

Supporting Information for

Low-Temperature Synthesis of Boron Nitride as a Large-Scale Passivation and Protection Layer for 2D Materials and High-Performance Devices

Zhanjie Lu¹, Meijie Zhu¹, Yifan Liu², Gehui Zhang¹, Zuoquan Tan¹, Xiaotian Li³, Shuaishuai Xu⁴, Le Wang¹, Ruifen Dou³, Bin Wang⁴, Yuan Yao⁵, Zhiyong Zhang², Jichen Dong⁶, Zhihai Cheng^{1*} and Shanshan Chen^{1*}

- ^{1.} Department of Physics and Beijing Key Laboratory of Optoelectronic Functional Natural Materials and Micro-nano Devices, Renmin University of China, Beijing 100872, People's Republic of China
- ^{2.} Key Laboratory for the Physics and Chemistry of Nanodevices and Center for Carbon-based Electronics, Peking University, Beijing, 100871, China
- ^{3.} Department of Physics, Beijing Normal University, Beijing, 100875, P. R. China
- ^{4.} Key Laboratory of Nanosystem and Hierarchical Fabrication, National Center for Nanoscience and Technology, Beijing 100190, China
- ^{5.} Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China
- ^{6.} Institute of Chemistry, Chinese Academy of Sciences, Beijing 100190, China

***E-mail:** schen@ruc.edu.cn and zhihaicheng@ruc.edu.cn

S1. The effect of AB heating temperature on the growth of BN on 2DMs at low temperature.

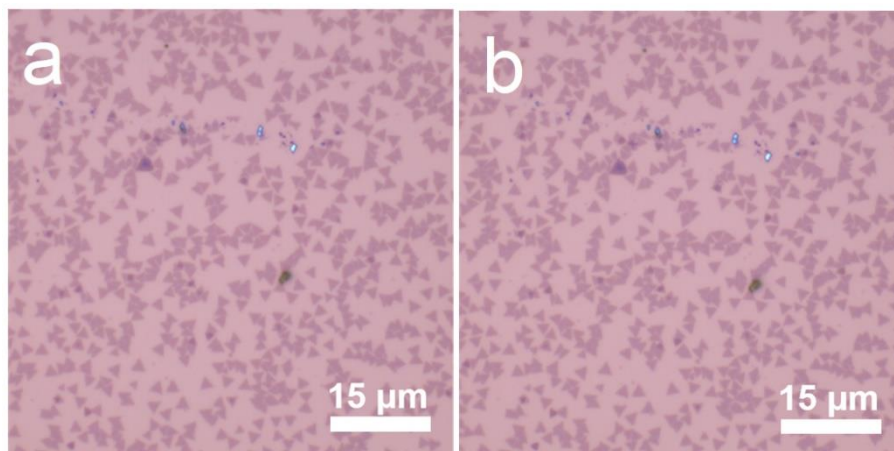


Figure S1. Optical images of the MoS₂/SiO₂/Si before (a) and after (b) BN growth at 500 °C under $T_{AB} = 70$ °C for 20 min. There is no color contrast difference between the samples before and after BN growth suggesting that no film has been deposited on the MoS₂ or the SiO₂/Si substrate.

S2. Growth of BN capping layer on MoS₂/SiO₂/Si at 800°C.

As shown in Figure S2, the Raman spectrum of the MoS₂ disappears after BN capping at 800°C, suggesting the degradation of MoS₂ during BN growth. On the other hand, the BN film shows clear E_{2g} mode from the B-N vibration at 1370 cm⁻¹, indicating the formation of high-quality *h*-BN film. Therefore, higher T_{growth} yields BN film with high quality, but causes harm to the underneath 2D materials.

