat, which was just out of the left end of the furnace. When the temperature of the furnace center was set to 800 °C, the temperature of this boat might be a bit higher than the melting point of Se, leading to slow evaporation of the Se powder. Therefore, a low concentration of Se vapor could be transported to the Na_2WO_4 -coated SiO_2/Si substrate for growing large 1L WSe_2 nanosheets. As the temperature of the furnace center increased to 900 °C, the temperature of the Se boat further increased. Thus, a higher concentration of Se vapor could be transported to the Na_2WO_4 -coated SiO_2/Si substrate, which accelerated the vertical growth of the WSe_2 nanosheet while the lateral growth was a bit decelerated. In this case, 2L WSe_2 nanosheets with smaller sizes than the 1L WSe_2 nanosheets were obtained. We also investigated the influence of growth time on the formation of 1L and 2L WSe_2 nanosheets. Figure S4 in SI shows the 1L and 2L WSe_2 nanosheets grown under the same conditions with growth times of 1, 5, and 10 min, respectively. The growth time shows a slight influence on the size of the 1L WSe_2 nanosheets. As shown in Figure S4a,b in SI, the size of the 1L WSe_2 nanosheets slightly increased as the growth time was changed from 1 min to 5 min. However, there were small, irregular WSe_2 flakes grown on top of the 1L WSe_2 as the growth time increased to 10 min. Figure S4d–f in SI show the OM images of 2L WSe_2 nanosheets at different growth times. The size of 2L WSe_2 showed little change at different growth times.

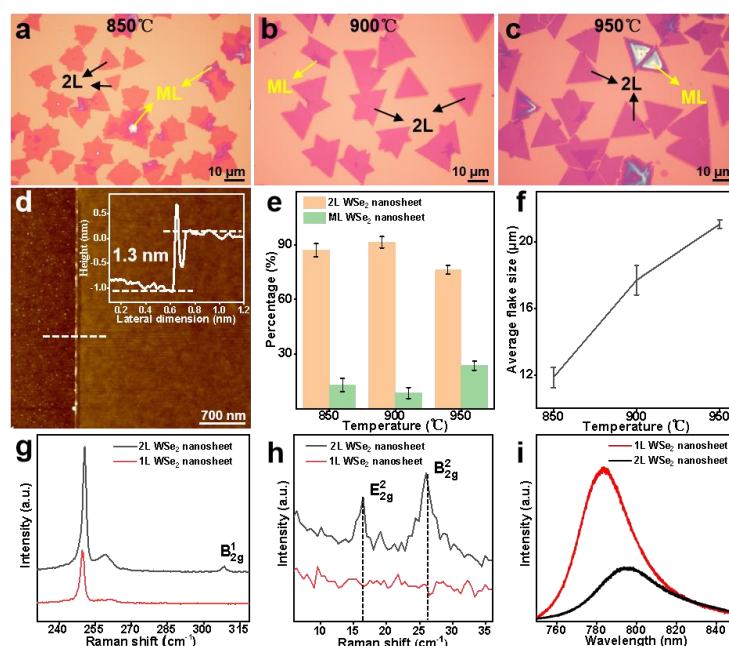


Figure 2. OM images of CVD-grown 2L WSe_2 nanosheets at (a) 850, (b) 900, and (c) 950 °C, respectively. (d) AFM image of the as-grown 2L WSe_2 nanosheet. Inset shows the height profile of the 2L WSe_2 nanosheet across the white dashed line. (e) The statistical histogram of 2L and 1L WSe_2 nanosheets grown at different temperatures. (f) The average flake size of 2L WSe_2 as a function of growth temperature. (g) High-frequency Raman, (h) low-frequency Raman, and (i) PL spectra of 1L and 2L WSe_2 nanosheets.

It is worth noting that the 2L WSe_2 nanosheets are triangle shaped, which are different from the hexagonal shape of the 1L WSe_2 nanosheets. This could be explained as follows.

The 1L WSe₂ nanosheets grown at lower temperature and precursor concentration exhibit symmetric six-pointed star shapes, which could be assigned to the slower growth rate and the surface diffusion energy (Figure 1a) [31]. When the concentration of WO₃ increases from 5 to 10 mg/mL, the ratio of W to the Se precursor increases, which promotes the lateral growth of the WSe₂ nanosheets. Thus, the 1L WSe₂ nanosheets are changed into hexagonal shapes. With the increase in temperature (~900 °C), the concentration of Se vapor increases, accelerating the vertical growth to obtain 2L WSe₂ nanosheets [43,44]. On the other hand, the kinetic-controlled attachment and detachment of atoms also affect the domain morphology. When 1L WSe₂ nanosheets are grown at a low precursor concentration under a relatively low temperature (800 °C), the growth rates at the W-terminated and Se-terminated ends are almost equal due to the low nucleation density, resulting in a hexagonal domain with zigzag edges. With the increase in the W precursor concentration, the hexagonal-shaped domain grows continuously, which is energy favorable. When the 2L WSe₂ nanosheets are grown at a higher temperature (900 °C), due to the increased concentration of Se vapor, the growth rate of the Se-terminated end is faster than that of the W-terminated end. In this case, the domain would be changed from a hexagon to a triangle. Moreover, the reaction rate is quite fast at high temperatures, and the W and Se atoms are not easy to diffuse to the energy-favorable position, resulting in the size of the 2LWSe₂ nanosheet being smaller than that of the 1L WSe₂ nanosheet [44]. Such a kind of shape evolution was also reported in the CVD growth of MoS₂ nanosheets [45].

