A wafer-scale synthesis of monolayer MoS2 and their field-effect transistors toward practical applications

Yuchun Liu and Fuxing Gu

Molybdenum disulfide (MoS2) has attracted considerable research interest as a promising candidate for downscaling integrated electronics due to the special two-dimensional structure and unique physicochemical properties. However, it is still challenging to achieve large-area MoS2 monolayers with desired material quality and electrical properties to fulfill the requirement for practical applications. Recently, a variety of investigations have focused on wafer-scale monolayer MoS2 synthesis with high-quality. The 2D MoS2 field-effect transistor (MoS2-FET) array with different configurations utilizes the high-quality MoS2 film as channels and exhibits favorable performance. In this review, we illustrated the latest research advances in wafer-scale monolayer MoS2 synthesis by different methods, including Au-assisted exfoliation, CVD, thin film sulfurization, MOCVD, ALD, VLS method, and the thermolysis of thiosalts. Then, an overview of MoS2-FET developments was provided based on large-area MoS2 film with different device configurations and performances. The different applications of MoS2-FET in logic circuits, basic memory devices, and integrated photodetectors were also summarized. Lastly, we considered the perspective and challenges based on wafer-scale monolayer MoS2 synthesis and MoS2-FET for developing practical applications in next-generation integrated electronics and flexible optoelectronics.

1. Introduction

In recent years, 2D transition metal dichalcogenides (TMD), especially molybdenum disulfide (MoS2), have attracted widespread attention for a variety of next-generation electronic and optoelectronic device applications.1–3 Compared with conventional silicon-based semiconductors, monolayer MoS2 is envisioned as an alternate building block for the next-generation electronic device and integrated circuit with short channel, thin thickness, small volume, light weight, fast speed, and high sensitivity.4–12 However, it is still very challenging to achieve large-area, high-quality MoS2 for practical applications. Since the traditional mechanical exfoliation method is difficult to

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meet the needs of wafer-scale MoS$_2$ synthesis in terms of the yield, size, thickness, and uniformity, most MoS$_2$ investigations synthesis have focused on developing the vapor phase growth of monolayer MoS$_2$. Generally, synthetic methods for large-area monolayers and few-layer MoS$_2$ films include traditional vapor–liquid–solid (VLS), atomic layer deposition (ALD), chemical vapor deposition (CVD), etc. Due to the development of synthetic methods, the large-area, high-quality continuous monolayer MoS$_2$ films have been successfully reported, with a wafer-scale even up to 8 inch, suggesting great potential in integrated devices compatible with silicon-based micro-fabrication processes.

In the past decade, 2D MoS$_2$ with atomic thickness is considered one of the most promising candidates for the downscaling trend in integrated electronics, which leads to continuing demands for minimizing the channel thickness. The wafer-scale 2D MoS$_2$ films can be reliably transferred and heterogeneously integrated onto a variety of substrates with the aid of polymethyl methacrylate (PMMA) or olydimethylsiloxane (PDMS), demonstrating many important applications in environment-friendly transient devices. Since the fabrication process of wafer-scale MoS$_2$-based devices can be more compatible with the traditional complementary metal oxide semiconductor (CMOS) fabrication process, many investigations have focused on developing wafer-scale monolayer MoS$_2$ and high-performance MoS$_2$ field-effect transistors (MoS$_2$-FET) to significantly promote their future device applications, especially electronic and optoelectronic applications. The fabricated MoS$_2$-FET have achieved attractive performance with high on/off ratios up to $10^{10}$ and a high mobility of about $167 \pm 20$ cm$^2$/V·s. Even though the reported field effect mobility of MoS$_2$-FET is still behind that of Si-based transistors, explorations are promising to advance one step further from a single MoS$_2$-FET to complex devices, such as basic logic gate circuits, basic memory devices, and integrated phototransistors. With the development of MoS$_2$ synthesis and FET techniques, 2D MoS$_2$ would play a great role in next-generation integrated circuits and flexible electronics.

In this review, we focus on wafer-scale synthesis of monolayer MoS$_2$ film and the high-performance MoS$_2$-FET toward practical applications. We first introduce the recent progresses in MoS$_2$ synthesis by different methods, including Au-assisted exfoliation, CVD, thin film sulfurization, MOCVD, ALD, VLS method, and the thermolysis of thiosalts. Then, an overview of the MoS$_2$-FET developments will be provided based on different device configurations. The basic characterization and device performance of different MoS$_2$-FET will also be summarized. Furthermore, we will present recent advances in applications of logic circuits, memory devices, and photodetectors based on 2D wafer-scale monolayer MoS$_2$ and MoS$_2$-FET. Lastly, we will discuss the perspective and challenges based on wafer-scale MoS$_2$ synthesis and MoS$_2$-FET for developing practical applications in integrated electronics and flexible optoelectronics. The recent advances in monolayer MoS$_2$ synthesis and MoS$_2$-FETs emphasize the opportunity and potential of the wafer-scale MoS$_2$ in terms of achieving the practical application in modern large-scale integrated devices based on the existing silicon-based micro-fabrication processes.

2. Wafer-scale MoS$_2$ synthesis

2D MoS$_2$ film can be synthesized by the top-down strategy and the bottom-up strategy. In the top-down strategy, the commercialized MoS$_2$ bulk crystal is physically peeled into the monolayer or few-layer MoS$_2$ flakes by mechanical exfoliation methods. In the bottom-up strategy, the MoS$_2$ film is prepared through chemical reaction on a specific substrate by CVD, MOCVD, ALD, etc. In order to realize wafer-scale monolayer MoS$_2$ synthesis, continuous efforts have been made to develop the synthetic method and synthetic system based on the top-down strategy and the bottom-up strategy.

2.1 Au-assisted exfoliation method

Due to the unique layered geometry and van der Waals (vdW) interactions in 2D materials, mechanical exfoliation provides a low-cost way to produce the monolayer and few-layer highly crystalline layered 2D materials. In a typical mechanical exfoliation process, appropriate thin MoS$_2$ crystals were first peeled off from the bulk crystal using adhesive scotch tape and then transferred onto a target substrate. After the scotch tape is removed, monolayer or few-layer MoS$_2$ can be obtained on the substrate. Generally, the sizes and thicknesses of 2D MoS$_2$ from scotch-tape exfoliation are limited, which is not suitable for mass-production and scaled-up applications. Gold is known to have a strong affinity for sulfur and can be exploited to exfoliate monolayer from the bulk crystal as a result of strong vdW interactions between Au and the topmost MoS$_2$ layer.

Recently, Liu et al. developed a facile method by developing ultraflat gold layers on polymer supports to disassemble vdW single crystals layer by layer into monolayers with near-unity yield, which can be applied to a broad range of vdW single crystals on various substrates. The ultraflat gold film on a polymer substrate was first evaporated on an ultraflat surface with an A-scale roughness and was then stripped off the substrate with a thermal release tape and an interfacial layer. Due to the intimate and uniform vdW contact between the ultraflat gold and 2D vdW crystal surface, a complete monolayer was exfoliated from the crystal and transferred onto the desired substrate. After removing the thermal release tape and the interfacial layer, the gold was etched in a mild etchant solution ($\text{I}_2/\Gamma^-$), resulting in a large-area monolayer film. In the Au-assisted method, MoS$_2$ monolayer in the centimeter scale was exfoliated from the bulk crystal and the dimensions are only limited by bulk crystal sizes. Similarly, Huang et al. reported a universal Au-assisted exfoliation of large-area 2D crystals, as shown in Fig. 1. Firstly, a thin layer of Au was deposited onto a substrate covered with a thin Ti or Cr adhesion layer. Then, a freshly cleaved layered bulk crystal on tape was brought in contact with the Au layer with a gentle pressure applied to establish a good layered crystal/Au contact. One or few large-area monolayer flakes were left on the Au surface after peeling off the tape and removing the major portion of the crystal.
Limited only by the size of the available bulk crystals, these monolayer flakes are usually macroscopic with a size in millimeters. This method can also be applied to CVD-grown wafer-scale MoS2 and the exfoliated monolayer flakes can be intactly transferred onto arbitrary substrates after removing the gold layer by the KI/I2 etchant.

