

Strain-induced Moiré Superlattice in 2D Materials Using Stressor Films

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Primary CNF Tools Used: SC4500 Evaporator, Zeiss Supra scanning electron microscope, Nabity Nanometer Pattern Generator System, Flexus film stress measurement

Abstract:

This project developed a scalable fabrication approach for constructing strain-induced moiré superlattices in two-dimensional (2D) materials using lithographically patterned thin-film stressors. Patterned $\text{Al}_2\text{O}_3/\text{SiO}_2/\text{Al}_2\text{O}_3$ stressor films were fabricated by electron beam lithography and electron beam evaporation to introduce localized heterostrain into exfoliated 2H- MoS_2 flakes. Raman spectroscopy confirmed the transferred strain, while scanning transmission electron microscopy (STEM) and four-dimensional STEM (4D-STEM) revealed the resulting lattice reconstruction and moiré superlattice formation. The induced strain generated distinct stripe and distorted hexagonal moiré patterns depending on the local strain symmetry. This work demonstrates a reproducible fabrication process for producing and characterizing strain-engineered 2D materials [1].

Summary of Research:

Moiré superlattices in 2D materials have become an important platform for studying emergent electronic phenomena. Conventionally, moiré superlattices are created by manually twisting and stacking atomically thin layers or by using intrinsic lattice mismatch between different materials. These approaches typically require repeated fabrication attempts to achieve the desired twist angle or stacking configuration and offer limited control over the resulting moiré geometry. Developing a scalable and deterministic method for constructing moiré superlattices therefore remains an important technical challenge. In this work, we developed a fabrication approach based on lithographically patterned thin-film stressors that locally introduce heterostrain into MoS_2 , enabling formation of strain-induced moiré superlattices using standard microfabrication processes.

We fabricated samples on both SiO_2/Si substrates

and SiN_x TEM grids to investigate stressor-induced heterostrain in MoS_2 . 2H- MoS_2 bulk crystals were mechanically exfoliated using Scotch tape onto pre-cleaned SiO_2/Si substrates. Target flakes were then identified by optical microscopy and transferred onto SiN_x membrane TEM grids and SiO_2/Si substrates using a polypropylene carbonate (PPC) stamp. The TEM grids were mounted onto a custom holder and spin-coated with poly(methyl methacrylate) as the electron-beam resist. Electron-beam lithography (Nabity NPGS, Zeiss Supra SEM) was used to write $500 \times 10 \mu\text{m}$ stripe patterns with $10 \mu\text{m}$ spacing. After pattern development, a stressor film of Al_2O_3 (10 nm)/ SiO_2 (50 nm)/ Al_2O_3 (10 nm) was deposited using e-beam evaporation (SC4500 Even-hour evaporator). The residual film stress was characterized using Flexus Film Stress Measurement System, which measured a compressive stress of -105.7 MPa .

Figure 1a shows a schematic of the sample geometry, consisting of a MoS_2 flake capped with a patterned stressor film. Figure 1b shows an optical image of a representative fabricated sample. The fabricated samples were characterized using Raman spectroscopy, atomic-resolution STEM, and 4D-STEM to evaluate the strain distribution and resulting structural reconstruction. In Figure 1c and 1d, Raman measurements showed shifts in the E_{2g} and A_{1g} vibrational modes, confirming successful strain transfer from the stressor films into the underlying MoS_2 without introducing significant sample damage (Fig. 1e). To understand how deeply the applied strain penetrates into the sample, cross-sectional high-angle annular dark-field (HAADF)-STEM imaging was performed on the top few MoS_2 layers near the edge of the patterned stressor film. Figure 2a shows local stacking changes induced by the stressor, while measured Mo-Mo interatomic distances in Figure 2b reveals that the applied strain was concentrated primarily within the top two MoS_2 layers.

We next investigated the resulting structural

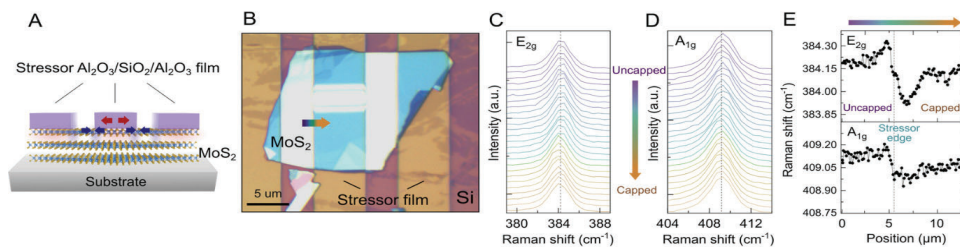


Figure 1: (A) Schematic of patterned $\text{Al}_2\text{O}_3/\text{SiO}_2/\text{Al}_2\text{O}_3$ stressor film transferring heterostrain onto MoS_2 locally. Red and blue arrows indicate the strain direction. (B) Optical image of a MoS_2 flake under the patterned film on the Si substrate. The Raman spectra shown in (C,D) come from regions indicated by the arrow. (C,D) Raman spectra of E_{2g} and A_{1g} modes of MoS_2 across the uncapped to capped regions, respectively. The spectra are plotted with a vertical offset for visual clarity, with the spectra from the uncapped region at the top and from the capped region at the bottom. (E) Corresponding E_{2g} and A_{1g} peak position profiles obtained by Lorentzian fitting.

