Scalable high performance radio frequency electronics based on large domain bilayer MoS\(_2\)

Qingguo Gao\(^1\), Zhenfeng Zhang\(^1\), Xiaole Xu\(^1\), Jian Song\(^1\), Xuefei Li\(^1\) & Yanqing Wu\(^1\)

Atomically-thin layered molybdenum disulfide (MoS\(_2\)) has attracted tremendous research attention for their potential applications in high performance DC and radio frequency electronics, especially for flexible electronics. Bilayer MoS\(_2\) is expected to have higher electron mobility and higher density of states with higher performance compared with single layer MoS\(_2\). Here, we systematically investigate the synthesis of high quality bilayer MoS\(_2\) by chemical vapor deposition on molten glass with increasing domain sizes up to 200 \(\mu\)m. High performance transistors with optimized high-\(\kappa\) dielectrics deliver ON-current of 427 \(\mu\)A \(\mu\)m\(^{-1}\) at 300 K and a record high ON-current of 1.52 mA \(\mu\)m\(^{-1}\) at 4.3 K. Moreover, radio frequency transistors are demonstrated with an extrinsic high cut-off frequency of 7.2 GHz and record high extrinsic maximum frequency of oscillation of 23 GHz, together with gigahertz MoS\(_2\) mixers on flexible polyimide substrate, showing the great potential for future high performance DC and high-frequency electronics.
Two-dimensional (2D) semiconductors have received great research attention for applications in the emerging field of ubiquitous electronics, such as sensors, memory, and logic applications owing to their atomically thin body and excellent carrier transport properties. Flexible electronics in wireless communication is one of the most promising fields which has witnessed rapid development of flexible passive components and active components. However, despite tremendous interest in graphene transistors for active radio frequency (RF) components, it still remains a challenging issue that the gapless nature of graphene gives rise to poor current saturation and large output conductance in these transistors, which are detrimental for amplifying and mixing high frequency signals. Recently, great progress has been made on high frequency transistors and circuits based on 2D transition metal dichalcogenides, such as molybdenum disulfide (MoS2), where the key disadvantage of graphene can be overcome. Mechanically exfoliated MoS2 on quartz substrates has shown high extrinsic radio frequency performances. In order to provide a low-cost scalable solution, large-area synthesis of MoS2 atomic films by chemical vapor deposition (CVD) was developed with progressive improvement by many research groups. Recently, RF transistors on flexible polyimide substrates based on monolayer MoS2 grown by CVD exhibited an extrinsic cut-off frequency $f_{\text{c}}$ of 2.7 GHz and maximum oscillation frequency $f_{\text{max}}$ of 2.1 GHz and, furthermore, an extrinsic $f_{\text{c}}$ of 3.3 GHz and $f_{\text{max}}$ of 9.8 GHz were demonstrated using an embedded gate structure on SiO2/Si substrates. However, these parameters are still well below the devices based on exfoliated MoS2 severely limiting their high frequency applications. It is known that the carrier mobility of bilayer MoS2 is higher than that of monolayer and, as a result, better performance can be obtained owing to the higher density of states and smaller bandgap which is more suitable for high frequency electronics. However, bilayer MoS2 growth by CVD suffers from small domain sizes and poor mobility, restricting its device performance.

Here, high mobility large domain bilayer MoS2 growth by CVD on molten glass is realized by adjusting the weight of MoO3 precursor during growth. The largest domain size of 200 μm can be obtained and the resulting single-crystal triangular bilayer MoS2 demonstrates a room temperature electron mobility of 36 cm2 V−1 s−1. A back-gated MoS2 transistor with 40 nm channel length exhibits a record high ON-current ($I_{\text{ON}}$) of 1.52 mA μm−1 at 4.3 K with optimized high-κ dielectrics. State-of-the-art RF transistors based on bilayer MoS2 are demonstrated with a record high extrinsic cut-off frequency $f_{\text{c}}$ of 7.2 GHz and maximum oscillation frequency $f_{\text{max}}$ of 23 GHz. Moreover, MoS2 RF transistors and frequency mixers on flexible substrates are demonstrated with a $f_{\text{c}}$ of 4 GHz and $f_{\text{max}}$ of 9 GHz where the mixer remains functional in gigahertz regime.

