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Atomically Thin Three-Dimensional Membranes of van der Waals Semiconductors by Wafer-Scale Growth

We report wafer-scale growth of atomically thin, three-dimensional (3D) van der Waals (*vdW*) semiconductor membranes. By controlling the growth kinetics in the near-equilibrium limit during metalorganic chemical vapor depositions of MoS_2 and WS_2 monolayer (ML) crystals, we have achieved conformal ML coverage on diverse 3D texture substrates, such as periodic arrays of nanoscale needles and trenches on quartz and SiO_2/Si substrates. The ML semiconductor properties, such as channel resistivity and photoluminescence, are verified to be seamlessly uniform over the 3D textures, and are scalable to wafer-scale. Additionally, we demonstrated that these 3D films can be easily delaminated from the growth substrates to form suspended 3D semiconductor membranes. Our work suggests that *vdW* ML semiconductor films can be useful platforms for patchable membrane electronics with atomic precision, yet in large-areas, on arbitrary substrates.

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Figures

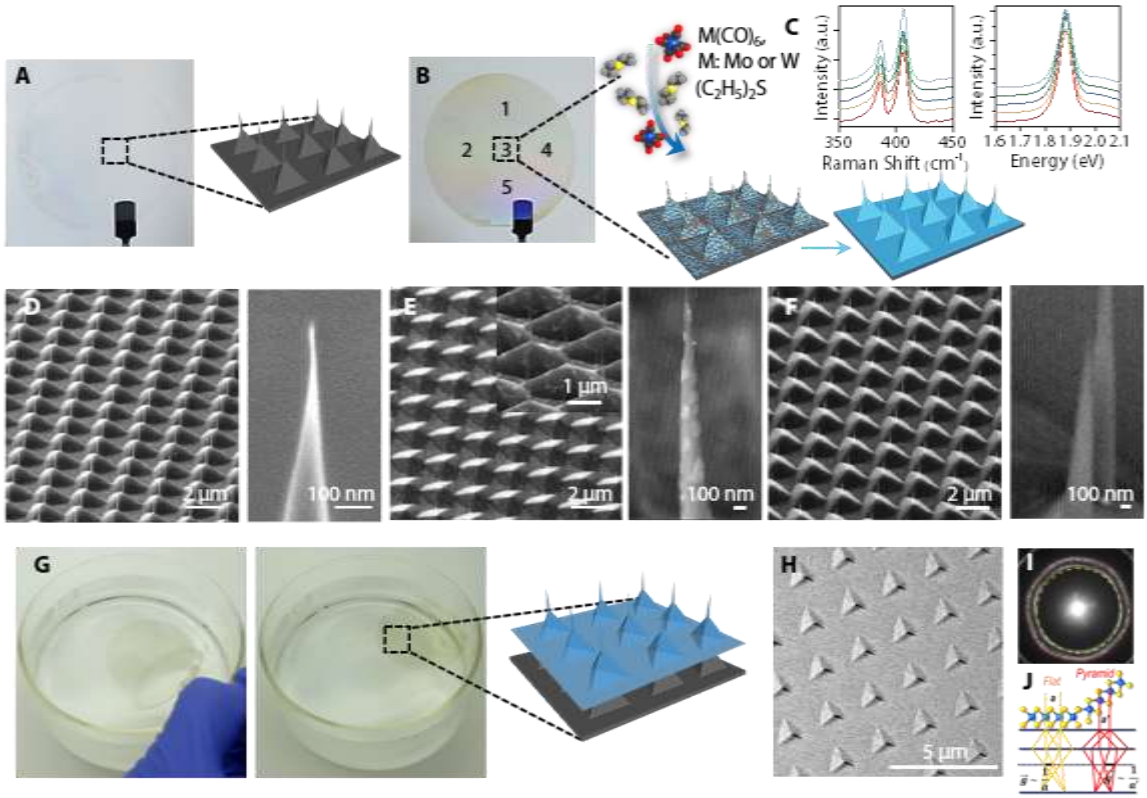

Figure 1: Conformal deposition of three-dimensional TMDC monolayer (ML) films on a quartz needle array and theirmembranes by delamination from 3D textured substrates. (**A-B**) Schematic of the growth of a TMDC ML films on a 4-in. wafer-scale quartz needle array, with photographs of (**A**) pristine and (**B**) as-grown MoS_2 on a quartz wafer. (**C**) Raman and PL spectra measured from marked spots of as-grown MoS_2 ML on a quartz wafer. (**D-F**) SEM images of (**D**) pristine arrays of pyramids and needles and (**E**) partially and (**F**) fully covered MoS_2 ML film on pyramids and needles. Inset: A partially covered MoS_2 ML on the pyramidal podia. (**G**) Photographs of the peel-off process and illustration of a delaminated *vdW* WS_2 membrane separated from the 3D substrate. (Photo credit: Gangtae Jin, POSTECH) (**H**) Low-magnification TEM image of a few-layer 3D WS_2 membrane at the -36.2º tilt angle. (**I**) SAED pattern of the 3D WS_2 membrane. (**J**) Diffracted beam path for planar and tilted TMDC crystals on the pyramidal array.