2.2 CVD method

In the traditional CVD synthesis of 2D MoS2, the solid-state precursors of MoO3 powder and sulfur (S) powder were first evaporated into gaseous states and then reacted with each other in a low-pressure chamber, and MoS2 nuclei formed and gradually enlarged into grains with the aid of carrier-gas flow on the downstream substrates. To achieve large-area continuous monolayer MoS2 films, many efforts have been devoted for improving the CVD synthesis of 2D MoS2, as shown in Fig. 2.\(^{31-41}\)

One strategy is to overcome the CVD setup limitations. Yu et al.\(^{31}\) reported a three-temperature-zone CVD system that employs independent carrier gas pathways for sulfur and MoO3 sources to successfully fabricate 2-inch wafer-scale uniform monolayer MoS2 films on sapphire. During the growth, the temperatures for the sulfur source, MoO3 source, and wafer substrate are 115, 930, and 530 °C, respectively, with a typical growth duration of 40 min. Xu et al.\(^{32}\) reported an improved wafer-scale growth of continuous MoS2 film based on atmospheric pressure within a two-temperature-zone CVD setup. As low pressure of 300 Pa can effectively promote the evaporation rate and provide a uniform concentration of the gaseous precursor in the tube to increase the lateral growth rate; thus, a uniform and continuous monolayer MoS2 film can be achieved by increasing the sulfurization time to 15 min. Recently, Wang et al.\(^{33}\) realized the epitaxy of highly oriented and large-domain monolayer MoS2 films at a 4-inch wafer scale via a facile multisource CVD growth method. In this setup, MoO3 sources are evenly loaded within the six minitubes and the S source is loaded within the center minitubes. The carrier gases for S and MoO3 sources are independently delivered through the minitubes. This multisource design provides homogeneous cross-sectional source supply, leading to uniform growth with only 0° and 60° oriented domains and domain size >180 μm. He et al.\(^{34}\) demonstrated a layer-by-layer scalable growth of MoS2 films on a moving sapphire substrate by local-feeding atmospheric-pressure CVD. By the linear moving of the substrate across the cone-shaped diffusion concentration gradient of Mo-containing species and controlling the moving cycles, large-scale growth, uniform monolayer, and few-layer MoS2 with sizes up to \(~4.7 \text{ cm} \times 6 \text{ mm}\) can be obtained. The 4-, 7-, and 9-cycle growth corresponding to dwelling times of 8, 14, and 18 min can form complete monolayer, bilayer, and trilayer MoS2 films, respectively. Durairaj et al.\(^{35}\) utilized SiO2 as a mechanical barrier to moderate the Mo flux so as to allow better controllability and high position selectivity for the CVD growth of homogeneous MoS2 monolayers. The barrier offered great control in controlling the Mo precursor vapor concentration at the substrate position, mitigating the secondary and intermediate phases as well as second layer nucleation, thus leading to a continuous monolayer with high surface homogeneity.

Another strategy for improving the CVD synthesis is to adjust the precursor or the substrate. Aside from elemental sulfur powder, hydrogen sulfide (H2S) gas has also proven to be a good sulfur source, which exhibits high vulcanization ability. Liu et al.\(^{36}\) demonstrated that a reproducible and low-cost method for growing wafer-scale (approximately \(9.5 \times 4.5 \text{ cm}^2\)) high-quality monolayer MoS2 by using H2S gas as the sulfur source and to stabilize the sulfur vapor pressure during the growth process. In addition, two independent carrier gas pathways for H2S and MoO3 sources were employed to prevent MoO3 poisoning and achieve an improved and stable growth condition. Yang et al.\(^{37}\) reported the epitaxial growth of wafer-scale single-crystal MoS2 monolayers on vicinal Au(111) thin film by a facile ambient-pressure CVD with MoO3 and S as the sources. 

Fig. 1  Mechanical exfoliation of different monolayer materials with macroscopic size. (a) Schematic of the exfoliation process. (b–d) Optical images of exfoliated MoS2 on SiO2/Si, sapphire, and plastic film. (e) 2-inch CVD-grown monolayer MoS2 film transferred onto a 4-inch SiO2/Si substrate.\(^{29}\) Reproduced with permission from ref. 30, copyright 2020 Springer Nature.
precursors. Single-crystal Au(111) substrate was obtained by melting and resolidifying the commercial Au foils at a designated temperature (~1050 °C) for 10 min on cleansed W foils. During the growth, the unidirectional oriented MoS2 domains on the Au(111) film with an area of ~3 × 3 cm² started to merge and eventually coalesced into a continuous film after 8 min at ~720 °C.

Besides these planer substrates, 2D MoS2 can also be synthesized on non-planar substrates. Liao et al.42 firstly proposed single-crystal monolayer MoS2 growth on tapered silica micro/nanofibers
(MNFs) and realized photoluminescence (PL) enhancement by high-density oxygen dangling bonds released from the tapered MNFs surface, as shown in Fig. 3. The monolayer MoS₂ grown on silica MNF exhibits a PL quantum yield from ~30% to 1% in a wide pump intensity range from $10^{-1}$ to $10^4$ W cm$^{-2}$ at room-temperature. Due to the taper-drawing process and high-intensity light irradiation, the Si–O bonds of silica can be broken directly and high-density oxygen dangling bonds can be released on the MNFs surface. These reactive oxygen dangling atoms then fill the sulfur vacancies or bridge with neighboring sulfur atoms in monolayer MoS₂, forming stable localized sites through electron transfer in MoS₂. Thus, the taper-drawing process and high-intensity light irradiation process will reduce the non-radiative carrier-recombination centers and strongly enhance the PL of the monolayer MoS₂ in a wide pump dynamic range at room temperature. These unique advantages based on the taper-drawing process enable the direct realization of low-threshold lasing without high-quality factor optical microcavities, which demonstrated great potential in different optical and optoelectronic applications.\footnote{42–44}

### 2.3 Thin film sulfuration method

Large-area 2D MoS₂ with excellent uniformity can be obtained by sulfuring the deposited Mo or MoO₃ in a chamber with a sulfur-rich environment. This thin film sulfuration method refers to a two-step process, namely, thin film deposition and the followed sulfuration, which is also classified into two-step CVD methods. As shown in Fig. 4, the Mo precursors can be deposited by various deposition techniques, including electron-beam evaporation, pulsed laser deposition, magnetron sputtering, spin-coating, and ALD. The sulfur source includes S vapor, H₂S, and carbon disulfide (CS₂).

Kim et al.\textsuperscript{45} demonstrated wafer-scale 2D MoS₂ growth via the sulfuration of transition metals deposited on the SiO₂/Si substrates using a home-built chamber. High-quality molybdenum (Mo) was deposited on cleaned SiO₂/Si wafers with a typical dimension of 1 × 3 cm$^2$ using an e-beam evaporation system and then placed at the center zone of the CVD furnace for sulfuration by sulfur vapor at 800 °C. Jo et al.\textsuperscript{46} developed the two-step synthesis of large-area MoS₂ thin film by depositing Mo metal films by electron-beam and sulfurizing the Mo film in mixtures of H₂S and O₂ gas. It was found that the presence of trace levels of O₂ accelerates the crystallization of MoS₂ and affects the layer orientation, without changing the kinetics of mass transport or the final film composition. Large-area MoS₂ films grown on 2-inch wafer, Al, glass, and indium tin oxide (ITO) at 400 °C were realized by this two-step method. Recently, Park et al.\textsuperscript{47} fabricated MoS₂ device arrays constructed on large-dimensional MoS₂ films grown using a radio-frequency (RF) magnetron sputtering deposition method combined with post-treatment processes. High-quality centimeter-scale trilayer MoS₂ was achieved by sputtering, EBI, and sulfurization. The post-treatments that rearrange the atoms in the MoS₂ films can result in an improvement of the MoS₂ crystallinity. Almeida et al.\textsuperscript{48} presented wafer-scale MoS₂ growth at arbitrary integer layer number by a technique based on the decomposition of CS₂.