Results

Material synthesis and characterization. Bilayer MoS2 was grown on molten glass by the vapor-phase reaction of sulfur and MoO3 in a thermal CVD system. Schematic view of the CVD setup is shown in Fig. 1a. The CVD growth process was carried out at ambient pressure where the temperatures of sulfur powders and MoO3 during growth were kept at 230 and 830 °C, respectively. Optical microscopy images of the resulting MoS2 domains on the molten glass with increasing weight of MoO3 are shown in Fig. 1b–e, where well-defined triangular shapes and clear uniform color contrast of CVD bilayer MoS2 are grown (for more details see Methods). As shown in Fig. 1b, monolayer triangular MoS2 domains tend to grow when the weight of MoO3 is less than 1 mg. As the weight of MoO3 slowly increases from 1.5 to 6 mg, bilayer MoS2 starts to grow with an increasing domain size for the same growth duration as shown in Fig. 1c–e. And, with the MoO3 weight of 6 mg, the largest domain size up to 200 μm is obtained. The shrinking size of bilayer MoS2 compared with the monolayer underneath may be due to the first layer has a faster growth rate than the second layer, and the growth time decreases from the first to second layer. This is the largest bilayer MoS2 domain among reported results to the best of our knowledge.

The shrinking size of bilayer MoS2 compared with the monolayer underneath may be due to the first layer has a faster growth rate than the second layer, and the growth time decreases from the first to second layer. This is the largest bilayer MoS2 domain among reported results to the best of our knowledge. As shown in Fig. 1f–h, the film thickness measured by atomic force microscopy (AFM) of the monolayer and bilayer CVD MoS2 is around 0.72 nm and 1.34 nm, respectively.

Raman spectroscopy is widely used to distinguish between monolayer and bilayer MoS2. Figure 2a shows the typical Raman spectra of monolayer and bilayer MoS2. The delta values between the $E_{\text{1g}}$ and $A_{\text{1g}}$ peaks of monolayer and bilayer MoS2 are 18.9 and 22.4 cm−1, respectively, consistent with previous reports. Figure 2b, c show Raman intensity mappings recorded at 385 cm−1 and 405 cm−1, respectively. Bilayer MoS2 region has a higher intensity of Raman signal than that of monolayer, and the uniform contrast indicates a good uniformity of the bilayer film. Figure 2d compares the typical photoluminescence (PL) spectra of the monolayer and bilayer MoS2, where the peaks corresponding to the A1 and B1 direct exciton transitions with the energy split from valence band spin–orbit coupling. The PL intensity of the bilayer MoS2 is about 60% lower than monolayer because of the transition from direct bandgap in monolayer to the indirect bandgap in bilayer. Figure 2e shows the PL intensity mapping of the bilayer domain recorded at 1.85 eV, further confirming the good uniformity of the bilayer MoS2. Transmission electron microscopy (TEM) and electron diffraction studies were performed to confirm the single crystalline nature and to determine the lattice structures of the bilayer MoS2 domains. Figure 2f shows the low-resolution TEM image of a CVD MoS2 domain transferred on copper grids. A magenta dotted line is used to indicate the boundary between monolayer and bilayer MoS2. Figure 2g shows the low-resolution TEM image of a CVD MoS2 domain transferred on copper grids. A magenta dotted line is used to indicate the boundary between the two layers.

DC characterizations on back-gated devices. To characterize the electronic properties of bilayer MoS2, back-gated field-effect transistors (FETs) with channel lengths from 3 μm down to 40 nm were fabricated on HfLaO substrates with a Si back gate. The Shrinking size of bilayer MoS2 compared with the monolayer underneath may be due to the first layer has a faster growth rate than the second layer, and the growth time decreases from the first to second layer. This is the largest bilayer MoS2 domain among reported results to the best of our knowledge. As shown in Fig. 1f–h, the film thickness measured by atomic force microscopy (AFM) of the monolayer and bilayer CVD MoS2 is around 0.72 nm and 1.34 nm, respectively.