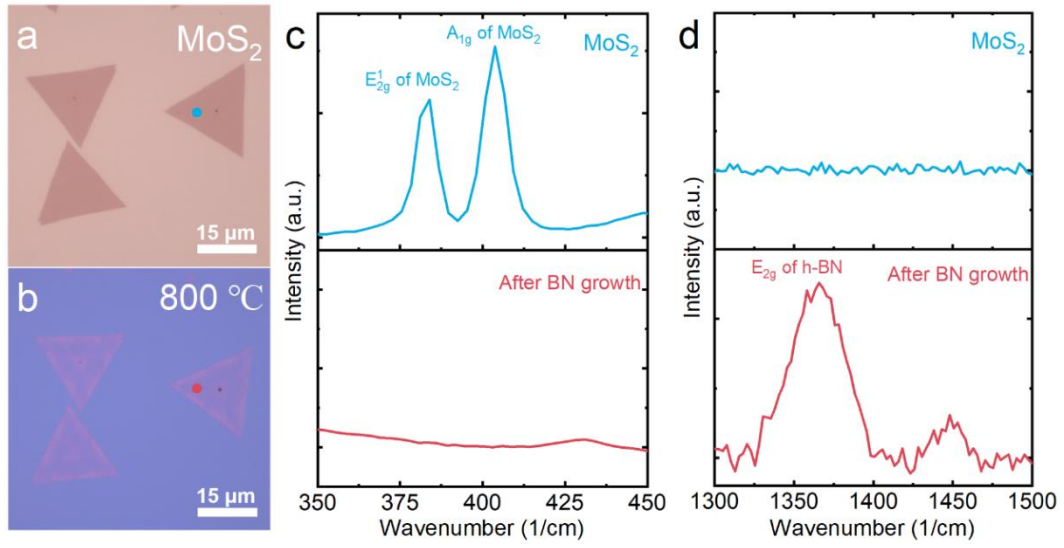


Figure S2. (a, b) Optical images of MoS₂ before (a) and after (b) BN growth at 800 °C for 20 min under $T_{\text{AB}} = 110$ °C. (c) Raman spectra of MoS₂ before and after BN growth. (d) Raman spectra of BN before and after growth.

S3. The effect of the amount of AB supply on the growth of BN on 2DMs at low temperature.

With low AB supply ($M_{AB} < 5$ mg), no BN film could be formed on both the SiO₂/Si substrate and the MoS₂. Figure S3a shows the optical image of MoS₂/SiO₂/Si after BN growth at 500°C under 2 mg AB for 20 min. As shown in Figure S3b, no BN film is formed on the substrate or the MoS₂ domain, which is evidenced by the disappearance of the MoS₂ domains after Raman scanning (5 mW).

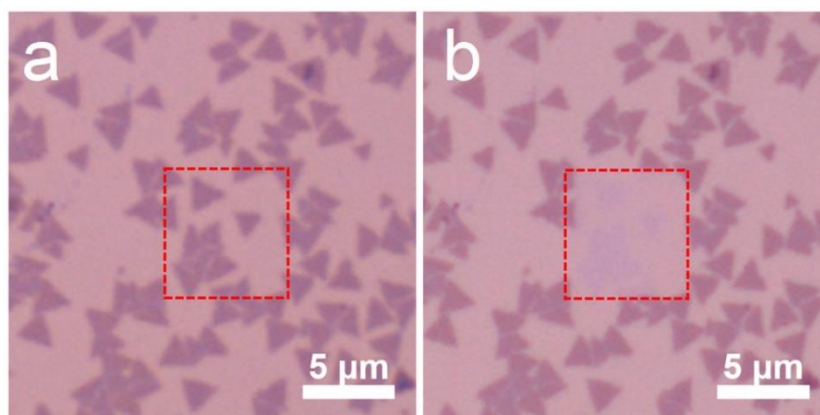


Figure S3. (a) Optical image of MoS₂ after BN growth at 500 °C with 2 mg AB. (b) Optical image of MoS₂ after laser area scanning with 10 mW for 10s at each 60 points (6×6 μm). Red dashed square marks the area of laser scanning.

Figure S4 a-c illustrate the thickness of BN on the SiO₂/Si substrate under various $M_{AB} = 10, 20$ and 30 mg. It is clear that the mass of AB strongly affects the thickness of the BN capping layer.

With high AB supply ($M_{AB} > 15$ mg), BN forms directly on top of both the SiO₂/Si substrate and the MoS₂, forming the vertical BN/MoS₂ heterostructure. Figure S4 a-c show the result of BN growth under $M_{AB} = 20$ mg for 20 min on MoS₂/SiO₂/Si substrate. BN film is deposited on the entire MoS₂/SiO₂/Si sample. The thickness difference measured from AFM in Figure S4 c is ~ 4.58 nm, in consistent with the value obtained under $M_{AB} = 30$ mg (See Figure 1g in the main text).

