

# Wafer-Scale 2D MoS<sub>2</sub> Transistors Using Transfer-Free Location-on-Demand Selective Synthesis

Chu-Te Chen<sup>1</sup>, Anthony Cabanillas<sup>2</sup>, Huamin Li<sup>2</sup>, and Fei Yao<sup>1</sup>

<sup>1</sup>Department of Materials Design and Innovation, University at Buffalo, The State University of New York, Buffalo, NY, USA

<sup>2</sup>Department of Electrical Engineering, University at Buffalo, The State University of New York, Buffalo, NY, USA

Email: feiyao@buffalo.edu and huaminli@buffalo.edu



## Introduction

2D semiconducting transition metal dichalcogenides (TMDs) show promise for device miniaturization, but challenges in scalability, uniformity, and substrate compatibility hinder commercial viability [1-7]. We address these issues with a novel location-on-demand selective growth method for high-quality TMD layers. Using MoS<sub>2</sub> as an example, we demonstrate wafer-scale, transfer-free growth of MoS<sub>2</sub> arrays using patterned MoO<sub>3</sub> seeding. We observe the chemical vapor deposition (CVD) growth of MoS<sub>2</sub> on micrometer scale within a few seconds and investigate the impact of dielectric interfaces (MoO<sub>3</sub> and SiO<sub>2</sub>) on MoS<sub>2</sub> FET performance. We find that polycrystalline MoS<sub>2</sub> with MoO<sub>3</sub> interfaces shows comparable and even superior characteristics to other growth methods. This work establishes a viable approach for integrating 2D semiconductors with Si-CMOS technology, paving the way for advanced electronic devices.