The shrinking size of bilayer MoS2 compared with the monolayer underneath may be due to the first layer has a faster growth rate than the second layer, and the growth time decreases from the first to second layer. This is the largest bilayer MoS2 domain among reported results to the best of our knowledge. As shown in Fig. 1f–h, the film thickness measured by atomic force microscopy (AFM) of the monolayer and bilayer CVD MoS2 is around 0.72 nm and 1.34 nm, respectively.
which help to improve the output performance of the transistors\(^3\)\(^{1,35}\) (details of the high-\(\kappa\) dielectrics are discussed in Supplementary Notes 6, 7). Optical microscope images and the corresponding SEM images of the back-gated MoS\(_2\) transistors are shown in Fig. 3a, b. Transfer characteristics of the transistors in the linear region based on monolayer and bilayer MoS\(_2\) with the same channel length of 3 \(\mu\)m are plotted in Fig. 3c. The current and transconductance are more than 50% higher in the bilayer MoS\(_2\) devices compared with the monolayer devices. Note here that the two devices were made on the same substrate with the same oxide thickness and fabrication process to remove processing-induced differences between the two cases. Output characteristics of the same 3 \(\mu\)m channel bilayer MoS\(_2\) device at 300 K and 4.3 K are shown in Fig. 3d, e, respectively. The output drain current increases from 35 \(\mu\)A \(\mu\)m\(^{-1}\) at 300 K to 65 \(\mu\)A \(\mu\)m\(^{-1}\) at 4.3 K, an improvement of over 80% compared to room temperature. Intrinsic field-effect mobility of bilayer FETs is calculated to be 36 and 127 cm\(^2\) V\(^{-1}\) s\(^{-1}\) at 300 K and 4.3 K, respectively (details of the mobility calculations are discussed in Supplementary Note 8). The detailed temperature dependence of mobility is plotted in Fig. 3f, showing a steady increase of mobility with decreasing temperature, which can be mainly attributed to the reduced phonon scattering and the temperature dependence coefficient is consistent with previous work shown in Supplementary Table 2\(^{6}\) (details of the

Fig. 1 Bilayer MoS\(_2\) synthesis on molten glass and morphology characterization. a Schematic of the CVD setup for the synthesis of bilayer MoS\(_2\) on molten glass. b–e Optical micrographs of CVD grown MoS\(_2\) on molten glass; the corresponding weight of MoO\(_3\) are 1, 1.5, 3, and 6 mg, respectively. Scale bars are 30, 40, 50, and 100 \(\mu\)m, respectively. f, g AFM images of bilayer MoS\(_2\) on SiO\(_2\)/Si substrates after transfer. Scale bars are 1 \(\mu\)m. h AFM data of line cut A–B, C–D, and E–F corresponding to the thickness of monolayer MoS\(_2\), the height difference of bilayer and monolayer MoS\(_2\), the thickness of bilayer MoS\(_2\), respectively. Panels f, g located at the edge and crack in the middle of bilayer MoS\(_2\) flake, respectively.
mobility analysis are discussed in Supplementary Note 9). As can be seen in Supplementary Table 1, the mobility of bilayer MoS2 growth on the molten glass in this work shows a clear improvement over the previous results9,27,28,30. Transfer characteristics at the linear region from transistors with reducing channel lengths down to 40 nm are shown in Fig. 3g, where the drain current increases as the channel length decreases (channel length-dependent output characteristics are discussed in Supplementary Note 10). Output characteristics of the 40 nm devices are measured at 300 K with an ON-current of 427 μA μm−1 and at 4.3 K with maximum Vgs up to 6 V where an ON-current of 1.52 mA μm−1 can be achieved as shown in Fig. 3h. This is the largest drive current of MoS2 transistors reported thus far36–38. We attribute this high ON-current at 300 K and 4.3 K to the optimized interface quality, better electrostatic control, high-κ doping effect by HfLaO34,35,39–43, and mobility boost at low temperatures6.

Top-gate high frequency transistors. Top-gated two-finger RF transistors based on bilayer MoS2 have been fabricated and shown in the schematic view in Fig. 4a, with different gate lengths of 90, 190, and 300 nm and the same gate width of 30 μm. Figure 4b shows SEM images of a device with a gate length of 90 nm, exhibiting the precise alignment of gate structure to the source/drain area. There is no overlap in our device design to avoid excess gate to source capacitance Cgs and gate to drain capacitance Cgd. At the same time, the gate to drain access length Lgd and gate to source access length Lgs is minimized to decrease the series resistance. DC characterizations of CVD bilayer MoS2 RF transistor is shown in Supplementary Note 11. Standard on-chip S-parameter measurements up to 30 GHz are used for RF measurement with Lakeshore probe station (for more details see Methods). Figure 4c–e show the as-measured extrinsic short-circuit current gain (|h21|), Mason’s unilateral power gain (U),
Curves at 300 K and 4.3 K for bilayer MoS₂ transistors with a channel length of 40 nm. A record μ step of 0.5 V.