Figure 2g–i show the ultralow frequency (ULF) and high-frequency Raman and PL spectra of the 2L WSe₂ nanosheet. There is a B_{2g}¹ peak at ~309 cm⁻¹ in the high-frequency Raman spectrum of the WSe₂ nanosheets (Figure 2g) that is absent in the 1L WSe₂ nanosheet, implying they are of 2L or larger thickness. As shown in Figure 2h, the WSe₂ nanosheet shows a shear mode peak at 16.4 cm⁻¹ and a layer breathing mode peak at 26.1 cm⁻¹ in the ULF Raman spectrum, which are the characteristic ULF peaks of 2L WSe₂ [46], confirming the 2L thickness of as-grown WSe₂ nanosheets. As shown in Figure 2i, the 2L WSe₂ shows a relatively weak PL peak at 794.4 nm, while the 1L WSe₂ shows a strong peak at 783.1 nm in the PL spectra, which are consistent with previous reports [19,47].

In order to evaluate the optoelectronic properties of 1L and 2L WSe₂ nanosheets grown on SiO₂/Si substrate, back-gate field-effect transistor devices were fabricated by using a TEM grid as a mask in the thermal evaporator. The typical I_{ds} - V_{ds} characteristics of 1L and 2L WSe₂ devices are shown in Figure 3a,c. The drain current decreases with the increase in the gate voltage, indicating the p-type behavior of the as-fabricated WSe₂ devices. The I_{ds} - V_g curves of the 1L and 2L WSe₂ devices are plotted in Figure 3b,d. The I_{ds} decreases monotonically with the increase in V_g , also confirming the p-type behavior. The field-effect mobility of WSe₂ devices is calculated by using the following formula.

$$\mu = \frac{L}{W \times \left(\frac{\epsilon_0 \epsilon_r}{d}\right) \times V_{ds}} \frac{dI_{ds}}{dV_g} \quad (3)$$

where L and W are the length and width of the device channel, ϵ_0 is 8.854×10^{-12} Fm⁻¹, ϵ_r for SiO₂ is 3.9, and d is the thickness of SiO₂ (300 nm). The dI_{ds}/dV_g represents the slope extracted from the linear region of the transfer curve [48,49].

The calculated mobilities were ~0.017 and ~0.9604 cm²V⁻¹s⁻¹ for 1L and 2L WSe₂ nanosheets when a constant voltage of 10V was applied between the source and drain, respectively, which are comparable to previous reports [3,50]. The 2L WSe₂ nanosheet showed much higher mobility than that of the 1L WSe₂ nanosheet, which is consistent with previous reports [17,47].

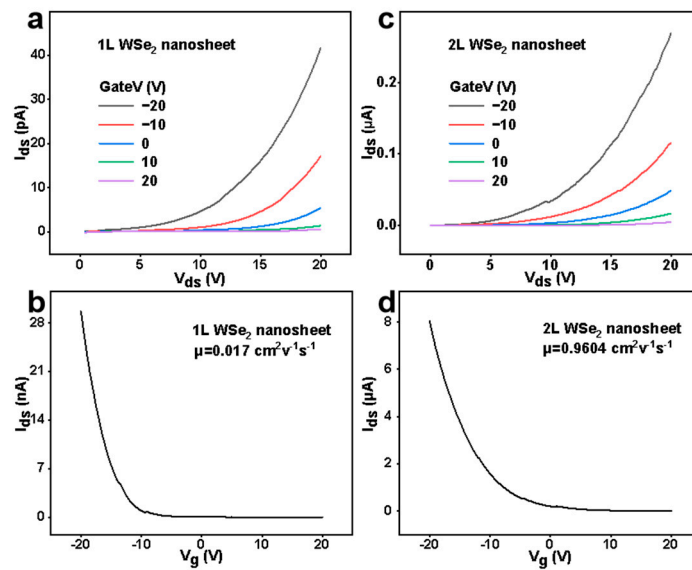


Figure 3. Output and transfer curves of devices based on (a,b) 1L and (c,d) 2L WSe₂ nanosheets.

Following the electrical measurement, the optoelectronic performance of the 1L and 2L WSe₂ devices was investigated under 405, 532, and 633 nm lasers with different power densities, respectively. As shown in Figure 4a, the I_{ds} of the 1L WSe₂ device linearly increased to 0.6 pA as the V_{ds} increased from 0 to 1.0 V under dark conditions. When the 1L WSe₂ device was illuminated by a 405 nm laser with a power density of 0.2 mW/mm², the I_{ds} increased to 1.4 pA as the V_{ds} increased from 0 to 1.0 V. As the power density of the 405 nm laser increased from 0.5 to 1.1 mW/mm², the I_{ds} of the 1L WSe₂ device also increased from 2.0 pA to 4.0 pA, indicating it has good optoelectronic performance under illumination. The I_{ds} of the 2L WSe₂ device linearly increased to 0.3 pA as the V_{ds} increased from 0 to 1.0 V under dark conditions, as shown in Figure 4b. Surprisingly, the I_{ds} of the 2L WSe₂ device greatly increased to 206 pA as the V_{ds} increased from 0 to 1.0 V when the device was illuminated by a 405 nm laser with a power density of 0.2 mW/mm². The I_{ds} continuously increased under the 405 nm laser with increased power density. Similar phenomena were also observed in both 1L and 2L WSe₂ devices under illumination with 532 and 633 nm lasers (Figure S5 in SI), indicating the I_{ds} has a strong dependence on the laser power density [51]. We also investigated the photoresponsivity (R), EQE, and specific detectivity (D^*) of the 1L and 2L WSe₂ devices by the following equations.

$$R = I_{ph}/PS \quad (4)$$

where I_{ph} is the photocurrent, P is the incident power density, and S is the effective illumination area of the device.

$$EQE = hcR/e\lambda \quad (5)$$

where h is the Planck's constant, c is the speed of light, e is the charge, and λ is the laser wavelength.

$$D^* = \frac{R_{\lambda} S^{1/2}}{(2eI_{dark})^{1/2}} \quad (6)$$

where R_{λ} is responsivity, S is the effective irradiated area, e is the charge, and I_{dark} is the dark current.