## Material Synthesis

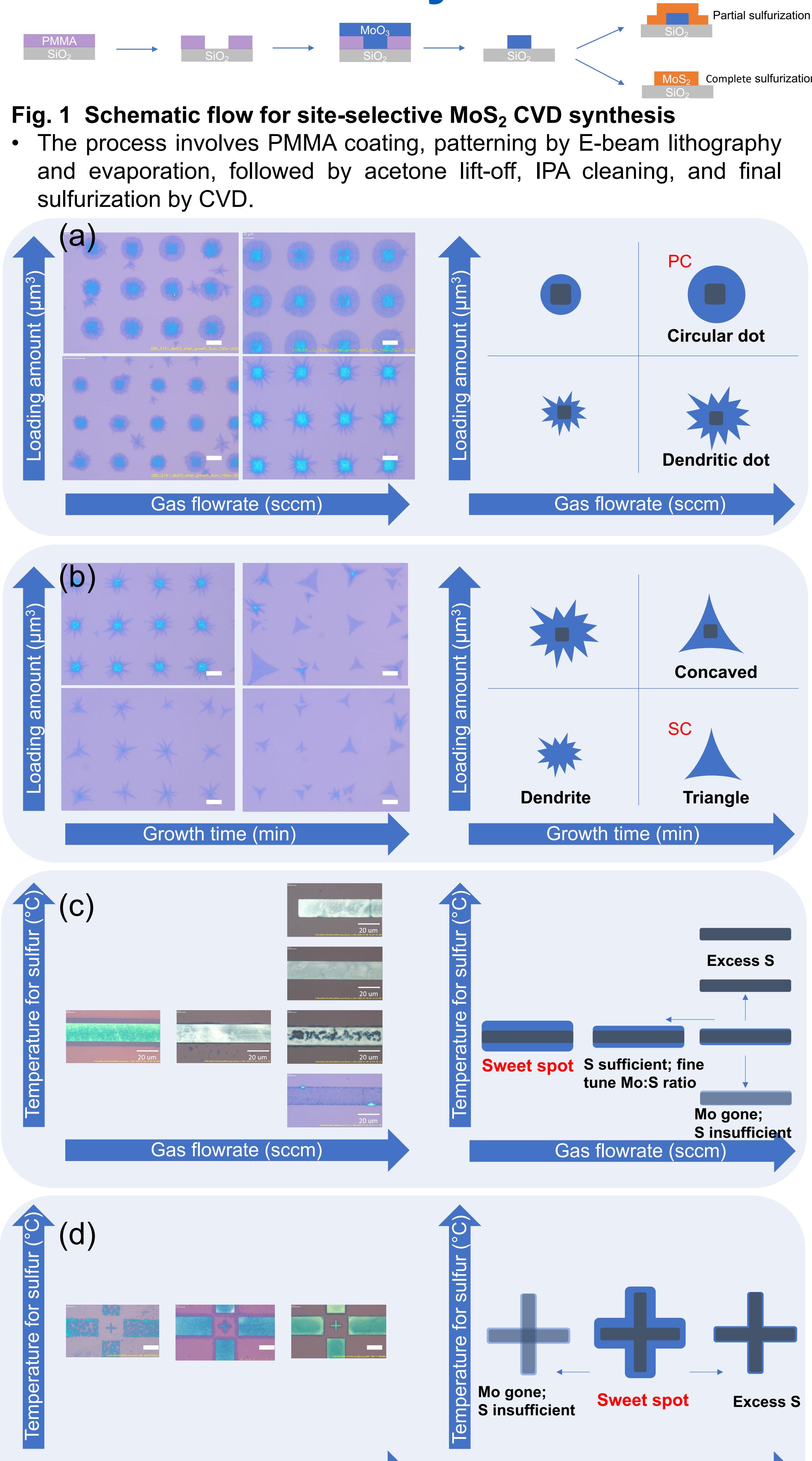


Fig. 1 Schematic flow for site-selective MoS<sub>2</sub> CVD synthesis

- The process involves PMMA coating, patterning by E-beam lithography and evaporation, followed by acetone lift-off, IPA cleaning, and final sulfurization by CVD.