The unilateral power gain versus frequency with an extrinsic Z attributed to the CVD bilayer MoS₂ with high carrier mobility from the short-circuit current gain is 7.2 GHz, the highest reported MoS₂ transistors with different channel lengths. Scale bar is 10 μm. The corresponding SEM images of the active device region and the zoom-in picture. Scale bar are 2 μm and 100 nm, respectively. The $I_{ds}$ – $V_{ds}$ transfer characteristics at 50 mV bias voltage and $g_{m}$ – $V_{ds}$ curves at 1 V bias voltage for the 3 μm channel length back-gated monolayer (blue line and open diamonds, respectively) and bilayer (magenta line and open diamonds, respectively) MoS₂ transistors. The $I_{ds}$ – $V_{ds}$ output characteristics of the bilayer MoS₂ transistor at 300 K and 4.3 K. The back-gate voltages vary from −1 to 3 V with a step of 0.5 V. The extracted intrinsic field-effect mobility versus temperature of bilayer MoS₂ FETs.

Fig. 3 DC electrical characterization of back-gated bilayer MoS₂ transistors at room temperature and low temperatures. a Optical micrograph of back-gated MoS₂ transistors with different channel lengths. Scale bar is 10 μm. b The corresponding SEM images of the active device region and the zoom-in picture. Scale bar are 2 μm and 100 nm, respectively.

c The $I_{ds}$ – $V_{ds}$ transfer characteristics at 50 mV bias voltage and $g_{m}$ – $V_{ds}$ curves at 1 V bias voltage for the 3 μm channel length back-gated monolayer (blue line and open diamonds, respectively) and bilayer (magenta line and open diamonds, respectively) MoS₂ transistors. d The $I_{ds}$ – $V_{ds}$ output characteristics of the bilayer MoS₂ transistor at 300 K and 4.3 K. The back-gate voltages vary from −1 to 3 V with a step of 0.5 V. e The extracted intrinsic field-effect mobility versus temperature of bilayer MoS₂ FETs. f The $I_{ds}$ – $V_{ds}$ transfer characteristics at 50 mV bias voltage at room temperatures for different channel lengths of 40 nm (magenta line), 500 nm (blue line), and 3 μm (black line). h The $I_{ds}$ – $V_{ds}$ output curves at 300 K and 4.3 K for bilayer MoS₂ transistors with a channel length of 40 nm. A record $I_{on}$ of 1.52 mA μm⁻¹ was achieved.

Gigahertz frequency mixers on flexible substrates. A frequency mixer is a key component of RF systems and is widely used in wireless communications. Currently, the demonstrated frequency mixers based on MoS₂ mainly work in MHz regime, mainly due to the relatively low extrinsic high frequency performance of reported MoS₂ RF transistors. Based on the RF transistors shown above, frequency mixers were measured where RF and local oscillator (LO) signals were combined, biased via a bias-Tee, and applied to the gate of the device. The intermediate frequency (IF = RF − LO) signal was measured with a signal analyzer as shown in Fig. 5a. Figure 5b shows the output spectrum of the
configured MoS$_2$ mixer in the gigahertz range, where an IF signal of $f_{\text{IF}} = 100$ MHz is clearly seen with $f_{\text{RF}} = 1.5$ GHz and $f_{\text{LO}} = 1.4$ GHz. The conversion gain versus the applied LO power is plotted in Fig. 5c, showing higher conversion gain can be achieved with increasing LO power from 3 to 9 dBm, consistent with previous work. A conversion gain of $-30.7$ dB was obtained at the LO power of 9 dBm. It should be noted that conversion gain here is defined as the ratio between the IF output signal power and the RF input signal power.