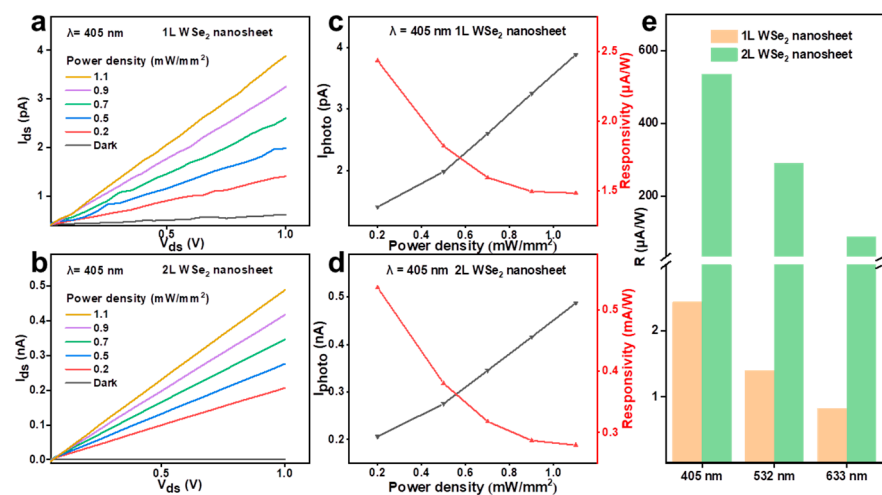


Figure 4. The output characteristics of photodetectors based on (a) 1L and (b) 2L WSe₂ nanosheets at $V_g = 0$ V illuminated by 405 nm laser with various power densities. The photocurrent and photoresponsivity of (c) 1L and (d) 2L WSe₂ devices illuminated by 405 nm lasers as a function of laser power density. (e) The statistical histogram of the photoresponsivity of photodetectors based on 1L and 2L WSe₂ nanosheets.

Figure 4c,d show the photoresponsivity and photocurrent characteristics of 1L and 2L WSe₂ devices under the 405 nm laser. The photocurrent of the 1L and 2L WSe₂ devices monotonously increased as the laser power density increased from 0.2 to 1.1 mW/mm². The photoresponsivity of the 2L WSe₂ photodetector was two orders of magnitude higher than that of the 1L WSe₂ photodetector. Figure S6 in SI shows the plots of the photocurrent and photoresponsivity of the 1L and 2L WSe₂ photodetectors as a function of laser power density under the 532 and 633 nm lasers, respectively, which are similar to the characteristics shown in Figure 4c,d. The 2L WSe₂ nanosheets also showed much higher D* and EQE than those of the 1L WSe₂ nanosheets under 405, 532, and 633 nm lasers. Table S1 in the SI compares the performance of this work with the previously reported photodetectors based on TMDC [52–55]. Compared with other photodetectors, our WSe₂ devices show comparable performance. The aforementioned results show that the 2L WSe₂ nanosheets exhibited much better performance than the 1L WSe₂ nanosheets, implying the influence of thickness on the optoelectronic performance [19,20,56].

In addition to photoresponsivity, photosensitivity is also an important parameter to evaluate the performance of photodetectors [51,57,58]. Photosensitivity is usually described as the photocurrent-to-dark-current ratio (PDR), which is defined by the following equation.

$$\text{PDR} = I_{\text{photo}} / I_{\text{dark}} \quad (7)$$

where I_{photo} is the photocurrent under illumination, and I_{dark} is the baseline current without illumination.

Figure 5a shows the photosensitivity of 1L and 2L WSe₂ devices as a function of time under illumination with a 405 nm laser with a power density of 1.8 mW/mm² and under dark conditions. The photodetectors based on the 1L and 2L WSe₂ nanosheets exhibited quite stable characteristics after multiple illumination–dark cycles. The PDR of the 1L WSe₂ device was ~100, while the 2L WSe₂ photodetector showed a PDR of ~760 (blue curve in Figure 5a), which is about one order of magnitude higher than that of the 1L WSe₂ photodetector (black curve in Figure 5a). Similarly, the 2L WSe₂ photodetector also shows a much higher PDR than that of the 1L WSe₂ photodetector under 532 and 633 nm lasers (Figure S7 in SI), implying the 2L WSe₂ nanosheet presents high photosensitivity and better optoelectronic performance. As shown in Figure 5b, the PDRs of the 1L and 2L WSe₂ devices under the 405 nm laser were plotted as a function of laser power density. With the decrease in laser power density, the PDR decreased accordingly, indicating it is highly

dependent on the laser power density [58]. As shown in Figure 5c, compared with the 1L WSe₂ photodetector, the PDR of the 2L WSe₂ photodetector greatly increased with the increasing laser power density under illumination with a 405 nm laser. Moreover, the PDRs of the 2L WSe₂ photodetectors also showed one order of magnitude higher than those of the 1L WSe₂ photodetectors under illumination of 532 and 633 nm lasers with various power densities (Figure S8 in SI), respectively. Therefore, the photodetector based on the 2L WSe₂ nanosheet showed much better photodetection performance than that based on the 1L WSe₂ nanosheet.

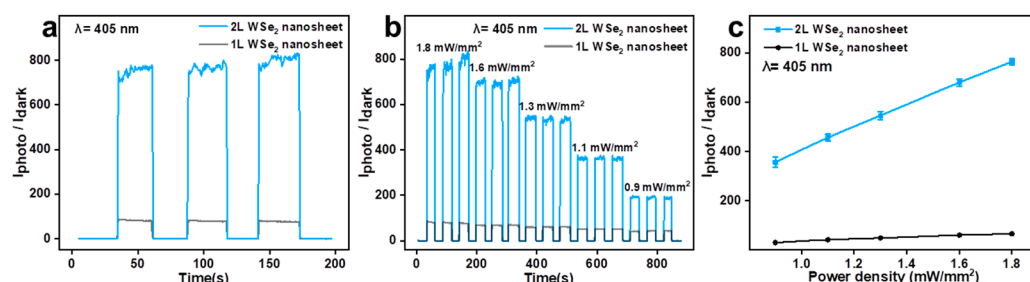


Figure 5. (a) The PDR plot of photodetectors based on 1L and 2L WSe₂ nanosheets under a 405 nm laser with a power density of 1.8 mW/mm². (b,c) The PDR plots of photodetectors based on the 1L and 2L WSe₂ nanosheets under a 405 nm laser as a function of the laser power density.