![Fig. 3](image-url)  
**Fig. 3** Monolayer MoS₂ grown on MNFs. (a) Conceptual illustration of monolayer MoS₂ grown on MNFs with uniform diameters and with microbottle structures. A single-crystal triangular domain first nucleates on the MNF surface and then laterally grows into a large-area monolayer structure. A 532 nm CW laser is used to excite the PL emissions. (b) Optical and PL images of a triangular layered MoS₂ on a microfiber ($D_{\text{fiber}}=6.1$ μm) with (c) a thickness of ~0.8 nm, as confirmed by an AFM scan. (d) Optical and PL images showing the clean surface and two sharp boundary edges of the MoS₂ monolayer/microfiber structure ($D_{\text{fiber}}=5.5$ μm). (e) Optical and PL images showing a large-area monolayer/microfiber ($D_{\text{fiber}}=5.4$ μm). Some guided emission is emitted at the distal end of the microfiber. (f) The generated oxygen dangling atoms can fill the sulfur vacancies, bridge with neighboring sulfur atoms, and form localized sites by transferring electrons from MoS₂, leading to enhanced PL emission.\textsuperscript{42} Reproduced with permission from ref. 42.
on a hot Mo filament. As CS₂ molecules decompose at the Mo filaments, MoSₓ precursors evolve, evaporate from the rods, and deposit onto the substrate at 650 °C, where they obtain stoichiometric sulfur contents from the environmental CS₂ and form into extended islands or evaporate again. Since the hue value of light from the hot Mo filaments reflected from the wafer substrate changes as the film grows layer by layer, the concomitant measurement of this hue was employed to control the growth process, which allows the precise targeting of any integer layer number.

Besides Mo films, oxidized Mo film is also a precursor source in the sulfurization method. Choi et al. synthesized the 2-inch-scale
monolayer MoS2 film using an atmospheric pressure reaction process as the result of the reaction between the oxidized Mo and gaseous H2S at a peak temperature of 780 °C. The growth is based on a unique reaction mechanism due to the self-limiting precursor source in a proximity reaction environment with a distance of only ~0.5 mm from the reaction zone, which provides a unique advantage of uniformity with the self-limiting reaction due to the limited MoO3 supply. Xu et al.29 realized high-quality MoS2 synthesis over 2-inch wafers through the two-step vapor-solid phase reaction (VSPR) process using MoO2 as the precursor. The epitaxial MoO2 film was firstly deposited on 2-inch wafers by pulsed laser deposition (PLD), then loaded into a tube furnace and annealed in a mixture of Ar and S at 900 °C for 1 h at low pressure, resulting in 2D epitaxial MoS2 films. This quasi-single-crystalline MoS2 film deposited over the 2-inch wafer was ~3 nm in thickness and can be successfully transferred onto different substrates. Xu et al.29 introduced a new capping layer annealing process (CLAP) to improve the crystalline quality of the as-deposited MoO2 films and minimized its defects in the synthesis of single-crystalline MoS2 films on 2-inch wafers. The epitaxial MoO2 sample was covered with a protective capping layer, such as SiO2 or Si3N4 with a thickness of 50 nm, and then annealed in the PLD chamber at 900 °C for 1 h. After annealing, the capping layer on MoO2 can be totally removed by buffered oxide etching (20 : 1) solution. Through the sulfurization of the CLAP-treated epitaxial MoO2 film in a CVD system with sulfur powder source, wafer-scale single-crystalline MoS2 films were obtained without texture. The MoO2 films with desired thickness deposited by ALD is a good candidate for the Mo source in the thin film sulfurization method. Shi et al.32 demonstrated the two-step growth of MoS2 on sapphire substrates by depositing the MoO3 film by ALD using Mo(CO)6 and oxygen plasma as the precursors. The MoO3 film was sulfurized at 500 °C for 20 min, and followed by 20 min annealing at 900 °C in the sulfur vapor to improve the crystallinity of MoS2.

2.4 MOCVD method

The MOCVD technique using metal–organic sources (as shown in Fig. 5), such as Mo(CO)6 and (C2H5)2S, is generally favorable due to highly uniform and accurately layered-controlled, thus avoiding the need for post-deposition treatment and benefiting large-area MoS2 synthesis.33–35 Mun et al.34 reported the kinetics-controlled low-temperature MOCVD method for the direct growth of spatially homogeneous 2D MoS2 film on a polyimide (PI) substrate at a record low process temperature of 250 °C with the precursors of Mo(CO)6 and high-purity H2S. As an alkali-metal catalyst, sodium chloride (NaCl) was precisely controlled in the MOCVD reactor along with the growth substrate. It takes 8 h to successfully obtained 4-inch scale monolayer MoS2 film on PI at 250 °C by the precise and continuous feeding of the alkali-metal catalyst during the MOCVD process. The fabricated flexible MoS2FET based on directly grown MoS2 demonstrate the excellent stability of the electrical properties following a 1000-cycle bending test with a 1 mm radius. Kalanyan et al.35 presented MoS2 film growth by pulsed MOCVD in a single-wafer reactor using the precursors of (NtBu)2(NMe2)2Mo and Et2S2. Each reaction cycle consisted of 1.5 s co-injections of (NtBu)2(NMe2)2Mo centered on 2 s injections of Et2S2 and then the reactor was purged with 400 sccm Ar for 4 s, resulting in a 6 s cycle time. Pulsed injections of the precursor vapors facilitated excellent control over the film thickness with a growth rate of 0.12 nm/pulse. The layered wafer-scale MoS2 films with thickness from ~1 nm to ~25 nm on the SiO2/Si substrates can be achieved at comparatively low reaction temperatures of 591 °C at short deposition times, from tens of seconds to several minutes. Shinde et al.36 proposed a gas-phase CVD approach for the synthesis of atomically thin MoS2 films over 2-inch sapphire wafers with suitable precursors of (NtBu)2(NMe2)2Mo and hydrogen sulfide (H2S). A graphite susceptor was designed for handling a 2-inch wafer facing at a 15° angle to the Ar gas flow. The homogeneous MoS2 films were obtained at 850 °C under 10 Torr with an H2S flow of 3 sccm. In this approach, the growth rate of continuous MoS2 was found to be 1 monolayer (S–Mo–S) per 4 min. Recently, Shinde et al.37 also realized the rapid and large-scale fabrication of the MoS2 layers directly on SiO2/Si (3.5 × 3.5 cm2) using (NtBu)2(NMe2)2Mo and H2S via gas-phase CVD. The seamless growth process allowed the deposition of monolayer MoS2 films in 4 min with excellent spatial homogeneity and optical quality.

Cun et al.38 developed the wafer-scale growth of high-quality monolayer MoS2 on single crystalline sapphire and SiO2 substrates at the 2-inch wafer scale by a facile MOCVD with a spin-coated Mo precursor and a non-toxic sulfur precursor. An aqueous solution of sodium molybdate (Na2MoO4) was provided as the Mo precursor by spin-coating on the substrates prior to the growth, and the amount of Mo can be controlled by the concentration of Na2MoO4 and the spin-coating speed. The single sulfur precursor was supplied by the non-toxic liquid organic compound diethyl sulphide (C2H5)2S, which is stored in a stainless-steel bubbler and connected to the quartz tube with a mass flow controller (MFC) to precisely control the amount of the required sulfur precursor during the growth. The obtained wafer-scale MoS2 films exhibit crystallinity and good electrical performance.

Seol et al.39 realized high-throughput production of 6-inch wafer-scale monolayer MoS2 and WS2 via a pulsed MOCVD technique. A scalable shower-head-type cold-wall reactor system was used and the gas-phase precursors included molybdenum hexacarbonyl (Mo(CO)6), (C2H5)3S, and H2. Each reaction cycle consisted of 2 min of co-injection of all the precursors, followed by interrupting the precursors’ supply and purging with N2 for 1 min. Periodic interruption of the precursor supply allowed the successful regulation of secondary nucleation even under high growth rates; as a result, wafer-scale monolayer MoS2 and WS2 were obtained within 12 min on 6-inch quartz substrates. Moreover, the as-grown TMD films show excellent spatial homogeneity and well-stitched grain boundaries, enabling facile transfer to various target substrates without degradation.