The 2D semiconductors have received high expectations in flexible electronics due to their ultrathin body nature and RF devices are essential for analog signal transmitting, amplifying and processing in those applications. As a result, we fabricated high frequency bilayer MoS$_2$ transistors on flexible polyimide films from Dupont using the same fabrication and measurement techniques, where the DC characteristics of a representative flexible transistor can be found in Supplementary Note 16. An extrinsic cut-off frequency $f_T$ of 4 GHz and maximum oscillation frequency $f_{\text{max}}$ of 9 GHz are achieved in a 300 nm gate length device as shown in Fig. 5d, showing significant improvement over previous results based on monolayer CVD MoS$_2$ on flexible polyimide substrates. The RF characteristics of the transistors after various bending conditions can be found in Supplementary Note 17. Moreover, we also constructed a gigahertz MoS$_2$ RF mixer on flexible substrates with the same test setup as on rigid substrates. The RF signal ($f_{\text{RF}} = 1.5$ GHz, $P_{\text{RF}} = 9$ dBm) and LO signal ($f_{\text{LO}} = 1.4$ GHz, $P_{\text{LO}} = 9$ dBm) are power combined and fed to the gate input of the mixer and the output spectra is measured with a signal analyzer, shown in Fig. 5e, where the intermediate frequency (100 MHz) along with all expected harmonics is clearly shown. This result represents the first demonstration of gigahertz MoS$_2$ mixer on flexible substrates showing great potential of bilayer MoS$_2$ for flexible RF communication. As shown in Fig. 5f, the conversion gain increases monotonically as the LO power increases from 3 to 9 dBm, similar to the rigid substrate case. The IF gains at various frequencies can be found in Supplementary Note 18. By further improving the DC performance and employing impedance matching techniques, the conversion gain can be further improved to match those on high resistivity rigid substrates.

**Discussion**

Systematic study on the large area synthesis of single-crystal bilayer MoS$_2$ films on molten glass using chemical vapor deposition has been carried out. The largest domain size achieved is up to 200 µm with optimized growth condition. The transistors fabricated based on bilayer MoS$_2$ show a high field-effect mobility as well as high ON-current. Notably, the ON-current reaches a record high value at 4.3 K on a short channel 40 nm device, among the highest in 2D materials. Moreover, high performance radio frequency transistors based on these bilayer MoS$_2$ are successfully demonstrated with record high extrinsic $f_T$ and $f_{\text{max}}$ based on top-gated RF transistors. Furthermore, frequency mixers
operating at gigahertz regime are demonstrated on rigid and flexible substrates for the first time. This work demonstrates the potential of CVD bilayer MoS2 for high frequency applications and flexible wireless communication.

**Methods**

**Bilayer MoS2 growth and characterization.** The bilayer MoS2 films were grown on molybdenum disulfide (MoS2) substrates by atmospheric pressure CVD. Prior to growth, the substrates were cleaned in acetone, isopropyl alcohol, and deionized water, followed by 5 min of O2 plasma treatment. Before the rise of temperature, the tube was pumped down to a base pressure, and followed by Ar to 1 atm pressure. Then, the temperatures of the zones I and II were raised to 230 °C and 380 °C, respectively. In the growth stage, 40 sccm Ar was used as carrier gas. The sulfur precursor (1.4 g) was loaded in an alumina boat and placed in zone I. The sulfur weight is adequate, determined by the experiment results of different sulfur weight. The MoO3 precursor was loaded in a SiO2/Si substrate and placed in zone II. The molten glass was placed in a piece of Mo foil, which was located on the top of the MoO3 precursor. The growth durations for all samples in this work were kept as 10 min. The morphology and structure of the bilayer MoS2 were characterized with optical microscopy, AFM (Shimadzu SPM-9700), Raman spectroscopy (LabRAM HR800, 532 nm laser wavelength) and HR-TEM (Titan G2 60-300, at 300 kV).

**Device fabrication.** Back-gated devices are fabricated on HfAlO dielectrics on highly degenerated silicon substrates, where the high-k dielectric layer was deposited by atomic layer deposition (ALD). Bilayer MoS2 was patterned with an electron beam lithography (EBL) step and etched using O2/Ar plasma source. Source and drain electrodes were formed with 20 nm Ni60 nm Au metal stack.

Top-gated RF devices are fabricated on both silicon and polyimide substrates. Bilayer MoS2 domains were transferred onto highly resistive HfLaO/Si or polyimide substrates and patterned with an EBL step and etched using O2/Ar plasma source. Source and drain electrodes were formed with 20 nm Ni/60 nm Au metal stack. A thin layer of naturally oxidized Al2O3 and an additional layer of HfO2 grown by ALD formed the top-gated dielectrics. The thickness of naturally oxidized Al2O3 and ALD-grown HfO2 layer are 6 nm and 11 nm, respectively. The overall gate capacitance is 0.36 μF cm−2. Two-fingered top-gates (20 nm Ni/60 nm Au) were defined by a final EBL and lift-off process.