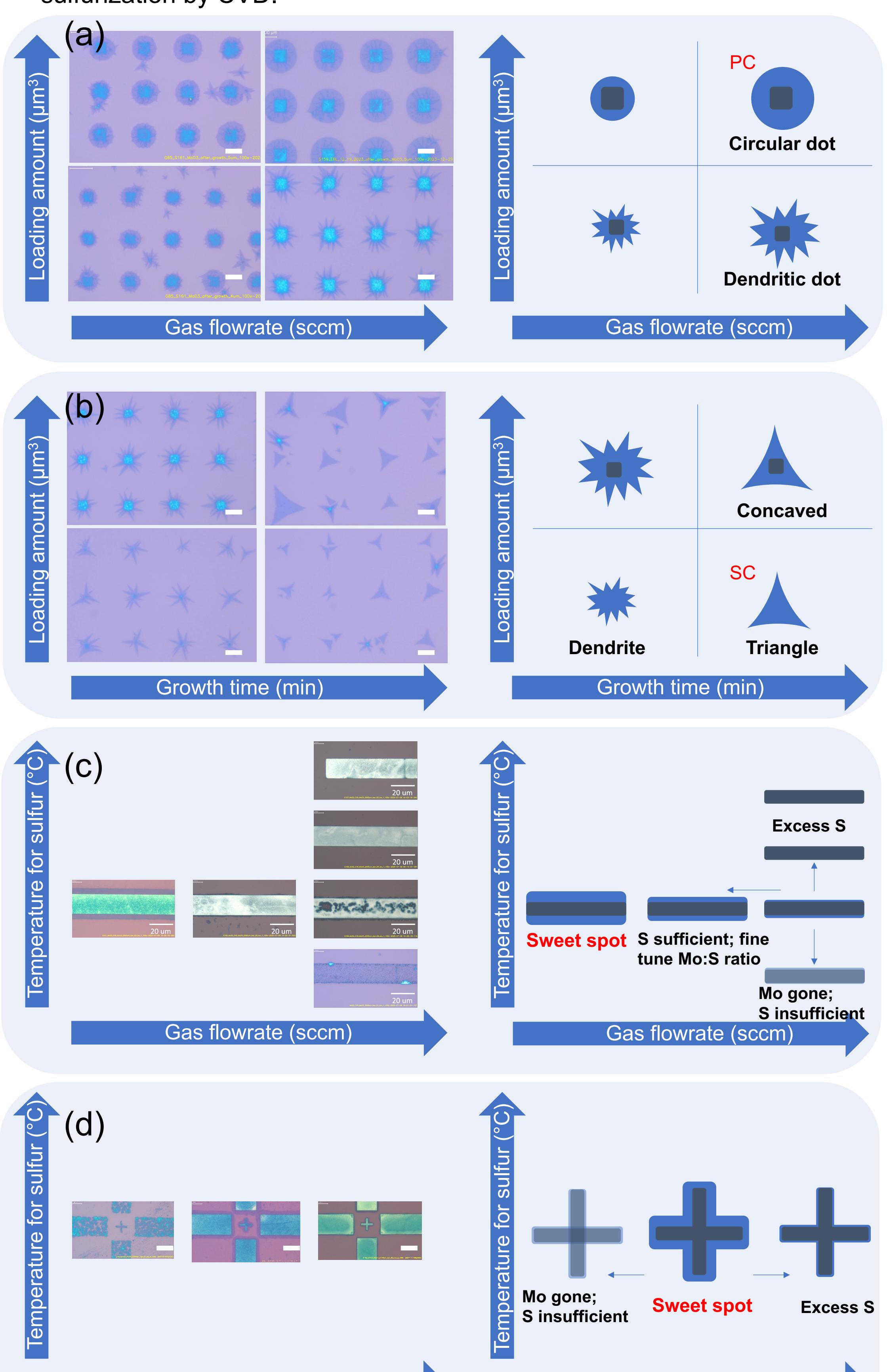


Fig. 2 Exploration of CVD parameters space and its schematic evolution

- Several variables influence the CVD synthesis of MoS<sub>2</sub>, including: (1) Amount of molybdenum (Mo) precursor, (2) Amount of sulfur (S) precursor, (3) Temperatures for Mo, (4) Temperatures for S, (5) Ramping rate for Mo and S, (6) Carrier gas flowrate, and (7) Growth duration.
- (a) Relationship between Mo precursor quantity and gas flow rate, resulting in the formation of polycrystalline (PC) MoS<sub>2</sub>.
- (b) Influence of Mo loading and growth time, which enables single-crystalline (SC) MoS<sub>2</sub> formation.
- (c-d) Effects of sulfur temperature and gas flowrate on the optimization of the various Transmission Line Model (TLM) patterns.

## Material Characterization

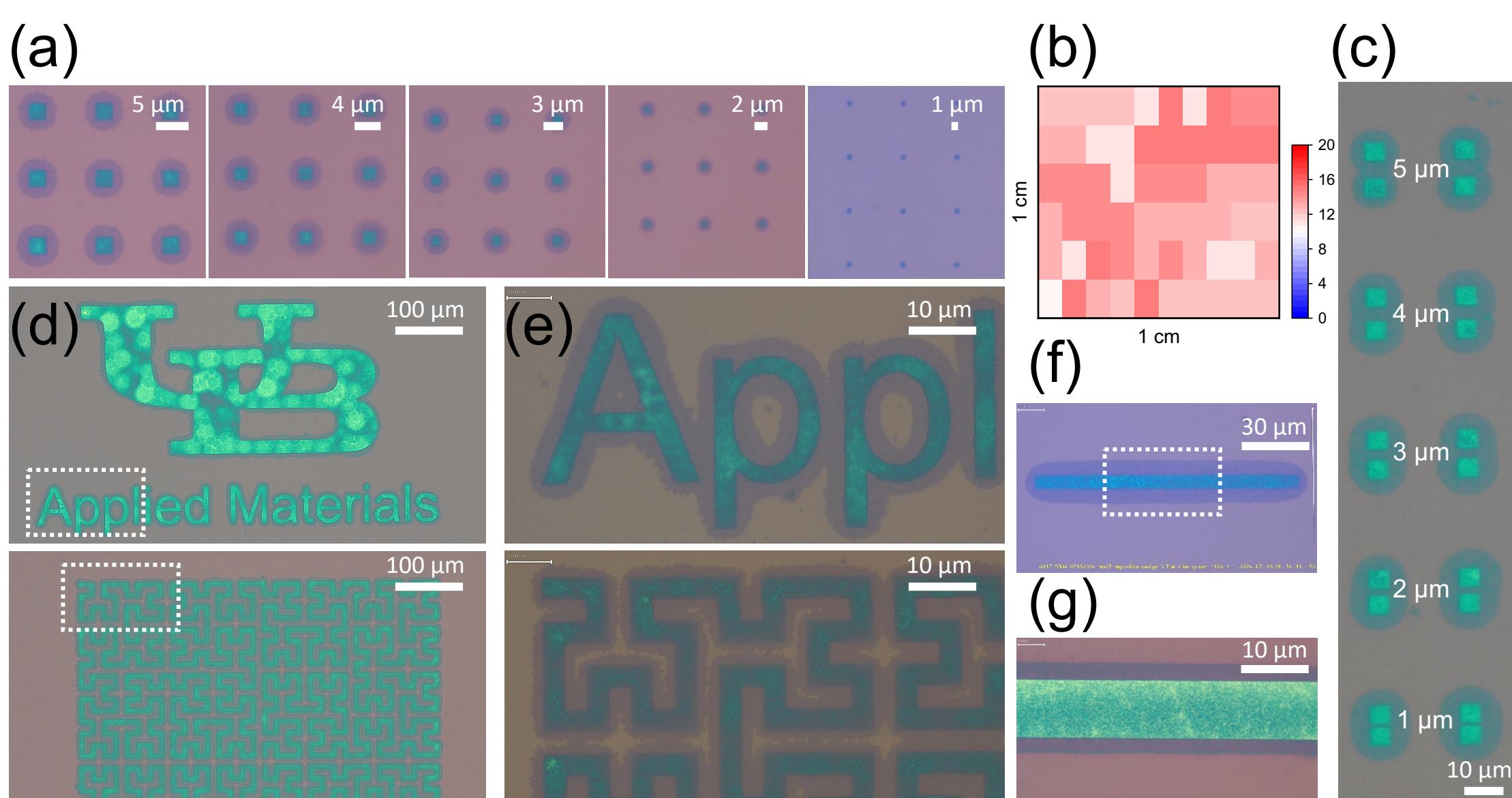


Fig. 3 Optical Microscopy (OM) images of various location-on-demand MoS<sub>2</sub> synthesis.