In addition, the photoresponse time and recovery time of the 1L WSe₂ photodetector are 1.5 s and 1.5 s (Figure S9 in SI), respectively, while the photoresponse time and recovery time of the 2L WSe₂ photodetector are 0.6 s and 0.5 s, respectively, indicating the 2L WSe₂ photodetector shows a much faster response than the 1L WSe₂ photodetector under illumination with a 405 nm laser. Similar phenomena were also observed for 1L and 2L WSe₂ photodetectors illuminated by 532 and 633 nm lasers (Figure S9 in SI). The detailed optoelectronic performance of the 1L and 2L WSe₂ devices is listed in Table 1. Compared with the 1L WSe₂ photodetector, the 2L WSe₂ photodetector shows much better performance.

Table 1. The detailed photocurrent, photoresponsivity, specific detectivity, external quantum efficiency, PDR, response time, and mobility of 1L and 2L WSe₂ devices under 405, 532, and 633 nm lasers, respectively.

Device	Wavelength	I _{Photo} (pA)	R (A/W)	D* (cm·Hz ^{1/2} W ^{−1})	EQE (%)	PDR	T _r (s)	μ (cm ² V ^{−1} S ^{−1})
1L	405 nm	1.41	2.44 × 10 ^{−6}	1.45 × 10 ⁹	7.46 × 10 ^{−4}	66	1.5	0.017
	532 nm	1.14	1.40 × 10 ^{−6}	8.20 × 10 ⁸	3.26 × 10 ^{−4}	82	1.4	
	633 nm	1.10	8.30 × 10 ^{−7}	5.24 × 10 ⁸	1.63 × 10 ^{−4}	76	1.4	
2L	405 nm	206	5.36 × 10 ^{−4}	4.42 × 10 ¹¹	1.64 × 10 ^{−1}	761	0.6	0.96
	532 nm	158	2.91 × 10 ^{−4}	2.35 × 10 ¹¹	6.80 × 10 ^{−2}	860	0.7	
	633 nm	77.6	8.79 × 10 ^{−5}	6.91 × 10 ¹⁰	1.72 × 10 ^{−2}	790	0.7	

4. Conclusions

In summary, 1L and 2L WSe₂ nanosheets were successfully grown on a SiO₂/Si substrate by using liquid precursor-mediated CVD. Different from the solid precursor used in typical CVD, WO₃ powder was dissolved in a NaOH solution and used as a liquid precursor. The size and thickness of the WSe₂ nanosheets were well regulated by optimizing the precursor concentration and growth temperature. As the precursor concentration increased, the size of the 1L WSe₂ nanosheet also increased. The 1L WSe₂ nanosheets were grown at 800 °C, while 2L WSe₂ nanosheets were obtained at 900 °C. The OM, AFM, and Raman and PL spectroscopy characterizations confirmed that the 1L and 2L

WSe₂ nanosheets were of good quality. Compared with the 1L WSe₂ nanosheet, the device based on the 2L WSe₂ nanosheet showed much better optoelectronic performance. The photoresponsivity, external quantum efficiency (EQE), carrier mobility, photoresponsivity, and specific detectivity of the 2L WSe₂ nanosheet were about two orders of magnitude higher than those of the 1L WSe₂ nanosheet. Moreover, the 2L WSe₂ nanosheet also showed a PDR about ten times higher than 1L WSe₂ nanosheet. Our results indicate that the 2L WSe₂ nanosheet shows much better optoelectronic performance than the 1L WSe₂ nanosheet and could be a promising candidate for high-performance optoelectronic devices.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/nano14242021/s1>, Figure S1: The statistics investigation of the surface area percentage of SiO₂/Si substrate covered by WSe₂ nanosheets. (a) Color image of WSe₂ nanosheets on SiO₂/Si substrate. (b) Gray-scale image of (a) processed by ImageJ (version 1.54g). (c) The coverage of WSe₂ nanosheets on SiO₂/Si substrate was statistically analyzed by ImageJ. Figure S2: (a) Schematic illustration of the evaporation of Se powder at various distances away from the SiO₂/Si substrate placed at the center of a CVD tube furnace. (b–e) OM images of 1L WSe₂ nanosheets grown at distances between the substrate and selenium powder of (b) 15.5, (c) 16.0, (d) 16.5, and (e) 17.0 cm, respectively. (f) The average flake size and density of 1L WSe₂ nanosheets as a function of distance. Figure S3: Schematic illustration of the evaporation of Se powder at (a) 800 and (b) 900 °C in a tube furnace. Figure S4: The OM images of (a–c) 1L and (d–f) 2L WSe₂ nanosheets grown at 800 and 900 °C with growth times of 1, 5, and 10 min, respectively. Figure S5: The output characteristics of photodetectors based on (a,c) 1L and (b,d) 2L WSe₂ nanosheets at V_g = 0 V under (a,b) 532 and (c,d) 633 nm lasers with various power densities. Figure S6: The photocurrent and photoresponsivity of (a,c) 1L and (b,d) 2L WSe₂ devices illuminated by (a,b) 532 and (c,d) 633 nm lasers as a function of laser power density. Table S1: Performance comparison of this work to the previously reported TMDC-based photodetector. Figure S7: The PDR plots of photodetectors based on 1L and 2L WSe₂ nanosheets under (a) 532 and (b) 633 nm lasers with power densities of 5.7 and 5.4 mW/mm², respectively. Figure S8: The PDR plots of photodetectors based on the 1L and 2L WSe₂ nanosheets under (a,c) 532 and (b,d) 633 nm lasers, respectively, as a function of the laser power density. Figure S9: Response and recovery time of photodetectors based on (a–c) 1L and (d–f) 2L WSe₂ nanosheets under (a,d) 405, (b,e) 532, and (c,f) 633 nm lasers, respectively.