**Device measurement.** The DC transport measurements were carried out using a Lakeshore probe station and an Agilent B1500A semiconductor parameter analyzer with an Agilent vector network analyzer (N5225A) for high frequency measurements. The on-chip microwave measurements are carried out in the range of 10 MHz–30 GHz. Before the microwave measurements, Short-Open-Load-Thru calibrations are done with standard calibration substrates (GGB CS-5). The mixer measurements are carried out in Lakeshore probe station at room temperature using an Agilent 5182B (or Agilent N5224A) signal generator and Ceyear AV1464B signal generator as the RF and LO input source, and an Agilent DSA90804A digital (or Agilent N9030B signal analyzer) for the IF signal detection. Bias-Tee (Keysight N1161B) are used both at the input and the output to combine DC and RF signals, and provide isolation between them. The LO and RF inputs were combined using external power combiner (Keysight N11636C). Coaxial cable with SMA connectors (Rosenberger LA3-C138-100, Rosenberger LUB-C043-1500, SUCOFLEX 101PEA) were used for the signal transmission and the IF signal detection between output bias-tee and signal analyzer. All the instruments, cables, and connectors met the frequency requirements for the mixer measurement. It should be noted that none of the impedance matching techniques were used in this work. Our measurements were carried out in vacuum to avoid the effects of adsorbents from measurement environment.