- (a) Arrays of circular dots with diameters ranging from 5  $\mu$ m to 1  $\mu$ m.
- (b) Spatial uniformity of the MoS<sub>2</sub> sizes across a 1  $\times$  1 cm<sup>2</sup> area. The average size is about 14  $\mu$ m.
- (c) Optical microscopy showing circular MoS<sub>2</sub> films merging as the distance between MoO<sub>3</sub> seed sites decreases from 5  $\mu$ m to 1  $\mu$ m.
- (d-e) Optical images of patterned text (such as the UB logo and Applied Materials) and a Hilbert curve, along with their magnified views.
- (f-g) Transmission Line Model (TLM) bar structure representations.

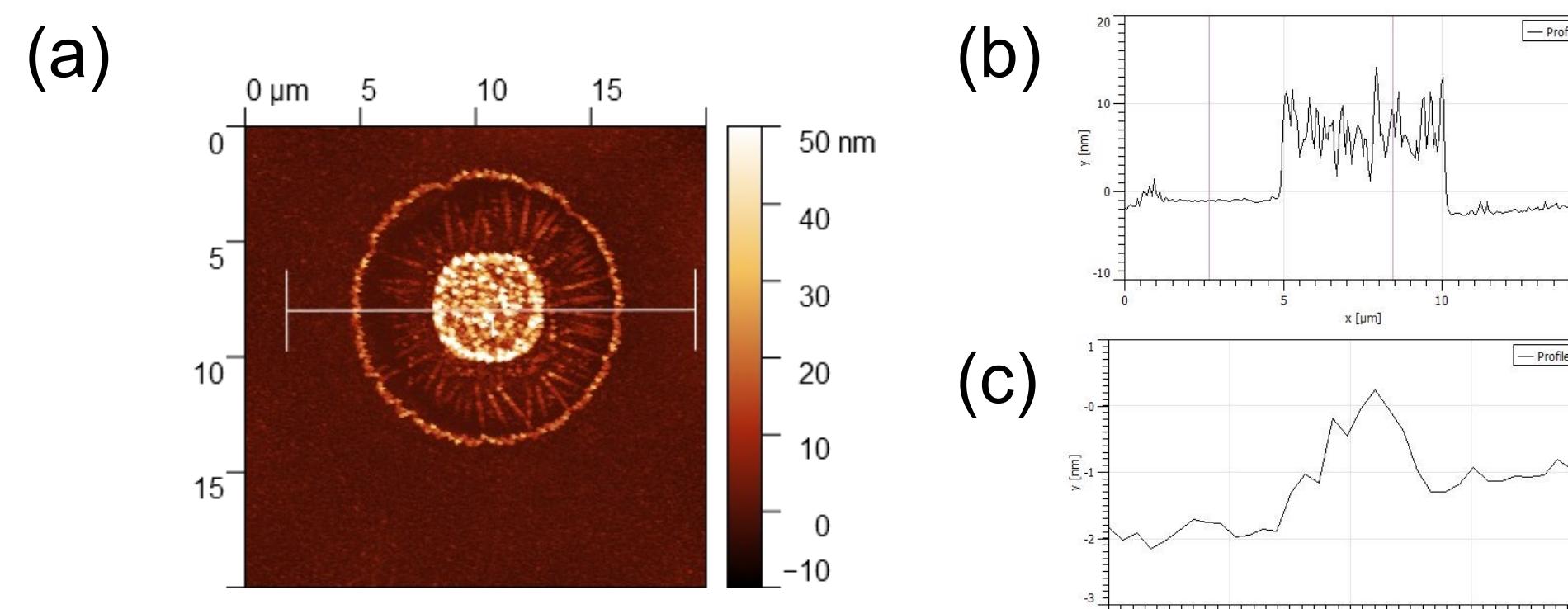


Fig. 4 Atomic Force Microscopy (AFM)

- (a) AFM topography of a circular MoS<sub>2</sub>/MoO<sub>3</sub>/SiO<sub>2</sub>/Si sample.
- (b-c) The edge region exhibits a thickness of approximately 1–2 nm, indicating the presence of bi/tri-layer MoS<sub>2</sub>, while the central area confirms MoS<sub>2</sub> coverage over the patterned MoO<sub>3</sub> dielectric layer.