Author Contributions: Conceptualization, H.L.; supervision and project administration, H.L.; methodology, H.L. and S.W.; formal analysis, S.W., P.W., H.T., S.Y., H.Y., X.F., J.D. and Y.Y.; investigation, S.W. and P.W.; writing—original draft preparation, H.L. and S.W.; revision of the manuscript, H.L. and S.W. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Natural Science Foundation of China (Grant No. 51832001, 21571101, and 51322202), the Natural Science Foundation of Jiangsu Province in China (Grant No. BK20161543), and the Natural Science Foundation of the Jiangsu Higher Education Institutions of China (Grant No. 15KJB430016).

Data Availability Statement: Data can be available upon request from the authors.

Conflicts of Interest: The authors declare no conflicts of interest.

References

- Li, H.; Lu, G.; Wang, Y.; Yin, Z.; Cong, C.; He, Q.; Wang, L.; Ding, F.; Yu, T.; Zhang, H. Mechanical Exfoliation and Characterization of Single- and Few-layer Nanosheets of WSe₂, TaS₂, and TaSe₂. *Small* **2013**, *9*, 1974–1981. [[CrossRef](#)] [[PubMed](#)]
- Tonndorf, P.S.; Schmidt, R.; Böttger, P.; Zhang, X.; Börner, J.; Liebig, A.; Albrecht, M.; Kloc, C.; Gordan, O.; Zahn, D.; et al. Photoluminescence Emission and Raman Response of Monolayer MoS₂, MoSe₂, and WSe₂. *Opt. Express* **2013**, *21*, 4908–4916. [[CrossRef](#)] [[PubMed](#)]
- Zhang, W.; Chiu, M.H.; Chen, C.H.; Chen, W.; Li, L.J.; Wee, A.T. Role of Metal Contacts in High-Performance Phototransistors Based on WSe₂ Monolayers. *ACS Nano* **2014**, *8*, 8653–8661. [[CrossRef](#)] [[PubMed](#)]
- Zhou, C.; Zhao, Y.; Raju, S.; Wang, Y.; Lin, Z.; Chan, M.; Chai, Y. Carrier Type Control of WSe₂ Field-Effect Transistors by Thickness Modulation and MoO₃ Layer Doping. *Adv. Funct. Mater.* **2016**, *26*, 4223–4230. [[CrossRef](#)]
- Huang, J.K.; Pu, J.; Hsu, C.L.; Chiu, M.H.; Juang, Z.Y.; Chang, Y.H.; Chang, W.H.; Iwasa, Y.; Takenobu, T.; Li, L.J. Large-Area Synthesis of Highly Crystalline WSe₂ Monolayers and Device Applications. *ACS Nano* **2014**, *8*, 923–930. [[CrossRef](#)]