2.5 Vapor–liquid–solid (VLS) method

The reported CVD of 2D MoS2 is generally conducted through a typical vapor–solid–solid mechanism or a vapor–gas-solid
mechanism using powdered precursors (MoO₃ and S) or mixed precursors (MoO₃ powders and H₂S gas), respectively. The vapor–liquid–solid (VLS) growth method often involves molten precursors (e.g., non-volatile Na₂MoO₄) at growth temperatures higher than their melting points, which presents great promise in large-area MoS₂ synthesis with large single crystals for electronics.

Recently, Li et al. demonstrated the VLS growth of uniform monolayer MoS₂ flakes on 4-inch SiO₂/Si wafers and continuous MoS₂ films with the grain size exceeding 100 μm on 2-inch sapphire substrates using non-volatile precursors. Na₂MoO₄ particles were first dispersed on the growth substrate by spin-coating its aqueous solution. Then, Na₂MoO₄ on the substrates was loaded in the tube furnace and started to melt into a liquid, wetting the substrate surface when the temperature was higher than its melting point (687 °C). Sulfur vapor dissolves into the Na–Mo–O droplets, and the MoS₂ monolayer nucleated and grew from the sulfur over-saturated Na–Mo–O–S liquid on the substrate at 750 °C. Moreover, the Na₂MoO₄ particles can be patterned on the substrate with the aid of the photolithography process; patterned MoS₂ monolayers with desired sites were grown on the substrate after sulfurization.

Chang et al. also utilized a self-capping vapor–liquid–solid (SCVLS) reaction for the growth of large single crystals and full-
coverage TMD films. As shown in Fig. 6, a solid precursor comprising ultra-thin MoO$_3$, SiO$_2$, and NaF layers was used for the controllable eutectic reaction of MoO$_3$ and NaF at high temperature. Firstly, MoO$_3$ vapor broke the SiO$_2$ layer, diffused upward, and reacted with the NaF layer at a temperature higher than 500°C to form liquid-phase Na$_2$MoO$_4$ and gas-phase MoO$_2$F$_2$. Simultaneously, the consumption of NaF generated holes and pathways in the NaF layer, which allowed Na$_2$MoO$_4$ and MoO$_2$F$_2$ to gradually rise to the top surface of the NaF. The as-formed eutectic liquid (Na$_2$Mo$_2$O$_7$) rose to the surface and was sulfurized into MoS$_2$ seeds, which acted as a self-capping layer and redirected the rising liquid into a horizontal direction. The residual liquid was continuously pushed along the growth direction and eventually sulfurized to form new MoS$_2$ at the edge of the MoS$_2$ seeds, thus making millimeter-sized MoS$_2$ single crystals formed on a c-plane sapphire.

2.6 ALD method

ALD exhibits advantages in the precise control of the film thickness, uniformity, and homogeneity over large-scale wafers due to the self-limiting growth mechanism. MoS$_2$ films with desired thickness can be obtained by varying the ALD cycles. The ALD procedure combines precursor exposure, purging, reactant exposure, and a final purging into a single cycle. The layers of the ALD MoS$_2$ films can be determined by the deposition temperatures and the ALD cycles. Large-area MoS$_2$ directly onto SiO$_2$/Si substrates have been achieved through the ALD method using molybdenum pentachloride (MoCl$_5$) and H$_2$S as the precursor and the reactant, respectively.$^{44}$ In different reports, the ALD growth temperatures of MoS$_2$ ranges from 350°C to 900°C.$^{61}$ Another well-investigated precursor pair for ALD MoS$_2$ is Mo(CO)$_6$/H$_2$S. This ALD process features the high vapor pressure of Mo(CO)$_6$ at room temperature and relatively low growth temperature. Jang et al.$^{65}$ reported MoS$_2$ film grown uniformly, reliably, and directly on a 4-inch wafer by ALD using an Mo(CO)$_6$ precursor and H$_2$S plasma as the precursor and reactant without a post-sulfurization process. The growth rate of MoS$_2$ on SiO$_2$/Si was approximately 0.05 nm per cycle and the deposition temperature ranged from 175 to 225°C. Pyeon et al.$^{66}$ presented wafer-scale synthesis of MoS$_2$ layers on a 4-inch SiO$_2$/Si wafer with precise thickness controllability and excellent uniformity by ALD in the narrow ALD window of 155–175°C, with Mo(CO)$_6$ as the Mo and S precursors, respectively. Post-annealing in the range of 500–900°C under an H$_2$S atmosphere efficiently improved the film properties, including the crystallinity and chemical composition. Extremely uniform film growth was achieved even on a 4-inch SiO$_2$/Si wafer. The growth temperature can be reduced in an ALD process using tetakis(dimethylamido)molybdenum(n) (TDMA-Mo, Mo(NMe$_2$)$_4$) and H$_2$S as the precursors with an ALD growth rate of 1.2 Å per cycle at 60°C.$^{67}$ Then, the obtained amorphous MoS$_2$ was treated at 1000°C under sulfur vapor to improve the crystallinity. Recently, Liu et al.$^{68}$ developed thickness-controlled MoS$_2$ synthesis using MoCl$_5$ and hexamethyldisilathiane (HMDST) as the ALD precursors; the films were uniformly deposited on a sapphire and SiO$_2$/Si substrate after different ALD cycles from 20 to 90. As shown in Fig. 7, the thickness of the as-grown MoS$_2$ film after 50 ALD cycles was measured for 2.9 nm on sapphire and ~5 nm on the SiO$_2$/Si wafer with high uniformity.

2.7 Thermolysis of thiosalts

MoS$_2$ synthesis by the thermolysis of thiosalts is based on the thermal decomposition of ammonium thiomolybdates...
ALD-grown MoS2 as the precursors. (b) Images of sapphire substrate; 20, 30, 40, 50, 60, 70, and 90 cycles of ALD-grown MoS2 on sapphire. (c) 3D AFM image of ALD-grown MoS2 film on a 10 µm × 10 µm area, with the roughness RMS of this region being 0.479 nm. (d) TEM images of an annealed 50-cycle MoS2 film of 2.9 nm thickness on the sapphire substrate. Reproduced with permission from ref. 68, copyright 2020 Springer Nature.

(NH4)2MoS4 in a specific environment, which results in the conversion of (NH4)2MoS4 to MoS2 at a higher temperature. The precursor solution of (NH4)2MoS4 can be deposited on different substrates and highly crystalline centimeter-scale MoS2 can be synthesized after thermal decomposition in a N2 or sulfur-rich atmosphere.68–72 Lim et al.73 reported large-area MoS2 layers by the simple coating of single source precursor with subsequent roll-to-roll-based thermal decomposition with N2 at 600 °C under 1.8 Torr pressure. An (NH4)2MoS4 solution was barcoated onto a Ni foil and subsequently thermally decomposed using the roll-to-roll process, resulting in 50 cm long MoS2 layers synthesized on Ni foils with excellent long-range uniformity and optimum stoichiometry. The number of MoS2 layers can be simply adjusted by optimizing the concentration of (NH4)2MoS4 and the solvent conditions. Park et al.74 introduced a direct and rapid method for the layer-selective synthesis of patterned MoS2 at the wafer-scale using a pulsed laser annealing system (λ = 1.06 µm, pulse duration ~100 ps) in ambient conditions. The (NH4)2MoS4 precursor was spin-coated on a Si/SiO2 wafer and annealed at 150 °C for 3 min to evaporate the residual solvents. Then, a pulsed fiber laser was used to induce a local photothermal reaction under sulfur-rich conditions to thermally decompose into MoS2. The heat treatment area was precisely defined and the precursor layer in the non-treated area was simply removed by the DMF solvent, leaving a patterned MoS2 film. Fig. 8(c) and (d) provide the mechanism of selective conversion of (NH4)2MoS4 precursors into MoS2. Moreover, the ultrafast and selective synthesis of individual patterned MoS2, WS2 layers, and stacked WS2/MoS2 heterojunction structure can be directly realized on a 4-inch wafer.