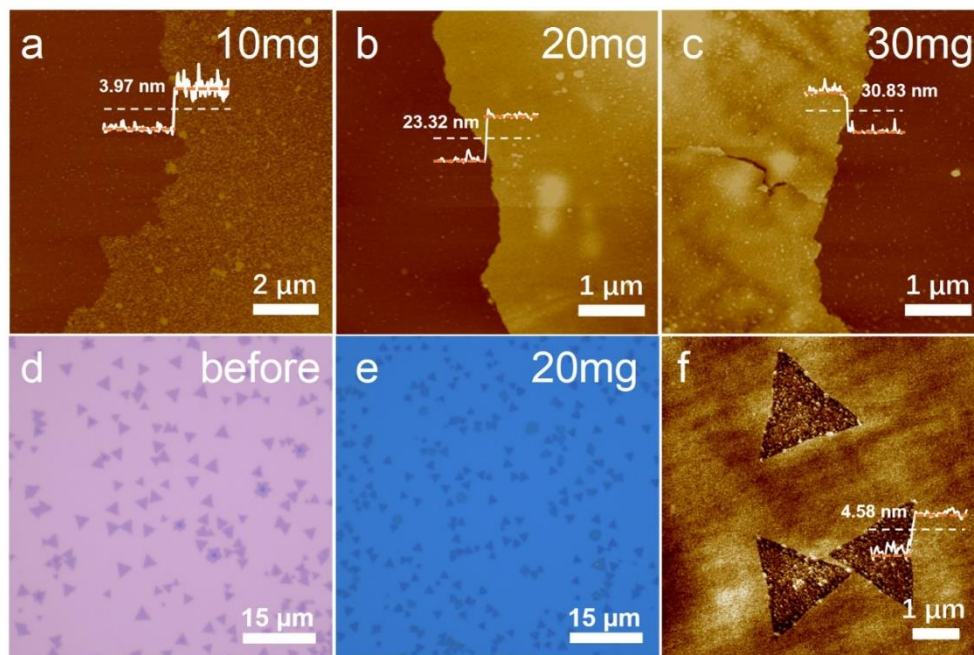


Figure S4 (a-c) AFM images of the BN capping layer grown under various M_{AB} . The thickness shows the BN layer on the SiO₂/Si substrate. (d, e) Optical images of MoS₂ before and after BN capping layer growth under $M_{AB} = 20$ mg at 500 °C. (f) AFM image of BN/MoS₂ grown at $M_{AB} = 20$ mg shows the height difference of ~ 4.58 nm, and the BN thickness difference is thus ~ 3.78 nm.

S4. The growth of BN on SiO₂/Si and MoS₂/SiO₂/Si.

A schematic diagram is shown in Figure S5 to clearly demonstrate the evolution of thickness difference of BN on SiO₂ and MoS₂. At the very beginning, the growth rate of BN on SiO₂ surface (v_{SiO_2}) is higher than MoS₂ (v_{MoS_2}) leading to the initial thickness difference of BN film on the two surfaces (Figure S5 a). After the BN film fully-covered the surface of both SiO₂ and MoS₂, BN starts to grow on BN/SiO₂ and BN/MoS₂ (Figure S5 b). At this stage, the growth rate of BN on BN/SiO₂ surface (v_{BN}) is still higher than BN/MoS₂ (v_{MoS_2}). With the increasing of BN thickness, the influence from the substrate gradually weakens. At certain critical thickness ($T_{critical}$, marked in yellow in Figure S5b), the influence from the MoS₂ as well as the SiO₂ is negligible. As shown in Figure S5 c and d, the growth rate of BN on BN/SiO₂ (v_{BN}) is now the same as the value on BN/MoS₂ (v_{BN}), thereby the thickness difference becomes a constant value (H_{Fixed}). The screening effect of BN with certain thickness ($T_{critical}$) to isolate the influence from the substrate is similar to the previous study that ~ 3 nm BN could screen the catalytic effect of the Cu substrate¹.