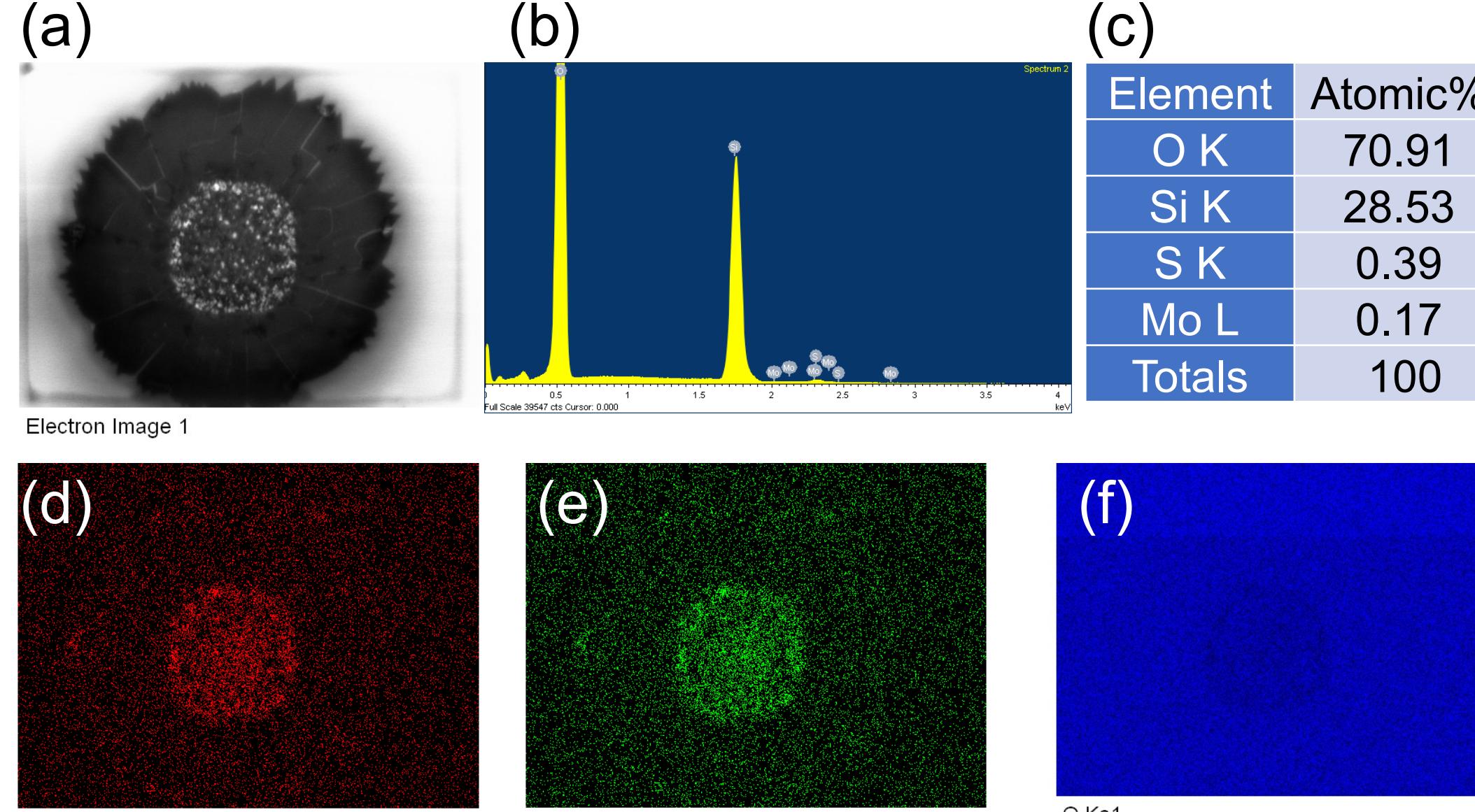


Fig. 5 Scanning Electron Microscopy with Energy Dispersive Spectroscopy (SEM/EDS)

- (a) SEM image of circular sample of MoS<sub>2</sub>/MoO<sub>3</sub>/SiO<sub>2</sub>/Si
- (b-c) EDS spectrum and chemical composition percentage
- (d-f) EDS mapping of molybdenum, sulfur, and oxygen.