3. Application in basic MoS2-FET

The downscaling trend of integrated electronics based on silicon-based micro-fabrication processes lead to continuing

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Au, Ni/Au, and Cr/Pt, which is deposited and patterned via electron beam evaporation and the lithography process. Due to the Schottky barrier and Fermi level pinning at the metal/semiconductor interface, different investigations in MoS₂-FET have been made to minimize the contact resistance and realize near-ohmic contacts by choosing appropriate work function metals, creating an ultra-clean interface, inserting a buffer layer, etc. In this regard, extensive efforts have been devoted to investigate 2D MoS₂-FET based on wafer-scale monolayer or few-layer MoS₂ with different device configurations and dielectric layers.

### 3.1 Configurations and fabrications

Similar to that of traditional silicon-based FET, different configurations of FET based on 2D MoS₂ have been studied in recent years. The most common configurations include: (1) back-gated MoS₂-FET, (2) top-gated MoS₂-FET, (3) dual-gated MoS₂-FET. These MoS₂-FET devices can be fabricated through a series of general processes with different processing sequences, including MoS₂ patterning, dielectric layer deposition, metal electrode deposition, and patterning. Most MoS₂ channels are patterned by controlled plasma etching or the lithographic method after MoS₂ synthesis or transfer, while other MoS₂ channels can be realized from the patterned thin-film Mo precursor after sulfurization. The dielectric layer of Al₂O₃, HfO₂, and ZrO₂ are usually deposited by ALD, while PVDF and PMMA are prepared by the spin-coating method. The metal electrodes can be defined and deposited by e-beam evaporation after the photolithography process or e-beam evaporation with shadow masks.

**i) Back-gated MoS₂-FET.** Back-gated MoS₂-FET with Si as the gate is the most widely used configuration in basic studies, with SiO₂ as a typical dielectric layer. In this configuration, 2D MoS₂ is directly grown or transferred on the SiO₂/Si substrate and then selectively etched to form the channel by plasma.
Finally, the source/drain contacts are prepared by a sequential lithography process, including photolithography, e-beam evaporation, and lift-off. For instance, Kim et al.\textsuperscript{75} presented the successful integration of the devices based on \( \sim 1200 \) back-gated MoS\(_2\)-FET arrays with a yield of 95\% on 4-inch SiO\(_2\)/Si wafers. As shown in Fig. 9, large-area MoS\(_2\) films were synthesized by MoO\(_3\) pre-deposition on a sapphire substrate via radio frequency (RF) sputtering and following sulfurization via CVD. The as-synthesized four-layered MoS\(_2\) film was transferred from the sapphire substrates onto the SiO\(_2\)/Si substrates by PMMA and then patterned for the channel region of the FET array devices via reactive ion etching. Au/Cr metallic electrodes were fabricated by a sequential lithography process. This growth technique could yield wafer-scale MoS\(_2\) thin film such that an array of approximately 1200 MoS\(_2\) transistors occupying a 2-inch active area of a 4-inch silicon wafer could function well, with excellent electrical characteristics.

Back-gated FET with patterned metal or semiconducting gate electrode is another configuration used in MoS\(_2\)-FET. Seol et al.\textsuperscript{55} fabricated back-gate MoS\(_2\)-FETs on a 6-inch wafer with Ti/Au as the back-gate contact and ALD-Al\(_2\)O\(_3\) as the gate dielectric. The as-grown MoS\(_2\) film was transferred by PMMA and patterned using photolithography and O\(_2\) plasma etching after the deposition of Ti/Au and Al\(_2\)O\(_3\). Wei et al.\textsuperscript{87} developed a flexible back-gated MoS\(_2\)-FET fabricated on low-cost polyethylene terephthalate (PET) substrates by 2D MoS\(_2\) and dielectric ceramic Bi\(_2\)MgNb\(_2\)O\(_9\) (BMN). Recently, Li et al.\textsuperscript{13} reported flexible MoS\(_2\)-FET arrays on the PET substrate with an improved device density of 1518 per cm\(^2\). The wafer-scale MoS\(_2\) monolayers grown on sapphire were transferred onto PET substrates with pre-deposited ITO and Al\(_2\)O\(_3\), which serve as the back-gate electrode and dielectric layer. It is also demonstrated that Au/Ti/Au rather than Ti/Au is an excellent contact structure to reduce contact resistance in the monolayer MoS\(_2\) devices. Lan et al.\textsuperscript{88} demonstrated both N-type and P-type MoS\(_2\)-FET by directly growing MoS\(_2\) on the fin oxide structure by the CVD method. The fin oxide structures selectively-implanted Si contacts lead to N-type and P-type MoS\(_2\) film growth on a wafer/chip, which can be compatible with the Si-based fabrication process. The SiO\(_2\) interfacial layer and HfO\(_2\) high-k dielectric were deposited on CVD-grown MoS\(_2\) by ALD, followed by metal-gate deposition. The Fin-FET based on MoS\(_2\) synthesized from the P\(^+\)-Si and N\(^+\)-Si contact presented P-type and N-type performance, respectively, which can be integrated as a complementary MoS\(_2\) inverter for basic integrated circuit complementary device applications.

(ii) Top-gated MoS\(_2\)-FET. The structure of the top-gated FET is similar to that of the back-gated one, with the main difference that the patterned gate electrode is placed above the 2D channel. In this configuration, the top gate insulator can

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**Fig. 9**  (a) Optical image of the 2D MoS\(_2\)-FET array devices integrated on a 4-inch SiO\(_2\)/Si wafer and (b) the sequence of the fabrication process for MoS\(_2\) array devices.\textsuperscript{75} Reproduced with permission from ref. 75, copyright 2017 American Chemical Society.
also work as an encapsulating layer covering the entire MoS₂ channel, which can both improve the stability and the mobility of MoS₂-FET.

Zhang et al. successfully fabricated top-gated MoS₂-FET arrays based on wafer-scale continuous MoS₂ film using wafer-scale Si shadow masks (Si-SMs) with customized patterns. Metal deposition and plasma etching by the Si-SMs exhibit well-defined patterns with sharp edges. As shown in Fig. 10, top-gated MoS₂-FET arrays were fabricated using two different processing strategies assisted by the Si-SMs: ‘etching-last’ and ‘channel-first’. For the ‘etching-last’ strategy, the metal contacts were deposited with the Si-SMs at the beginning, followed by the plasma etch to isolate a continuous film with Si-SM as the protective layer. For the ‘channel-first’ method, a layer of Mo metal defined by Si-SM was deposited on the sapphire substrate. Then, the patterned Mo was subsequently sulfurized in a sulfur-rich atmosphere at 900 °C to form a patterned polycrystalline MoS₂ film. The MoS₂-FET arrays can be obtained after dielectric growth and top gate deposition, without suffering from photoresist residue and long-time immersion in the photoresist remover.

Wang et al. built top-gated FET with a high-k HfO₂ directly fabricated from the CVD-grown monolayer MoS₂. The MoS₂ active regions for the transistors were defined in a patterning step, followed by a CHF₃-based reactive ion etching process. After that, Ti/Au source/drain electrodes were formed by electron beam evaporation, following the patterning step. The gate dielectric of HfO₂ was grown by ALD and the top-gate Ti/Au was deposited, followed by a standard lift-off process. Similar to the back-gate FET, P(VDF-TrFE) and PMMA were also reported as the gate dielectric by spin-coating in the top-gated MoS₂-FET.

