



Inducing Strain in Atomically Thin Sheets of Molybdenum Disulfide



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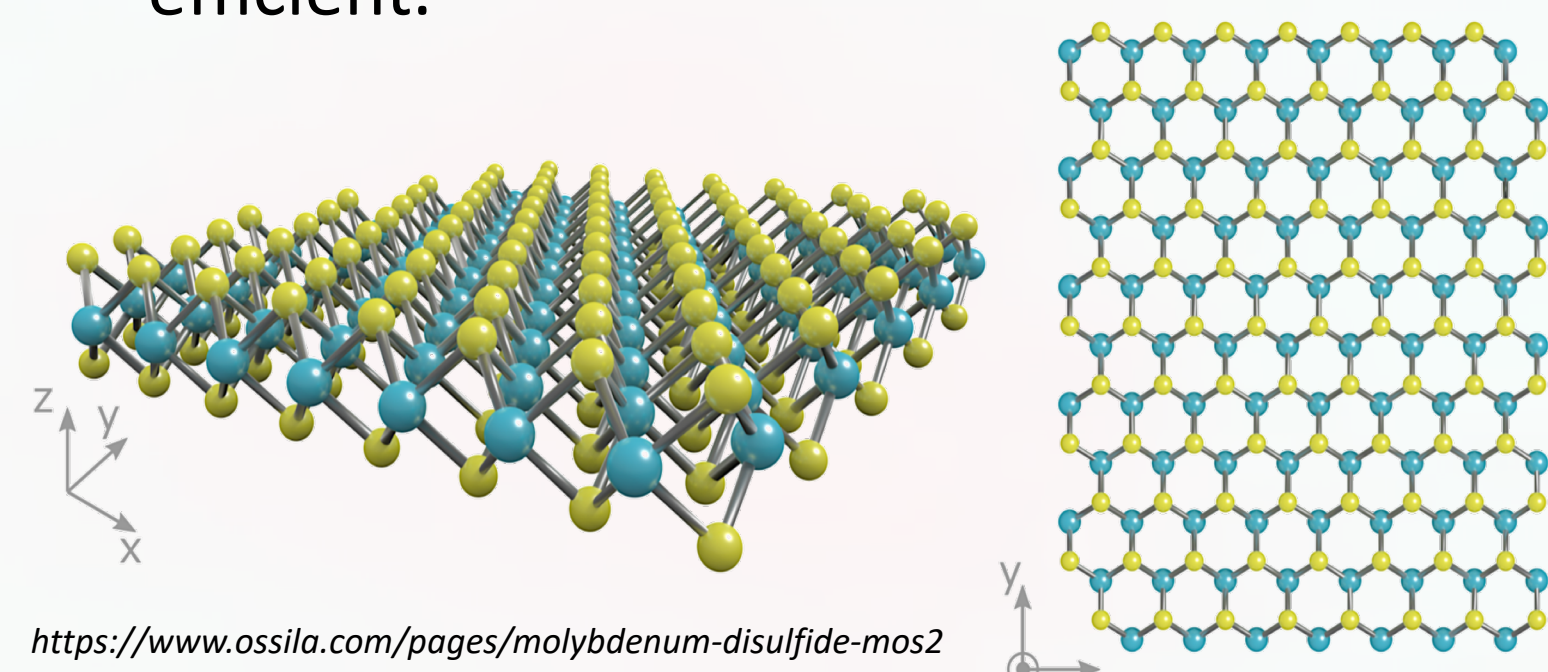
2-D materials are as thin as physically possible that can be an insulator, conductor, or semiconductor. Electronic properties in 2-D materials can be tuned with strain to optimize the performance of next-generation electronics.

Introduction

What is 2-D Molybdenum Disulfide?

MoS₂ is a 3-D semiconducting crystal made up of 2-D layers. MoS₂ will exhibit unique physical and electronic properties as the number of layers approaches the single layer, such as:

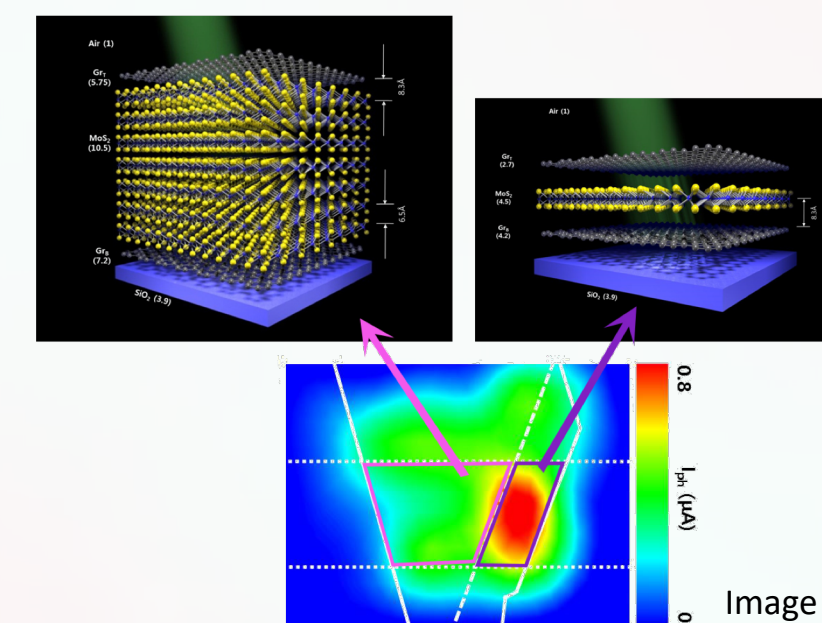
- Flexibility - Single layer MoS₂ can sustain very high elastic strain before rupturing¹.
- Direct bandgap - Conserves momentum in the lattice when electrons go from the valance band to the conduction band. This allows MoS₂ to be a light-sensitive semiconductor.
- High conductivity - Conductivity measures how well the material conduct electricity, or heat (thermal conductivity). Higher conductivity is more energy efficient.



Atomic structure of MoS₂. Without out-of-plane bonding, MoS₂ can bend, twist, and stretch to a significant amount before rupturing.

These properties are promising for applications in electronics, such as:

- Transistors
- Optoelectronics
- Photovoltaic cells
- Flexible electronics
- Low power electronics

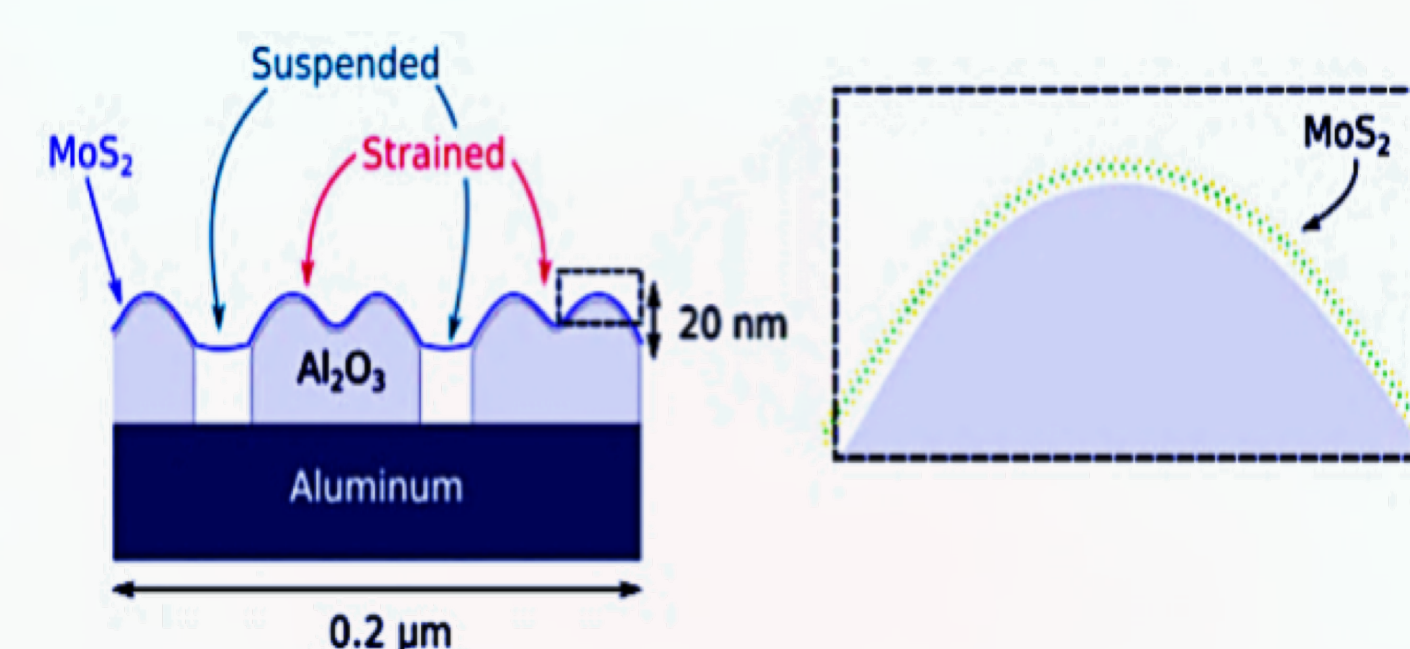


The thinnest photodetector in the world. Single layer MoS₂ exhibits stronger photocurrent than its 3-D crystal.