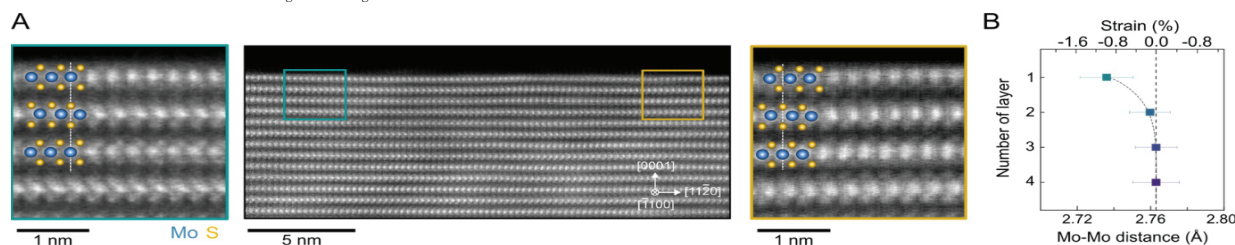


Figure 2: (A) Cross-sectional atomic-resolution HAADF-STEM images of MoS_2 under the region close to the stressor edge. The panels on the left and right show magnified views of the regions highlighted by the green and yellow boxes in the center image. (B) Layer-dependent Mo-Mo interatomic distances from the experiment obtained by quantitative atom tracking from (A).

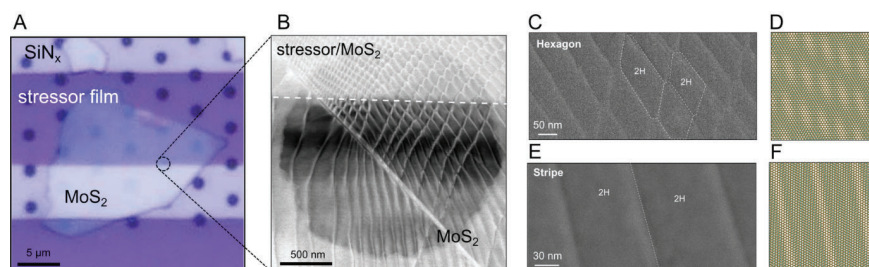


Figure 3: (A) Optical microscopy image of MoS_2 under the patterned stressor film. (B) Reconstructed virtual annular dark-field image from the 4D-STEM dataset. The image corresponds to a zoomed-in region near the stressor film edge marked in (A). (C) Plan-view low magnification HAADF-STEM image of distorted hexagonal moiré with domain boundaries highlighted by white dashed lines. (D) Schematic of rigid moiré pattern generated by biaxial and shear heterostrain. (E) Low-magnification HAADF-STEM image of stripe-type moiré with domain boundaries highlighted by white dashed lines. (F) Schematic of rigid moiré pattern generated by uniaxial and shear heterostrain.

reconstruction in plan view. Figure 3a shows an optical image of the sample on a TEM grid. Figure 3b presents a reconstructed virtual annular dark-field (ADF) STEM image from the 4D-STEM dataset, focusing on the region near the edge of the patterned stressor film where the strain variations are most pronounced. Two distinct types of strain-induced moiré patterns are observed. Near the stressor edge, where the applied strain is relatively biaxial, a distorted hexagonal moiré pattern forms (Figures 3c and 3d). Farther away from the stressor, the strain becomes predominantly uniaxial, and the moiré structure gradually evolves into a stripe pattern (Figures 3e and 3f). This spatial transition demonstrates that the local symmetry of the applied strain determines the resulting moiré geometry.

Conclusions and Future Steps:

We demonstrated a scalable and deterministic approach for constructing heterostrain-induced moiré superlattices in MoS_2 using lithographically patterned stressor films. By combining Raman spectroscopy, atomic-resolution STEM, and 4D-STEM, we resolved the induced strain, lattice reconstruction, and resulting moiré geometries. This scalable fabrication strategy provides a practical route for engineering strain-controlled moiré superlattices in 2D materials. Future work will extend this approach to other layered materials and stressor designs to achieve greater control over moiré geometries and their associated electronic properties.

References:

- [1] Y.-M. Wu et al. Proceedings of the National Academy of Sciences 123, e2602234123 (2026).