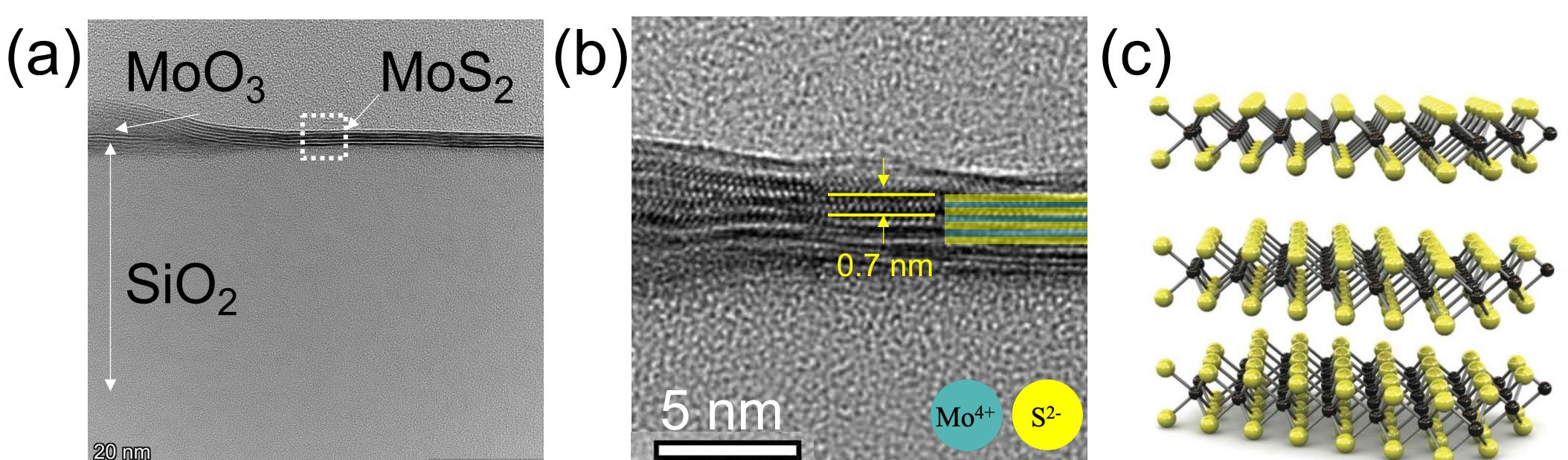


Fig. 6 Transmission electron microscopy (TEM)

- (a) Cross-sectional TEM image displaying the MoS<sub>2</sub>/MoO<sub>3</sub>/SiO<sub>2</sub>/Si layers, with a 20 nm scale bar.
- (b) Enlarged region from (a) highlighting the atomic arrangement of molybdenum and sulfur and illustrating a single MoS<sub>2</sub> layer with a thickness of approximately 0.7 nm.
- (c) Schematic representation depicting the crystal structure of MoS<sub>2</sub> [8]

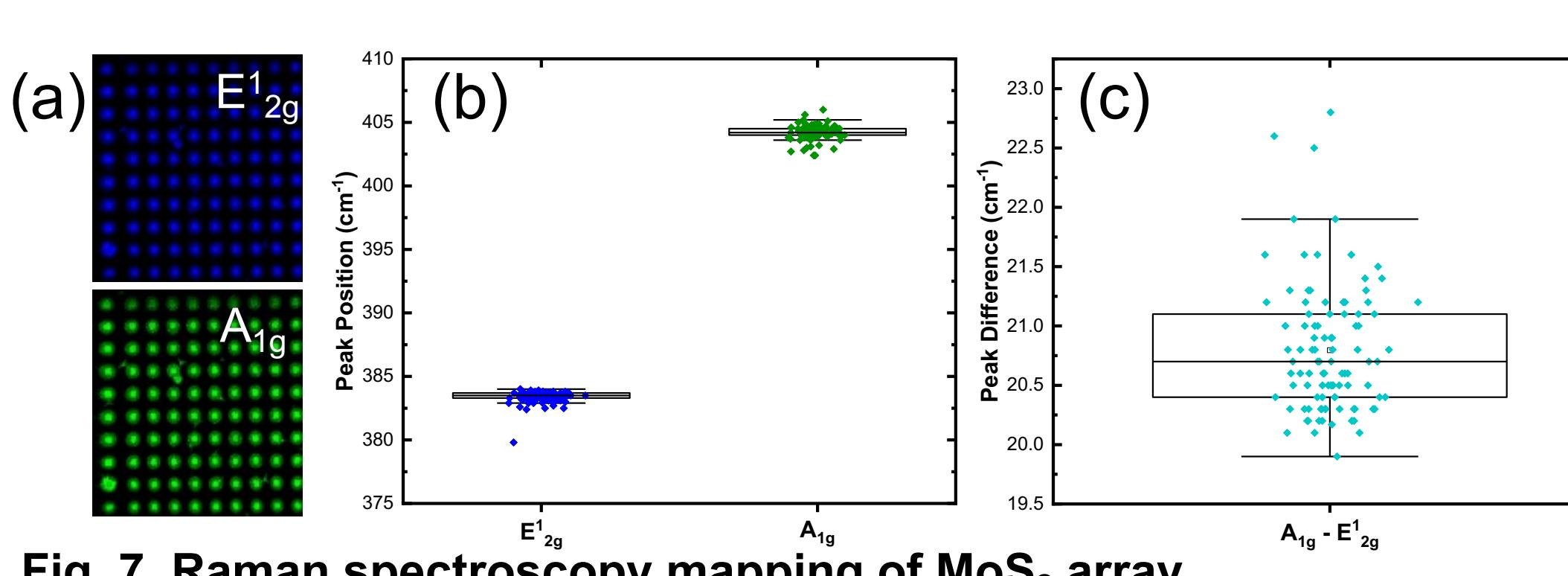


Fig. 7 Raman spectroscopy mapping of MoS<sub>2</sub> array.