6. Kang, W.; Cho, I.; Roh, J.; Lee, C.; Lee, J. High-Gain Complementary Metal-Oxide-Semiconductor Inverter Based on Multi-Layer WSe₂ Field Effect Transistors Without Doping. *Semicond. Sci. Technol.* **2016**, *31*, 105001–105007. [\[CrossRef\]](#)
7. Liu, B.; Fathi, M.; Chen, L.; Abbas, A.; Ma, Y.; Zhou, C. Chemical Vapor Deposition Growth of Monolayer WSe₂ with Tunable Device Characteristics and Growth Mechanism Study. *ACS Nano* **2015**, *9*, 6119–6127. [\[CrossRef\]](#)
8. Jin, Z.; Li, X.; Mullen, J.T.; Kim, K.W. Intrinsic Transport Properties of Electrons and Holes in Monolayer Transition-Metal Dichalcogenides. *Phys. Rev. B* **2014**, *90*, 045422–045428. [\[CrossRef\]](#)
9. Li, Y.; Xiao, J.; Cao, X.; Gu, Z.; Zhang, W. Lateral WSe₂ Homo Junction through Metal Contact Doping: Excellent Self-powered Photovoltaic Photodetector. *Adv. Funct. Mater.* **2023**, *33*, 2213385. [\[CrossRef\]](#)
10. Easy, E.; Gao, Y.; Wang, Y.; Yan, D.; Goushehgar, S.M.; Yang, E.-H.; Xu, B.; Zhang, X. Experimental and Computational Investigation of Layer-Dependent Thermal Conductivities and Interfacial Thermal Conductance of One- to Three-Layer WSe₂. *ACS Appl. Mater. Interfaces* **2021**, *13*, 13063–13071. [\[CrossRef\]](#)
11. Zhang, J.; Ji, T.; Jin, H.; Wang, Z.; Zhao, M.; He, D.; Luo, G.; Mao, B. Mild Liquid-Phase Exfoliation of Transition Metal Dichalcogenide Nanosheets for Hydrogen Evolution. *ACS Appl. Nano Mater.* **2022**, *5*, 8020–8028. [\[CrossRef\]](#)
12. Ross, J.S.; Klement, P.; Jones, A.M.; Ghimire, N.J.; Yan, J.; Mandrus, D.G.; Taniguchi, T.; Watanabe, K.; Kitamura, K.; Yao, W.; et al. Electrically Tunable Excitonic Light-Emitting Diodes Based on Monolayer WSe₂ p-n Junctions. *Nat. Nanotechnol.* **2014**, *9*, 268–272. [\[CrossRef\]](#) [\[PubMed\]](#)
13. Nguyen, D.A.; Oh, H.M.; Duong, N.T.; Bang, S.; Yoon, S.J.; Jeong, M.S. Highly Enhanced Photoresponsivity of a Monolayer WSe₂ Photodetector with Nitrogen-Doped Graphene Quantum Dots. *ACS Appl. Mater. Interfaces* **2018**, *10*, 10322–10329. [\[CrossRef\]](#) [\[PubMed\]](#)
14. Si, M.; Jiang, C.; Chung, W.; Du, Y.; Alam, M.A.; Ye, P.D. Steep-Slope WSe₂ Negative Capacitance Field-Effect Transistor. *Nano Lett.* **2018**, *18*, 3682–3687. [\[CrossRef\]](#)
15. Wu, S.; Huang, C.; Aivazian, G.; Ross, J.S.; Cobden, D.H.; Xu, X. Vapor-Solid Growth of High Optical Quality MoS₂ Monolayers with Near-Unity Valley Polarization. *ACS Nano* **2013**, *7*, 2768–2772. [\[CrossRef\]](#)
16. Kong, D.; Dang, W.; Cha, J.J.; Li, H.; Meister, S.; Peng, H.; Liu, Z.; Cui, Y. Few-Layer Nanoplates of Bi₂Se₃ and Bi₂Te₃ with Highly Tunable Chemical Potential. *Nano Lett.* **2010**, *10*, 2245–2250. [\[CrossRef\]](#)
17. Zhou, H.; Wang, C.; Shaw, J.C.; Cheng, R.; Chen, Y.; Huang, X.; Liu, Y.; Weiss, N.O.; Lin, Z.; Huang, Y.; et al. Large Area Growth and Electrical Properties of p-Type WSe₂ Atomic Layers. *Nano Lett.* **2015**, *15*, 709–713. [\[CrossRef\]](#)
18. Lee, J.; Pak, S.; Giraud, P.; Lee, Y.W.; Cho, Y.; Hong, J.; Jang, A.R.; Chung, H.S.; Hong, W.K.; Jeong, H.Y.; et al. Thermodynamically Stable Synthesis of Large-Scale and Highly Crystalline Transition Metal Dichalcogenide Monolayers and their Unipolar n-n Heterojunction Devices. *Adv. Mater.* **2017**, *29*, 1702206. [\[CrossRef\]](#)
19. Wang, X.; Shi, X.; Gu, C.; Guo, Q.; Liu, H.; Li, X.; Wu, Y. High-Performance n-Type Transistors Based on CVD-grown Large-Domain Trilayer WSe₂. *APL Mater.* **2021**, *9*, 071109. [\[CrossRef\]](#)
20. Fang, X.; Wei, P.; Wang, L.; Wang, X.; Chen, B.; He, Q.; Yue, Q.; Zhang, J.; Zhao, W.; Wang, J.; et al. Transforming Monolayer Transition-Metal Dichalcogenide Nanosheets into One-Dimensional Nanoscrolls with High Photosensitivity. *ACS Appl. Mater. Interfaces* **2018**, *10*, 13011–13018. [\[CrossRef\]](#)
21. Liang, L.; Li, K.; Xiao, C.; Fan, S.; Liu, J.; Zhang, W.; Xu, W.; Tong, W.; Liao, J.; Zhou, Y.; et al. Vacancy Associates-Rich Ultrathin Nanosheets for High Performance and Flexible Nonvolatile Memory Device. *J. Am. Chem. Soc.* **2015**, *137*, 3102–3108. [\[CrossRef\]](#) [\[PubMed\]](#)
22. Khan, U.; May, P.; O'Neill, A.; Bell, A.P.; Boussac, E.; Martin, A.; Semple, J.; Coleman, J.N. Polymer Reinforcement Using Liquid-Exfoliated Boron Nitride Nanosheets. *Nanoscale* **2013**, *5*, 581–587. [\[CrossRef\]](#) [\[PubMed\]](#)
23. Coleman, J.N.; Lotya, M.; O'Neill, A.; Bergin, S.D.; King, P.J.; Khan, U.; Young, K.; Gaucher, A.; De, S.; Smith, R.J.; et al. Two-Dimensional Nanosheets Produced by Liquid Exfoliation of Layered Materials. *Science* **2011**, *331*, 568–571. [\[CrossRef\]](#) [\[PubMed\]](#)
24. Tian, M.; Li, X.; Li, T.; Gao, Q.; Xiong, X.; Hu, Q.; Wang, M.; Wang, X.; Wu, Y. High-Performance CVD Bernal-Stacked Bilayer Graphene Transistors for Amplifying and Mixing Signals at High Frequencies. *ACS Appl. Mater. Interfaces* **2018**, *10*, 20219–20224. [\[CrossRef\]](#)
25. Chen, J.; Liu, B.; Liu, Y.; Tang, W.; Nai, C.T.; Li, L.; Zheng, J.; Gao, L.; Zheng, Y.; Shin, H.S.; et al. Chemical Vapor Deposition of Large-Sized Hexagonal WSe₂ Crystals on Dielectric Substrates. *Adv. Mater.* **2015**, *27*, 6722–6727. [\[CrossRef\]](#)
26. Zhao, B.; Dang, W.; Liu, Y.; Li, B.; Li, J.; Luo, J.; Zhang, Z.; Wu, R.; Ma, H.; Sun, G.; et al. Synthetic Control of Two-Dimensional NiTe₂ Single Crystals with Highly Uniform Thickness Distributions. *J. Am. Chem. Soc.* **2018**, *140*, 14217–14223. [\[CrossRef\]](#)
27. Naylor, C.H.; Parkin, W.M.; Ping, J.; Gao, Z.; Zhou, Y.R.; Kim, Y.; Streller, F.; Carpick, R.W.; Rappe, A.M.; Drndic, M.; et al. Monolayer Single-Crystal 1T'-MoTe₂ Grown by Chemical Vapor Deposition Exhibits Weak Antilocalization Effect. *Nano Lett.* **2016**, *16*, 4297–4304. [\[CrossRef\]](#)
28. Tang, L.; Tan, J.; Nong, H.; Liu, B.; Cheng, H.-M. Chemical Vapor Deposition Growth of Two-Dimensional Compound Materials: Controllability, Material Quality, and Growth Mechanism. *Acc. Mater. Res.* **2020**, *2*, 36–47. [\[CrossRef\]](#)
29. Zhang, T.; Fu, L. Controllable Chemical Vapor Deposition Growth of Two-Dimensional Heterostructures. *Chem* **2018**, *4*, 671–689. [\[CrossRef\]](#)
30. Shaw, J.C.; Zhou, H.; Chen, Y.; Weiss, N.O.; Liu, Y.; Huang, Y.; Duan, X. Chemical Vapor Deposition Growth of Monolayer MoSe₂ Nanosheets. *Nano Res.* **2015**, *7*, 511–517. [\[CrossRef\]](#)