**Data availability**

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

Received: 27 March 2018 Accepted: 15 October 2018

Published online: 14 November 2018

**References**

1. Radisavljevic, B., Radenovic, A., Brivio, J., Giacometti, V. & Kis, A. Single-layer MoS2 transistors. *Nat. Nanotechnol.* 6, 147–150 (2011).
2. Sarkar, D. et al. MoS2 field-effect transistor for next-generation label-free biosensors. *ACS Nano* 8, 3992–4003 (2014).
3. Vu, Q. A. et al. Two-terminal floating-gate memory with van der Waals heterostructures for ultrahigh on/off ratio. *Nat. Commun.* 7, 12725 (2016).
4. Huang, M. et al. Multifunctional high-performance van der Waals heterostructures. *Nat. Nanotechnol.* 12, 1148 (2017).
5. Wachter, S., Polyushkin, D. K., Bethge, O. & Mueller, T. A microprocessor based on a two-dimensional semiconductor. *Nat. Commun.* 8, 14948 (2017).
6. Li, X. et al. Performance potential and limit of MoS2 transistors. Adv. Mater. 27, 1547–1552 (2015).
7. Desai, S. B. et al. MoS2 transistors with 1-nanometer gate lengths. Science 354, 99 (2016).
8. Si, M. et al. Steep-slope hysteresis-free negative capacitance MoS2 transistors. Nat. Nanotechnol. 13, 24–28 (2018).
9. Rai, A. et al. Progress in contact, hysteresis and mobility engineering of MoS2: an overview of 2D semiconductor. Crystals 8, 316 (2018).
10. Zhang, J. et al. Flexible indium–gallium–zinc–oxide Schottky diode operating beyond 2.45 GHz. Nat. Commun. 6, 7561 (2015).
11. Wu, Y. et al. High-frequency, scaled graphene transistors on diamond-like carbon. Nature 472, 74–78 (2011).
12. Wu, Y. et al. State-of-the-art graphene high-frequency electronics. Nano Lett. 12, 3062–3067 (2012).
13. Cheng, R. et al. Few-layer molybdenum disulfide transistors and circuits for high-speed flexible electronics. Nat. Commun. 5, 5143 (2014).
14. Krasnozhan, D., Lembke, D., Nyffeler, C., Leblebici, Y. & Kis, A. MoS2 transistors operating at gigahertz frequencies. Nano Lett. 14, 5905–5911 (2014).
15. Sanne, A. et al. Radio frequency transistors and circuits based on CVD MoS2. Nano Lett. 15, 5939–5945 (2015).
16. Chang, H.-Y. et al. Large-area monolayer MoS2 for flexible low-power RF nanoelectronics in the GHz regime. Adv. Mater. 28, 1818–1823 (2016).
17. Sanne, A. et al. Embedded gate CVD MoS2 microwave FETs. npj 2D Mater. Appl. 1, 26 (2017).
18. Lee, H. et al. Synthesis of large-area MoS2 atomic layers with chemical vapor deposition. Adv. Mater. 24, 2320–2325 (2012).
19. Zhan, Y., Liu, Z., Najmaei, S., Ajayan, P. M. & Lou, J. Large-area vapor-phase growth and characterization of MoS2 atomic layers on a SiO2 Substrate. Small 8, 966–971 (2012).
20. van der Zande, A. M. et al. Grains and grain boundaries in highly crystalline monolayer molybdenum disulfide. Nat. Mater. 12, 354 (2013).
21. Kang, K. et al. High-mobility three-atom-thick semiconductor films with wafer-scale homogeneity. Nature 520, 656–660 (2015).
22. Ji, Q. et al. Unravelling orientation distribution and merging behavior of monolayer MoS2 domains on sapphire. Nano Lett. 15, 198–205 (2015).
23. Chen, W. et al. Oxygen-assisted chemical vapor deposition growth of large single-crystal and high-quality monolayer MoS2. J. Am. Chem. Soc. 137, 15632–15635 (2015).
24. Chen, J. et al. Chemical vapor deposition of large-size monolayer MoS2 crystals on molten glass. J. Am. Chem. Soc. 139, 1073–1076 (2017).
25. Ju, M. et al. Universal substrate-trapping strategy to grow strictly monolayer transition metal dichalcogenide crystals. Chem. Mater. 29, 6095–6103 (2017).
26. Wang, H. et al. Integrated circuits based on bilayer MoS2 transistors. Nano Lett. 12, 4674–4680 (2012).
27. Zheng, J. et al. High-mobility multilayered MoS2 flakes with low contact resistance grown by chemical vapor deposition. Adv. Mater. 29, 160450 (2017).
28. Jang, J. et al. Layer-controlled CVD growth of large-area two-dimensional MoS2 films. Nanoscale 7, 1688–1695 (2015).
29. Wang, X., Feng, H., Wu, Y. & Iiao, L. Controlled synthesis of highly crystalline MoS2 flakes by chemical vapor deposition. J. Am. Chem. Soc. 135, 5304–5307 (2013).
30. Zobel, A. et al. Chemical vapour deposition and characterization of uniform bilayer and trilayer MoS2 crystals. J. Mater. Chem. C 4, 11081–11087 (2016).
31. Ye, H. et al. Toward a mechanistic understanding of vertical growth of van der Waals stacked 2D materials: a multiscale model and experiments. ACS Nano 11, 12780–12788 (2017).
32. Li, H. et al. From bulk to monolayer MoS2 evolution of raman scattering. Adv. Funct. Mater. 22, 1385–1390 (2012).
33. Splendiani, A. et al. Emerging photoluminescence in monolayer MoS2, Nano Lett. 10, 1271–1275 (2010).
34. Li, T. et al. High field transport of high performance black phosphorus transistors. Appl. Phys. Lett. 110, 163507 (2017).
35. Xiong, X. et al. High performance black phosphorus electronic and photonic devices with HfOx dielectric. IEEE Electron Dev. Lett. 39, 127–130 (2018).
36. English, C. D., Shire, G., Dorgan, V. E., Saraswat, K. C. & Pop, E. Improved contacts to MoS2 transistors by ultra-high vacuum metal deposition. Nano Lett. 16, 3824–3830 (2016).
37. Liu, Y. et al. Pushing the performance limit of sub-100 nm molybdenum disulfide transistors. Nano Lett. 16, 6337–6342 (2016).
38. Nourbakhsh, A. et al. MoS2 field-effect transistors with sub-10 nm channel length. Nano Lett. 16, 7798–7806 (2016).
39. Rai, A. et al. Air stable doping and intrinsic mobility enhancement in monolayer molybdenum disulfide by amorphous titanium suboxide encapsulation. Nano Lett. 15, 4329–4336 (2015).
40. Amirthraj, V., Jixon, C., Amrithesh, R., Leonard, F. R. & Sanjay, K. B. Theoretical and experimental investigation of vacancy-based doping of monolayer MoS2 on oxide. 2D Mater. 2, 045009 (2015).