- (a-b) The statistic data of Raman mapping 10  $\times$  10 array indicate that the average E<sub>12g</sub> and A<sub>1g</sub> Raman shift at the edge of the circular flakes is 383 cm<sup>-1</sup> and 404 cm<sup>-1</sup> separately.
- (b) The differences between E<sub>12g</sub> and A<sub>1g</sub> peaks are between 20 cm<sup>-1</sup> – 22 cm<sup>-1</sup>, which correspond to bilayer MoS<sub>2</sub>. [9]

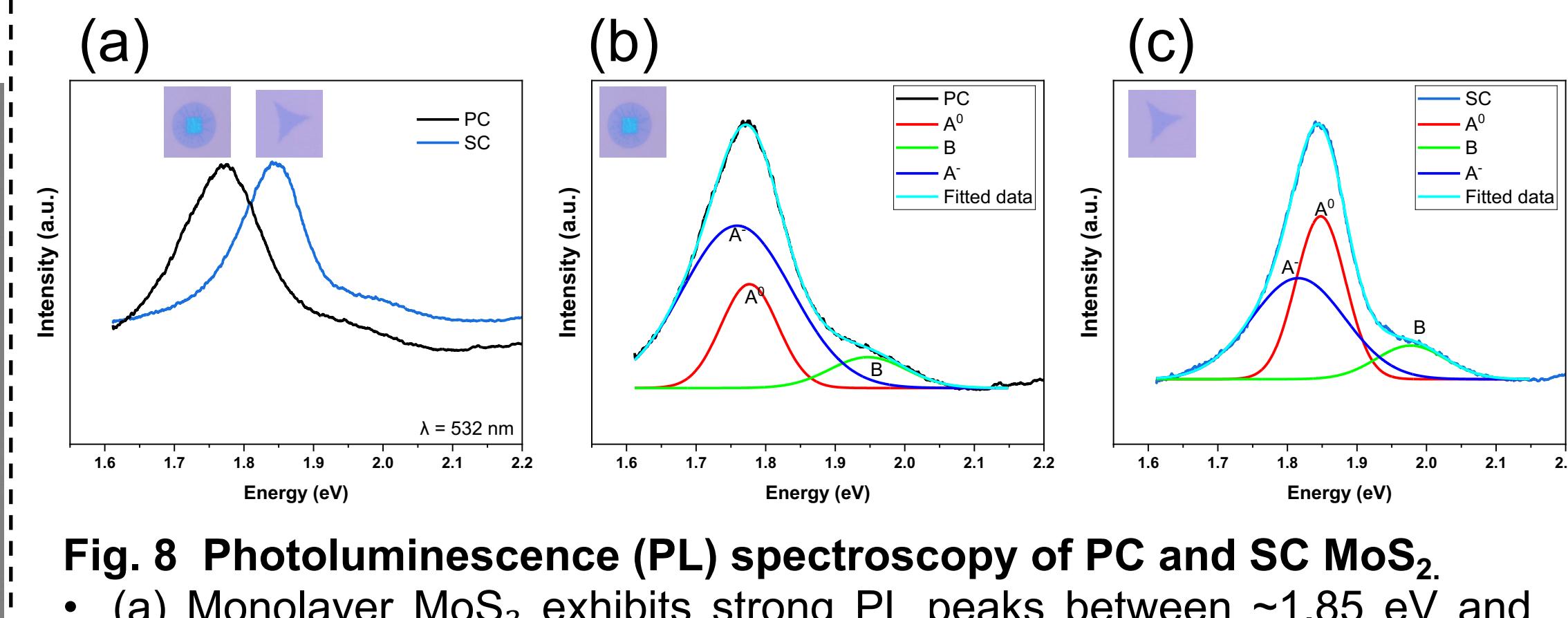


Fig. 8 Photoluminescence (PL) spectroscopy of PC and SC MoS<sub>2</sub>.

- (a) Monolayer MoS<sub>2</sub> exhibits strong PL peaks between ~1.85 eV and 2.00 eV; the SC sample falls within this range, consistent with monolayer or bilayer behavior, while the PC sample shows a redshift, indicative of multilayer MoS<sub>2</sub>.
- (b-c) PL spectra deconvolution reveals two main features: the dominant A exciton peak (1.8–1.9 eV) and a B exciton shoulder (>1.9 eV). The ~0.15 eV separation matches the spin-orbit splitting of the valence band at the K-point in 1L-MoS<sub>2</sub>. [10]