31. Feng, Q.; Zhu, M.; Zhao, Y.; Liu, H.; Li, M.; Zheng, J.; Xu, H.; Jiang, Y. Chemical Vapor Deposition Growth of Sub-centimeter Single Crystal WSe₂ Monolayer by NaCl-Ssistant. *Nanotechnology* **2019**, *30*, 034001–034010. [\[CrossRef\]](#) [\[PubMed\]](#)
32. Bandyopadhyay, A.S.; Adhikari, N.; Kaul, A.B. Quantum Multibody Interactions in Halide-Assisted Vapor-Synthesized Monolayer WSe₂ and Its Integration in a High Responsivity Photodetector with Low-Interface Trap Density. *Chem. Mater.* **2019**, *31*, 9861–9874. [\[CrossRef\]](#)
33. Gong, Y.; Lin, Z.; Ye, G.; Shi, G.; Feng, S.; Lei, Y.; Elias, A.L.; Perea-Lopez, N.; Vajtai, R.; Terrones, H.; et al. Tellurium-Assisted Low-Temperature Synthesis of MoS₂ and WS₂ Monolayers. *ACS Nano* **2015**, *9*, 11658–11666. [\[CrossRef\]](#) [\[PubMed\]](#)
34. Guan, H.; Zhao, B.; Zhao, W.; Ni, Z. Liquid-Precursor-Intermediated Synthesis of Atomically Thin Transition Metal Dichalcogenides. *Mater. Horiz.* **2023**, *10*, 1105–1120. [\[CrossRef\]](#)
35. Jeon, Y.; Seo, J.; Kim, J.; Rhee, D.; Jung, M.; Park, H.; Kang, J. Wafer-Scale Two-Dimensional Molybdenum Diselenide Phototransistor Array via Liquid-Precursor-Assisted Chemical Vapor Deposition. *Adv. Opt. Mater.* **2021**, *10*, 2101492. [\[CrossRef\]](#)
36. Wang, S.; Chen, Y.; Tan, T.; Sui, Y.; Tian, C.; Kong, Z.; Wang, H.; Zhao, S.; Xiao, R.; Chen, Z.; et al. One-Step Synthesis of a Bilayer MoS₂/WS₂ Lateral Heterojunction for Photoelectric Detection. *ACS Appl. Nano Mater.* **2022**, *5*, 17203–17211. [\[CrossRef\]](#)
37. Bai, X.; Li, S.; Das, S.; Du, L.; Dai, Y.; Yao, L.; Raju, R.; Du, M.; Lipsanen, H.; Sun, Z. Single-step Chemical Vapour Deposition of Anti-Pyramid MoS₂/WS₂ Vertical Heterostructures. *Nanoscale* **2021**, *13*, 4537–4542. [\[CrossRef\]](#)
38. Mandyam, S.V.; Zhao, M.Q.; Masih Das, P.; Zhang, Q.; Price, C.C.; Gao, Z.; Shenoy, V.B.; Drndic, M.; Johnson, A.T.C. Controlled Growth of Large-Area Bilayer Tungsten Diselenides with Lateral P-N Junctions. *ACS Nano* **2019**, *13*, 10490–10498. [\[CrossRef\]](#)
39. Gao, X.; Bian, G.; Zhu, J. Electronics from Solution-Processed 2D Semiconductors. *J. Mater. Chem. C* **2019**, *7*, 12835–12861. [\[CrossRef\]](#)
40. Cun, H.; Macha, M.; Kim, H.; Liu, K.; Zhao, Y.; LaGrange, T.; Kis, A.; Radenovic, A. Wafer-Scale MOCVD Growth of Monolayer MoS₂ on Sapphire and SiO₂. *Nano Res.* **2019**, *12*, 2646–2652. [\[CrossRef\]](#)
41. Oh, H.M.; Han, G.H.; Kim, H.; Jeong, M.S. Influence of Residual Promoter to Photoluminescence of CVD Grown MoS₂. *Curr. Appl. Phys.* **2016**, *16*, 1223–1228. [\[CrossRef\]](#)
42. Kim, H.; Han, G.H.; Yun, S.J.; Zhao, J.; Keum, D.H.; Jeong, H.Y.; Ly, T.H.; Jin, Y.; Park, J.-H.; Moon, B.H.; et al. Role of Alkali Metal Promoter in Enhancing Lateral Growth of Monolayer Transition Metal Dichalcogenides. *Nanotechnology* **2017**, *28*, 36LT01. [\[CrossRef\]](#) [\[PubMed\]](#)
43. Zheng, W.; Qiu, Y.; Feng, W.; Chen, J.; Yang, H.; Wu, S.; Jia, D.; Zhou, Y.; Hu, P. Controlled Growth of Six-Point Stars MoS₂ by Chemical Vapor Deposition and Its Shape Evolution Mechanism. *Nanotechnology* **2017**, *28*, 395601–395609. [\[CrossRef\]](#) [\[PubMed\]](#)
44. Chen, S.; Gao, J.; Srinivasan, B.M.; Zhang, G.; Sorkin, V.; Hariharaputran, R.; Zhang, Y.-W. Origin of Ultrafast Growth of Monolayer WSe₂ via Chemical Vapor Deposition. *npj Comput. Mater.* **2019**, *5*, 28–35. [\[CrossRef\]](#)