(iii) Dual-gated MoS₂-FET. This device configuration with both back-gate and top-gate can provide the highest degree of controllability of the charge carriers in the 2D channel, which can use a doped-Si substrate or patterned back-gate. Zhang et al. demonstrated a dual-gated FET structure to improve the electrostatic control of MoS₂-FET with bilayer MoS₂. In this configuration, a patterned Au electrode array and 15 nm HfO₂ layer were deposited on the SiO₂/Si substrate to form the back gate and the back gate dielectric layer, respectively, as shown in Fig. 11. The bilayer-MoS₂ film was then transferred onto this substrate and patterned by plasma etching. After source/drain electrode deposition, a second layer of 15 nm HfO₂ layer as the top dielectric layer and Au top gate electrodes were deposited, leading to a dual-gated FET structure to the back and top gates with a symmetric high-k dielectric layer. Compared with the single-gated MoS₂-FET, the array with 81 dual-gated bilayer MoS₂-FETs exhibits an excellent solution to compensate for the degradation of electrostatic control. Liao et al. reported similar dual-gated MoS₂-FET with symmetric back-gated and top-gated architecture based on exfoliated MoS₂ and CVD-

![Fig.10](image-url)
synthesized MoS$_2$ continuous film. Furthermore, dual-gated MoS$_2$-FET with multi-layer graphene floating gate (FG) and ionic top gate are also reported in multiple operating conditions to demonstrate different electronic applications.$^{84,101}$

3.2 Characterization and performances

The characterization of synthesized MoS$_2$ films and fabricated MoS$_2$-FETs is essential for both fundamental research and practical application. The basic characterization of 2D MoS$_2$ consists of lateral size, thickness, morphology, PL spectroscopy, and Raman spectroscopy, which can be measured by optical microscopy, atomic force microscopy (AFM), photoluminescence spectrometry, and Raman spectroscopy, as shown in Fig. 7(c), (d) and 8(e), (h). Further information of the 2D MoS$_2$ film, such as grain size, grain boundaries, lattice orientations, phase composition, and structural defect determination, can be inferred from various microscopy techniques, such as scanning tunneling microscopy (STM), high-resolution transmission electron microscopy (HRTEM), and low-energy electron diffraction (LEED). In addition, the X-ray diffraction (XRD) technique, X-ray photoelectron spectroscopy (XPS), and ultraviolet-visible (UV-vis) spectrophotometry were also applied for the investigation of the film quality and the optoelectronic property based on 2D MoS$_2$.

The typical characterization of 2D MoS$_2$-FETs refers to the current flowing between the drain and the source ($I_{ds}$), which can be controlled by tuning the gate voltage ($V_g$) and the drain-source voltage ($V_{ds}$). The main figures of merit of an FET are the transfer characteristic ($I_{ds}$ vs. $V_g$ for a specific $V_{ds}$) and the output characteristic ($I_{ds}$ vs. $V_{ds}$ for various $V_g$). The measurement transfer characteristic ($I_{ds}$ – $V_g$) and the output characteristic ($I_{ds}$ – $V_{ds}$) of the 2D MoS$_2$-FET were usually carried out on a semiconductor parameter analyzer (such as Keithley 4200-SCS) at room temperature. From the transfer characteristic, several important operational parameters of the FET can be extracted, such as the current ratio between the ON and OFF states ($I_{on}/I_{off}$), threshold voltage ($V_{th}$), field effect mobility ($\mu_{FE}$), and subthreshold slope (SS). The value field effect mobility and subthreshold slope can be evaluated using eqn (1) and (2)

$$\mu_{FE} = \frac{dI_{ds}}{dV_g} \times \frac{L}{W} \frac{C_m}{V_{th}}$$

$$SS = \frac{d \log I_{ds}}{dV_g} = \frac{dV_g}{d \log I_{ds}}$$ (2)

in which $L$ is the channel length, $W$ is the channel width, and $C_m$ is the capacitance between the channel and the gate per unit area.

Since the performance is directly affected by the MoS$_2$ quality and device configuration, different factors should be considered in 2D MoS$_2$-FETs, such as film thickness, grain size, defect situation, electrode/channel contact resistance, dielectric layer, channel length, and channel width. The improved quality of the wafer-scale MoS$_2$ films with larger grain size and less defects is preferred in MoS$_2$-FET with different configurations. The resistance of the electrode/channel contact caused by the Schottky barrier and Fermi-level pinning at the metal/channel interface can be reduced by the post-annealing process, optimizing the stacked metal electrode, and inserting a buffer layer.$^{85-87,90-92}$ Since the large dielectric constant of the high-k material contributes to the reduction of the effective size of the Coulomb impurities, different dielectric layers, such as SiO$_2$, HfO$_2$, Al$_2$O$_3$, LiNbO$_3$, CaF$_2$, PMMA, PVDF, h-BN, and graphene, have been utilized as the gate dielectric to improve the mobility of 2D MoS$_2$-FET.$^{73-84}$ The dielectric layer can also be used on the top of the MoS$_2$ channel, function as the encapsulation layer, and to provide a dielectric environment to improve the device performance and reliability. The performance of different 2D MoS$_2$-FETs based on the monolayer and few-layer MoS$_2$ films are summarized in Table 1.

From Table 1, it can be inferred that the performance of MoS$_2$-FET varies considerably from device to device. Different factors, such MoS$_2$ thickness, device configuration, dielectric choice, channel size, and fabrication process, interact and simultaneously affect the performance of MoS$_2$-FET. Even though the field effect mobility is still behind the highest reported value ($167 \pm 20$ cm$^2$ V$^{-1}$ s$^{-1}$) from the exfoliated MoS$_2$,$^{14}$ the $I_{on}/I_{off}$ ratio and field effect mobility of MoS$_2$-FET based on wafer-scale monolayer MoS$_2$ is encouraging. Considering the complicated fabrication procedures and different repeatability, it is difficult to make simple comparisons between different devices based on the monolayer MoS$_2$ film from different synthetic methods. Overall, more developments are needed for realizing high-performance MoS$_2$-FET with larger mobility,
Table 1 Performance parameters of 2D MoS2-FETs based on wafer-scale MoS2 films

| MoS2 | Configurations | Dielectrics | \( L (\mu m) \) | \( \mu_{FE} \) (cm²V⁻¹s⁻¹) | \( I_{on}/I_{off} \) ratio | SS (mV dec⁻¹) | Ref. |
|------|----------------|-------------|----------------|-----------------------------|---------------------------|----------------|-----|
| Monolayer on sapphire by CVD | Top-gated | HfO₂ | 3.5 | 0.1–3 | >10⁵ | 130 | 8 |
| 4-inch monolayer by CVD | ITO back-gated | Al₂O₃ | 6 | ~55 | 10¹⁰ | 13 |
| Few-layer by exfoliation | Back-gated | SiO₂ | 2 | 167 ± 20 | 14 |
| 8-Inch monolayer by MOCVD | Back-gated | SiO₂ | 10 | 0.47 | 5.4 × 10⁴ | 18 |
| 4-inch-scale by MOCVD | Back-gated | SiO₂ | 7–12 | 10⁻³–10⁻⁷ | 21 |
| 6-Inch monolayer by CVD | Back-gated | SiO₂ | 1 | 6.3–11.4 | 10⁻²–10⁻⁶ | 24 |
| Monolayer by Au-assisted exfoliation | Top-gated | SiO₂ | 30 | ~70 | 10⁴ | 32 |
| 4-Inch monolayers by CVD | Back-gated | SiO₂ | 10 | ~70 | 10⁴ | 33 |
| Monolayer by APCVD | Back-gated | Al₂O₃ | 0.033 | 5.8 × 10⁵ | 34 |
| Wafer-scale monolayer by CVD | Back-gated | SiO₂ | 2.87 | 3.2 | 3.5 |
| Monolayers on Au by CVD | Back-gated | SiO₂ | 1 | ~9.8 | 3.1 × 10⁶ | 40 |
| Continuous monolayer by CVD | Back-gated | SiO₂ | 1 | ~11.2 | 7.7 × 10⁵ | 37 |
| 2-Inch by PLD and sulfurization | Top-gated | HfO₂ | 90 | 8.85 | ~10⁵ | 50 |
| Monolayer by MOCVD | Back-gated | SiO₂ | 10 | 21.6 | 51 |
| Monolayer on 2-inch sapphire | Top-gated | Al₂O₃ | 0.76 | ~10⁻⁷ | 52 |
| 3.5 × 3.5 cm² monolayer by CVD | Back-gated | SiO₂ | 1.3 × 10⁻² | ~10⁻¹⁴ | 8300 | 55 |
| 2-Inch monolayer by MOCVD | Back-gated | SiO₂ | 20 | 1.2 | 35 |
| Monolayer by MO/CVD | Ti/Au back-gated | Al₂O₃ | 10 | 21.6 | 56 |
| Monolayers by VLS | Back-gated | SiO₂ | 3.4 ± 0.3 | 10⁷ | 57 |
| 1.5 × 1.5 cm² monolayer by VLS | Back-gated | SiO₂ | 1.48 | 33 | >10³ | 980 |
| Few-layer on sapphire by ALD | Top-gated | Al₂O₃ | 25 | 0.56 | 10⁶ | 68 |
| Continuous monolayer by CVD | Back-gated | Al₂O₃ | 6.44 | >10³ | 76 |
| 10 × 10 mm² monolayer by CVD | Back-gated | HfO₂ | 6 | 118 | 10⁸ | 77 |
| Monolayer and bilayer by CVD | Dual-gated | Y₂O₃/HfO₂ | 10 | 1–9 | >10⁵ | 90 |
| Monolayer by CVD | Back-gated | SiO₂ | 2.87 | 3.2 × 10⁶ | 96 |
| Bilayer by CVD | Dual-gated | HfO₂ | 10 | 32.5 | ~800 | 99 |

higher \( I_{on}/I_{off} \) ratio, steeper subthreshold slope, and better stability. With the development of MoS₂ synthesis and MoS₂-FET engineering, the improved basic performance of wafer-scale MoS₂ devices will render the wafer-scale MoS₂ film to be a promising candidate for next-generation electronics, which can be compatible with the traditional silicon-based fabrication process.