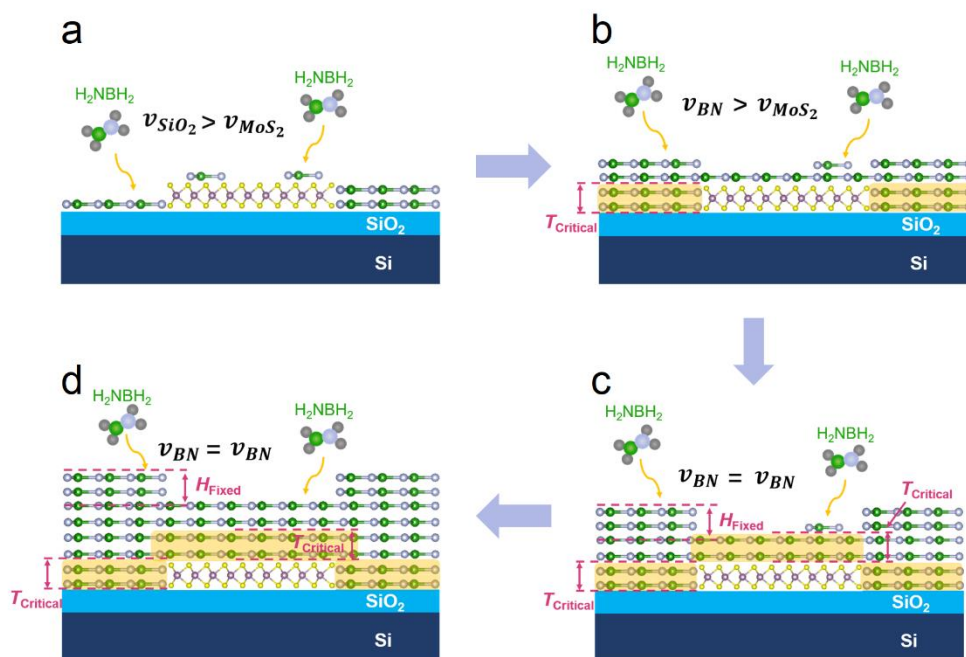


Figure S5 Schematic diagram of the thickness evolution of BN growth on SiO₂/Si and MoS₂/SiO₂/Si. (a) The initial growth rate of BN on SiO₂ surface (v_{SiO_2}) is higher than MoS₂ (v_{MoS_2}), i.e. $v_{SiO_2} > v_{MoS_2}$. (b) At certain critical thickness ($T_{critical}$, marked in yellow), the influence from the SiO₂ is negligible, and the growth rate of BN on BN/SiO₂ surface (v_{BN}) is still higher than v_{MoS_2} . (c) After the thickness of BN on BN/MoS₂ reaches $T_{critical}$, the growth rate of BN on BN/SiO₂ (v_{BN}) is now the same as the value on BN/MoS₂ (v_{BN}), thereby the thickness difference becomes a constant value (H_{Fixed}). (d) With the increasing of BN thickness, H_{Fixed} maintains constant.

S5. Characterization of BN film by TEM and ATR-FTIR.

The BN films grown on SiO₂/Si surface was further transferred to copper grid by polymethyl methacrylate (PMMA) assisted wet transfer technique for TEM study. The SiO₂ was etched away in 1 mol/L NaOH at 60°C. The PMMA/BN film was then rinsed in deionized water for several min to further remove the residual solvent. Finally, PMMA was removed by acetone.

Before characterize BN film by attenuated total reflectance Fourier transform infrared (ATR-FTIR) spectrometer, BN film obtained on SiO₂/Si was transferred to copper foil by the same transfer method. Cu foil was applied to eliminate the strong absorption signals from the SiO₂ substrate in the infrared spectral region.