## Device applications

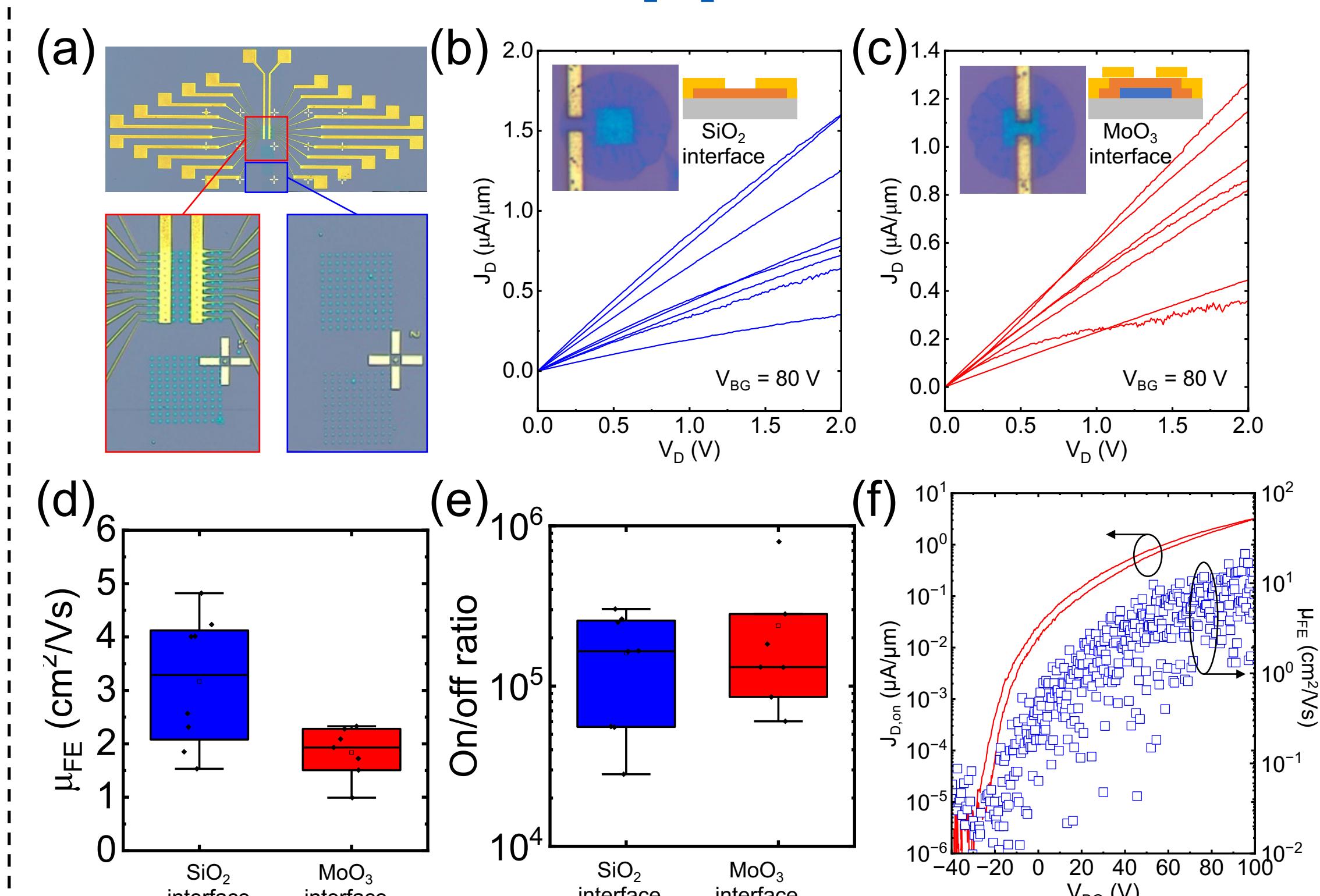


Fig. 9 Comparison of synthetic MoS<sub>2</sub> FETs with SiO<sub>2</sub> and MoO<sub>3</sub> dielectric interfaces.

- (a) Microscope images of the wafer-scale MoS<sub>2</sub> FET arrays with MoO<sub>3</sub> dielectric interfaces
- (b-c) The linear  $J_D$ - $V_D$  characteristics suggest Ohmic contact for both FET types.
- (d-e) Statistical analysis of the MoS<sub>2</sub> FETs with SiO<sub>2</sub> and MoO<sub>3</sub> dielectric interfaces, including  $\mu_{FE}$ , on/off ratio.
- (f) The best back-gate MoS<sub>2</sub> FET with MoO<sub>3</sub> dielectric interfaces possesses  $J_{D, on}$  of 3  $\mu$ A/ $\mu$ m,  $\mu_{FE}$  of 20 cm<sup>2</sup>/Vs, and an on/off ratio up to 10<sup>6</sup>.

## Conclusion

In this work, we presented wafer-scale MoS<sub>2</sub> FET arrays using transfer-free location-on-demand selective growth. This technique allows time- and cost-efficient synthesis of 2D semiconductor channel arrays at designed locations, and the controlled sulfurization creates MoO<sub>3</sub> dielectric interfaces to enhance FET performance. Our devices show comparable and even superior performance, such as  $J_{D, on}$ ,  $\mu_{FE}$ , and on/off ratios, compared to other MoS<sub>2</sub> FETs using selective and non-selective growth, and demonstrate great potential to ease the integration of 2D semiconductors for various electron devices.

## References

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APPLIED MATERIALS

ECCS 1944095  
University at Buffalo

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