4. Toward practical application

Although the charge carrier mobility of 2D MoS₂-FET is not directly comparable to that of Si-based devices, the high \( I_{on}/I_{off} \) ratios and low stand-by power suggests suitable application for low-power electronics and optoelectronics. To advance one step further from a single FET to a complex device, the explorations of electronic devices and optoelectronic devices based on 2D MoS₂, such as N-metal-oxide-semiconductor (NMOS) inverters, logic gate circuits (NAND, NOR, NOT, AND), content-addressable memory (TCAM), and integrated photodetectors, presents great potential application of 2D MoS₂-FET for future integrated electronics and flexible optoelectronics.¹³,²⁵,⁵⁶,⁹⁹,¹⁰¹–¹⁴²

4.1 Logic devices

To build a working logic device, basic requirements are necessary for voltage switching and high frequency operation, such as high \( I_{on}/I_{off} \) ratio (>10⁰⁰) and moderate mobility. In practical applications, different individual MoS₂-FET can be integrated with necessary designs for realizing an inverter. Shin et al. realized a logic inverter and NAND gate based on the GaS/MoS₂ heterostructure comprising a switching transistor and a load resistor. The upper transistor is the load resistor with the transistor gate connected to the output electrode, while the lower transistor acts as a switch by applying an input signal to the gate.

Liu et al.⁶⁸ realized an inverter from two top-gated MoS₂-FETs and constructed several complex logic devices from 3 or 5 MoS₂-FETs. The top-gated FETs based on the wafer-scale MoS₂ synthesized by the ALD method show a high on/off ratio at 10⁶ and a carrier mobility of 0.56 cm² (V⁻¹ s⁻¹). An inverter with a fast response was fabricated using two N-type MoS₂-FETs (a load FET and a pull-down FET) with a different width of the channel, while the gate electrode of the pull-down FET serves as the input terminal. The NAND and NOR gates with three or five FETs were built successfully based on the load FET and the pull-down FET with channel sizes of \( L = 5 \) μm, \( W = 50 \) μm, and \( L = W = 5 \) μm. Two different input voltages, −5 V and 8 V, correspond with the input state of ‘0’ and ‘1’, respectively. The AND and OR gates were realized by connecting the NAND and NOR gates with the inverter logic afterwards.

Li et al.¹³ fabricated flexible top-gated MoS₂-FETs with different channels and demonstrated the application in integrated flexible logic devices. The devices exhibit on/off ratios of ~10⁻¹⁰, carrier mobilities of ~55 cm² V⁻¹ s⁻¹, and good stability and strong tolerance under strain. As shown in Fig. 12, flexible
logic devices such as inverters, NOR gates, NAND gates, SRAMs, AND gates, and five-stage ring oscillators can be realized by integrating 2, 2, 3, 4, 5, and 12 MoS2-FETs, respectively. The inverter shows high voltage gains of 43 and 107 at bias voltages of $V_{dd} = 2 \, \text{V}$ and $4 \, \text{V}$, respectively. The outputs of the NOR and NAND gates are in two states (0 V and 2 V) by combining two input voltages logically at $V_{dd} = 2 \, \text{V}$ and are stable after bending. Two different input voltages, 0 V and 5 V, correspond to the input state of ‘0’ and ‘1’, respectively. The flip-flop memory cell (SRAM) consisting of two inverters exhibit two stable output states, 0 V and 2 V, at $V_{dd} = 2 \, \text{V}$. The AND gate is constructed from a NAND gate and an inverter at $V_{dd} = 2 \, \text{V}$, with a settable state 0 V or 2 V by modifying the two input voltage states. A five-stage ring oscillator was integrated by five inverters and an additional inverter as the output buffer to eliminate the interference. Oscillation frequencies of 860 kHz and 13 MHz were achieved in the flexible ring oscillator when applying $V_{dd} = 5 \, \text{V}$ and $V_{dd} = 15 \, \text{V}$, respectively.

### 4.2 Memory devices

Memory devices, such as dynamic random access memory (DRAM), static random access memory (SRAM), and resistive RAM (RRAM), are essential for digital data storage. 2D MoS2-

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**Fig. 12**  (a) Photographs of different MoS2 integrated devices on flexible substrates. (b) Output voltage of an inverter as a function of input voltage when under different bending states. Inset: voltage gain of the inverter under an input of 4 V. Output characteristics of flexible NOR (c) and NAND (d) gates before and after bending at $V_{dd} = 2 \, \text{V}$. Logic ‘0’ and ‘1’ mean 0 V and 5 V, respectively, for these and all the following logic devices. Output characteristics of flexible SRAM (e) and AND (f) gates at $V_{dd} = 2 \, \text{V}$. (g) Output waveform of a five-stage ring oscillator at $V_{dd} = 15 \, \text{V}$. (h) Output frequency as a function of supply voltage $V_{dd}$. Reproduced with permission from ref. 13, copyright 2020 Springer Nature.
FET is also advantageous in the applications of memory devices. The low leakage currents and high off state in monolayer MoS$_2$-FET can reduce the total power consumption and lead to high speed. Meanwhile, MoS$_2$ with atom thickness is immune to short channel effects suitable for large-scale and tight integration with small footprints. Liao et al.$^{100}$ reported DRAM applications based on dual-gated MoS$_2$-FET with excellent electrostatic control of the channel current. A 1T1C DRAM unit cell consisting of a metal–insulator–metal capacitor and a dual-gated MoS$_2$-FET was fabricated on a sapphire substrate. Yang et al.$^{110}$ demonstrated a TCAM architecture formed by integrating monolayer MoS$_2$-FET with HfO$_x$-RRAM in a two-transistor-two-resistor (2T2R) layout, as shown in Fig. 13. The MoS$_2$-FETs are based on continuous, CVD-grown monolayer MoS$_2$ and have 5 nm HfO$_x$ and 22 nm Al$_2$O$_3$ as the top gate dielectric, with channel width $W$ = 50 $\mu$m and channel length $L$ = 0.8 $\mu$m. The high on/off ratio up to $2 \times 10^7$ not only provides enough current drive to the RRAMs but also sustains sufficiently large voltages for programming the RRAMs. In a device with one-transistor-one-resistor (1T1R) configuration, when the FET turned on, the programming voltage is applied on the top electrode of the RRAM. Then, the RRAM is repeatedly reset/set to HRS/LRS by applying negative/positive voltages on TE ($V_{TE}$) while grounding the source.$^{111}$ The monolayer MoS$_2$-FET drives enough current to the RRAM and reliably controls the current compliance during the RRAM set process. Due to the low off-state current of MoS$_2$-FET and the robust current control in the 1T1R driving scheme, the MoS$_2$-TCAM cells show very large $R$-ratios up to $8.5 \times 10^3$. These results represent a key application of transistors based on the CVD-grown monolayer MoS$_2$, taking advantage of their high performance yet low leakage. MoS$_2$-FET is highly promising for data-intensive applications involving high-throughput matching and searching, and the TCAM array can be potentially integrated into the 3D circuits for energy-efficient computing.