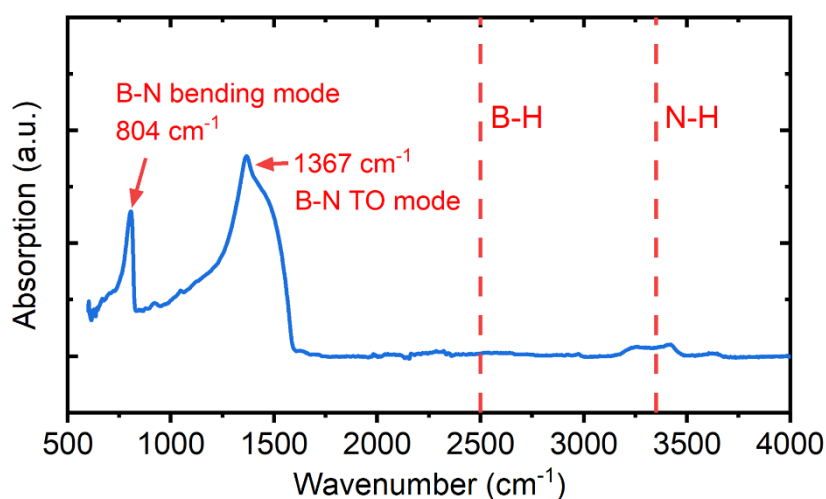


Figure S6 ATR-FTIR spectrum of the low-temperature grown BN film.

S6. Performance of BN/MoS₂ FET.

The optical images of MoS₂ FETs before and after BN capping are shown in Figure S5 a-b. The transfer and the output characteristic of MoS₂ FET before and after BN capping are illustrated in Figure S5 c-f. The field effect mobilities are calculated to be 0.038 cm²V⁻¹s⁻¹ and 0.115 cm²V⁻¹s⁻¹ ($L = 10.75\ \mu\text{m}$, $W = 8.15\ \mu\text{m}$) before and after BN capping.

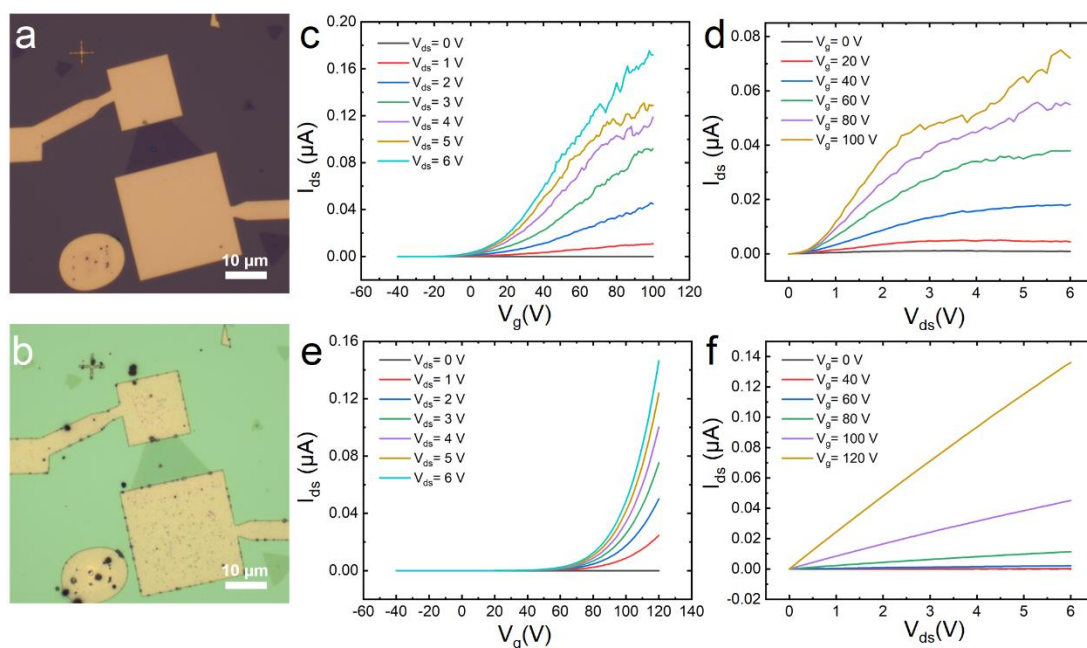


Figure S7 (a-b) Optical images of the MoS₂ FETs before (a) and after (b) BN capping. (c-d) Transfer and output characteristic curves of the MoS₂ FET before BN capping. (e-f) Transfer and output characteristic curves of the MoS₂ FET after BN capping.

Reference

(1) Wang, M.; Kim, M.; Odkhuu, D.; Park, N.; Lee, J.; Jang, W.-J.; Kahng, S.-J.; Ruoff, R. S.; Song, Y. J.; Lee, S., Catalytic Transparency of Hexagonal Boron Nitride on Copper for Chemical Vapor Deposition Growth of Large-Area and High-Quality Graphene. *ACS Nano* **2014**, 8 (6), 5478-5483.