45. Najmaei, S.; Liu, Z.; Zhou, W.; Zou, X.; Shi, G.; Lei, S.; Yakobson, B.I.; Idrobo, J.-C.; Ajayan, P.M.; Lou, J. Vapour Phase Growth and Grain Boundary Structure of Molybdenum Disulphide Atomic Layers. *Nat. Mater.* **2013**, *12*, 754–759. [\[CrossRef\]](#)
46. Zhao, Y.; Luo, X.; Li, H.; Zhang, J.; Araujo, P.T.; Gan, C.K.; Wu, J.; Zhang, H.; Quek, S.Y.; Dresselhaus, M.S.; et al. Interlayer Breathing and Shear Modes in Few-Trilayer MoS₂ and WSe₂. *Nano Lett.* **2013**, *13*, 1007–1015. [\[CrossRef\]](#)
47. Zhang, Z.; Liu, Y.; Dai, C.; Yang, X.; Chen, P.; Ma, H.; Zhao, B.; Wu, R.; Huang, Z.; Wang, D.; et al. Highly Selective Synthesis of Monolayer or Bilayer WSe₂ Single Crystals by Pre-annealing the Solid Precursor. *Chem. Mater.* **2021**, *33*, 1307–1313. [\[CrossRef\]](#)
48. Ye, H.; Tang, H.; Yu, S.; Yang, Y.; Li, H. Rhodamine 6G/Transition Metal Dichalcogenide Hybrid Nanoscrolls for Enhanced Optoelectronic Performance. *Molecules* **2024**, *29*, 2799–2813. [\[CrossRef\]](#)
49. Yu, S.; Ye, H.; Wang, S.; Tang, H.; Wang, P.; Pei, C.; Yang, Y.; Huang, X.; Li, H. Centrifugal Force-Assisted Preparation of Closely Packed Transition Metal Dichalcogenide Nanoscrolls for Enhanced Optoelectronic Performance. *ACS Appl. Nano Mater.* **2024**, *7*, 18801–18810. [\[CrossRef\]](#)
50. Huang, J.; Yang, L.; Liu, D.; Chen, J.; Fu, Q.; Xiong, Y.; Lin, F.; Xiang, B. Large-Area Synthesis of Monolayer WSe₂ on a SiO₂/Si Substrate and Its Device Applications. *Nanoscale* **2015**, *7*, 4193–4198. [\[CrossRef\]](#)
51. Wang, L.; Li, X.; Pei, C.; Wei, C.; Dai, J.; Huang, X.; Li, H. Single- and Few-Layer 2H-SnS₂ and 4H-SnS₂ Nanosheets for High-Performance Photodetection. *Chin. Chem. Lett.* **2022**, *33*, 2611–2616. [\[CrossRef\]](#)
52. Guskov, A.; Lavrov, S.; Galiev, R. Polarization Sensitive Photodetectors Based on Two-Dimensional WSe₂. *Nanomaterials* **2022**, *12*, 1854–1864. [\[CrossRef\]](#) [\[PubMed\]](#)
53. You, J.; Jin, Z.; Li, Y.; Kang, T.; Zhang, K.; Wang, W.; Xu, M.; Gao, Z.; Wang, J.; Kim, J.K.; et al. Epitaxial Growth of 1D Te/2D MoSe₂ Mixed-Dimensional Heterostructures for High-Efficient Self-Powered Photodetector. *Adv. Funct. Mater.* **2024**, *34*, 2311134. [\[CrossRef\]](#)
54. Talib, M.; Tripathi, N.; Manzoor, S.; Sharma, P.; Pavelyev, V.; Volkov, V.S.; Arsenin, A.V.; Novikov, S.M.; Mishra, P. TiS₃ Nanoribbons: A Novel Material for Ultra-Sensitive Photodetection across Extreme Temperature Ranges. *Sensors* **2023**, *23*, 4948–4962. [\[CrossRef\]](#)
55. Groenendijk, D.J.; Buscema, M.; Steele, G.A.; Michaelis de Vasconcellos, S.; Bratschitsch, R.; van der Zant, H.S.J.; Castellanos-Gomez, A. Photovoltaic and Photothermoelectric Effect in a Double-Gated WSe₂ Device. *Nano Lett.* **2014**, *14*, 5846–5852. [\[CrossRef\]](#)
56. Han, A.; Aljarb, A.; Liu, S.; Li, P.; Ma, C.; Xue, F.; Lopatin, S.; Yang, C.-W.; Huang, J.-K.; Wan, Y.; et al. Growth of 2H Stacked WSe₂ Bilayers on Sapphire. *Nanoscale Horiz.* **2019**, *4*, 1434–1442. [\[CrossRef\]](#)

57. Fan, H.; Wang, J.; Li, X.; You, H.; Li, X.; Pei, C.; Huang, X.; Li, H. Direct CVD Growth of MoS₂ on Chemically and Thermally Reduced Graphene Oxide Nanosheets for Improved Photoresponse. *APL Mater.* **2021**, *9*, 051105–051114. [[CrossRef](#)]
58. Zhao, Y.; You, H.; Li, X.; Pei, C.; Huang, X.; Li, H. Solvent-Free Preparation of Closely Packed MoS₂ Nanoscrolls for Improved Photosensitivity. *ACS Appl. Mater. Interfaces* **2022**, *14*, 9515–9524. [[CrossRef](#)]

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