4.3 Photodetectors

Owing to the atomic thickness, tunable bandgap, and strong light interaction, the practical application of 2D MoS$_2$ is attractive in environment-friendly optoelectronic devices, especially in photodetectors. For instance, Zhang et al.$^{112}$ demonstrated high gain phototransistors based on CVD-grown monolayer MoS$_2$ with a photosresponsivity up to 2200 A/W under the irradiation of 532 nm laser. Lim et al.$^{113}$ fabricated MoS$_2$-based visible-light photodetector arrays based on top-gated MoS$_2$-FETs on a 4-inch SiO$_x$/Si wafer with a 1-buty-3-methylimidazolium (BmimPF$_6$) liquid dielectric. As shown in Fig. 14, these 100 devices exhibit a narrow photocurrent distribution (0.05–0.1 nA) at an illumination power of 12.5 mW cm$^{-2}$ and a voltage bias of 20 V. Under periodic illumination using a halogen lamp with a tunable power, the photocurrent demonstrated abrupt switching behavior, regardless of the bias voltages. The photocurrent is linearly dependent on the voltage and illumination power due to the increase in the carrier drift velocity and the carrier generation rate, suggesting excellent tunability for multifaceted optoelectronic applications. Liu et al.$^{114}$ developed MoS$_2$/PbS hybrid device arrays based on the CVD-synthesized monolayer MoS$_2$ and PbS quantum dots. The hybrid devices were obtained by spin-coating PbS quantum dots on the MoS$_2$-FET array and exhibited broad spectral photoresponse (457–1064 nm), rapid response rate, and high responsivity of approximately $1.8 \times 10^4$ A W$^{-1}$. Kim et al.$^{115}$ demonstrated phototransistors based on the monolayer MoS$_2$ film with uniform substitutional doping on the 2-inch wafers. The Nb-doped MoS$_2$ devices exhibited improved optoelectronic performance and stable electrical properties in ambient conditions.

**Fig. 13** 2T2R TMD-TCAM and 1T1R component with MoS$_2$-FET. (a) 3D schematic illustration of the 2T2R TCAM cell, with two MoS$_2$ FETs and two HfO$_x$-based RRAMs. (b) Top-view optical image of the 2T2R TCAM cell. (c) Circuit diagram of the 2T2R TCAM cell showing the definition of match and mismatch states, with the stored data bit ‘1’. (d) 3D schematic of the 1T1R structure, as a component of the 2T2R TCAM cell. (e) Circuit diagram of the 1T1R structure. Measured representative $I_d$ = $V_{TG}$ (f) and $I_d$ = $V_{LS}$ (g) characteristics of the top-gated monolayer MoS$_2$-FET with 25 nm HfO$_x$ as the gate dielectric, with $W$ = 50 $\mu$m, $L$ = 0.8 $\mu$m, measured at $V_{BG}$ = 0 V and with the source grounded.$^{112}$ Reproduced with permission from ref. 112, copyright 2019 Springer Nature.
conditions. The obtained photoresponsivity, detectivity, and response rate were $5 \times 10^{7}$ A W$^{-1}$, $5 \times 10^{12}$ Jones, and 5 ms, respectively, suggesting great feasibility of practical applications based on functionalized 2D MoS$_2$. Kim et al. reported fully printed transparent MoS$_2$ phototransistor arrays on flexible polyethylene-naphthalate (PEN) substrates. The patterned CVD-synthesized MoS$_2$ film was transferred onto a PEN substrate, followed by sequentially inkjet-printed poly(3,4-ethylenedioxythiophene) polystyrenesulfonate (PEDOT:PSS) source/drain electrodes, a cross-linked PVP gate dielectric layer, and a PEDOT:PSS top-gate electrode. The printed transparent MoS$_2$ phototransistors exhibited not only comparable photoresponsivity and photodetectivity over the entire visible range from 400 to 800 nm but also good stability under repetitive bending cycle tests. Furthermore, the performance of MoS$_2$ photodetectors can be dramatically improved and optimized by forming MoS$_2$ hybrid heterostructures with graphene, other TMD, etc. The photoresponsivity, detectivity, and photoresponse of the MoS$_2$-based hybrid photodetectors can vary by several orders of magnitude depending on the nature of the heterostructures, doping situation, wavelengths, and intensity of the applied incident power. The flexible photodetectors developed from MoS$_2$ and MoS$_2$-based hybrid heterostructures provide great potential for the future application in integrated nano-optoelectronic systems and wearable devices.

5. Conclusion and outlook

This review focused on the recent advances in the wafer-scale monolayer MoS$_2$ synthesis and 2D MoS$_2$-FET for practical application in electronics and optoelectronics. Wafer-scale monolayer MoS$_2$ have been realized by different methods, including Au-assisted exfoliation, CVD, thin film sulfurization, MOCVD, VLS method, ALD, and the thermolysis of thiosalts. However, these synthetic methods show different advantages and shortcomings in MoS$_2$ productions and related costs. Au-assisted exfoliation is convenient in laboratory research, but the repetition rate and size uniformity are difficult to control. CVD is relatively low-cost and possible to mass produce for wide applications, although the growth rate and repetition rate should be improved. The thin film sulfurization method is low-cost but leaves behind some problems, such as difficulty in
controlling the thickness of Mo and the MoO<sub>3</sub> layer. MOCVD exhibits great advantages in producing high quality MoS<sub>2</sub> monolayers with high repetition rate, but the long production cycle and special production conditions lead to the high cost. The VLS method seems cost-low in wafer-scale MoS<sub>2</sub> monolayers syntheses, but it is still at the earlier stages of research. ALD can realize wafer-scale MoS<sub>2</sub> monolayers with high repetition rate, but the long production cycle and special production conditions lead to the high cost. MO can realize wafer-scale MoS<sub>2</sub> monolayers with high repetition rate, but the long production cycle and special production conditions lead to the high cost. MO can realize wafer-scale MoS<sub>2</sub> monolayers with high repetition rate, but the long production cycle and special production conditions lead to the high cost.

The precise control of MoS<sub>2</sub> thickness is necessary for the performance improvement in basic MoS<sub>2</sub>-FET. Based on the overall consideration of above synthetic methods, CVD and MOCVD present obvious advantages in the synthesis of wafer-scale MoS<sub>2</sub> monolayers with large quantities. Even though there is considerable room for improvement in monolayer MoS<sub>2</sub> synthesis, more and more efforts are being made to optimize the growth conditions and reduce the costs. Thus, wafer-scale high-quality MoS<sub>2</sub> monolayers could be obtained in the near future with the desired thickness, good uniformity, large grain size, and less defects.

The 2D MoS<sub>2</sub>-FET array with different configurations utilizes high-quality MoS<sub>2</sub> as the channel and exhibits favorable performance. The MoS<sub>2</sub>-FET fabricated from the wafer-scale monolayer MoS<sub>2</sub> demonstrates a mobility of several tens and a on/off ratio even up to 10<sup>10</sup>, demonstrating great potential in practical applications based on basic MoS<sub>2</sub>-FET for modern integrated electronics and flexible optoelectronics, such as logic circuits, memory devices, and photodetectors. Although significant progress has been made in research laboratories for monolayer MoS<sub>2</sub> synthesis and MoS<sub>2</sub>-FET devices, the mass production of wafer-scale and high-quality 2D MoS<sub>2</sub>-FET is still challenging. In the future, more new investigations are needed to fulfill the usage demands of fundamental studies and practical applications, especially different circuit-level applications. The repeatability of wafer-scale uniform MoS<sub>2</sub> synthesis should be improved for device applications. Functionalization and strain engineering based on wafer-scale monolayer MoS<sub>2</sub> are needed to be considered for the improvement of carrier mobility and PL quantum yields. The precise control of MoS<sub>2</sub> transfer and MoS<sub>2</sub>-channel patterning is required for integrated devices fabrication. Further study on the effect of photolithography and the lift-off process on monolayer MoS<sub>2</sub> is also necessary for the performance improvement in basic MoS<sub>2</sub>-FET. Looking forward, with more comprehensive advancement in both fundamental research and practical application, 2D MoS<sub>2</sub> film and MoS<sub>2</sub>-FET will demonstrate great potential and prospect in realizing MoS<sub>2</sub>-based integrated electronics and flexible optoelectronics for modern applications.

**Conflicts of interest**

There are no conflicts to declare.

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