We can optimize the performance of these applications for commercial use by tuning the electronic properties. One of the way to tune the electronic properties is to induce strain.

What is strain in 2-D materials?

Strain is the stretching or compression between atoms in a crystal lattice. Strain is induced by deforming the crystal lattice at the atomic level. Here we induced strain to MoS₂ by using a nanopatterned substrate to deform the crystal lattice.



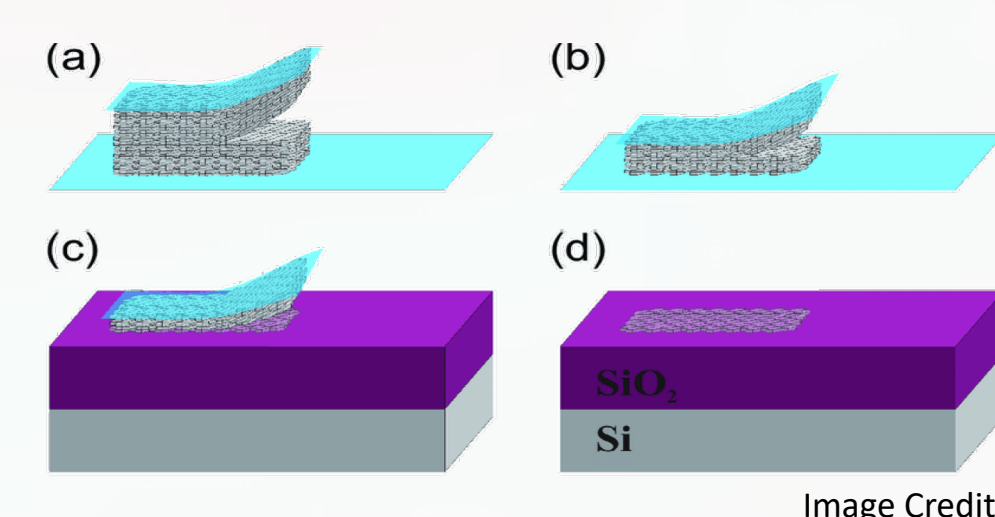
MoS₂ sheet conformed on the anodized aluminum oxide (AAO), with regions with highest strain predicted at the hill tops and suspended region at the valleys.

Acknowledgements

- ❖ I acknowledge the Hamel Center for Undergraduate Research for their funding.
- ❖ I acknowledge Dr. Shawna Hollen, Caitlyn Meditz, and Steven Arias for their assistance in this project.
- ❖ I acknowledge professor Todd Gross for his permission to use the AFM, as well as professor Young Jo Kim for his Raman spectrometer.

Methods

Isolate Thin Sheets of MoS₂



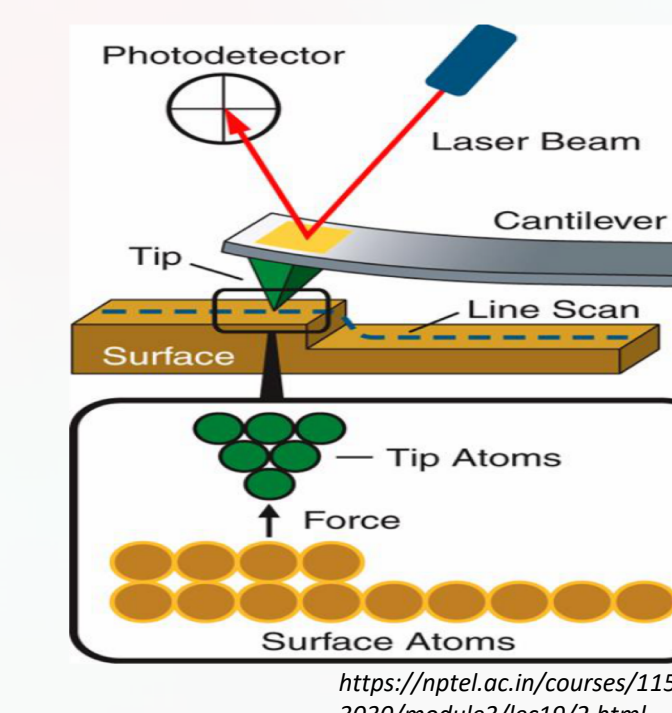
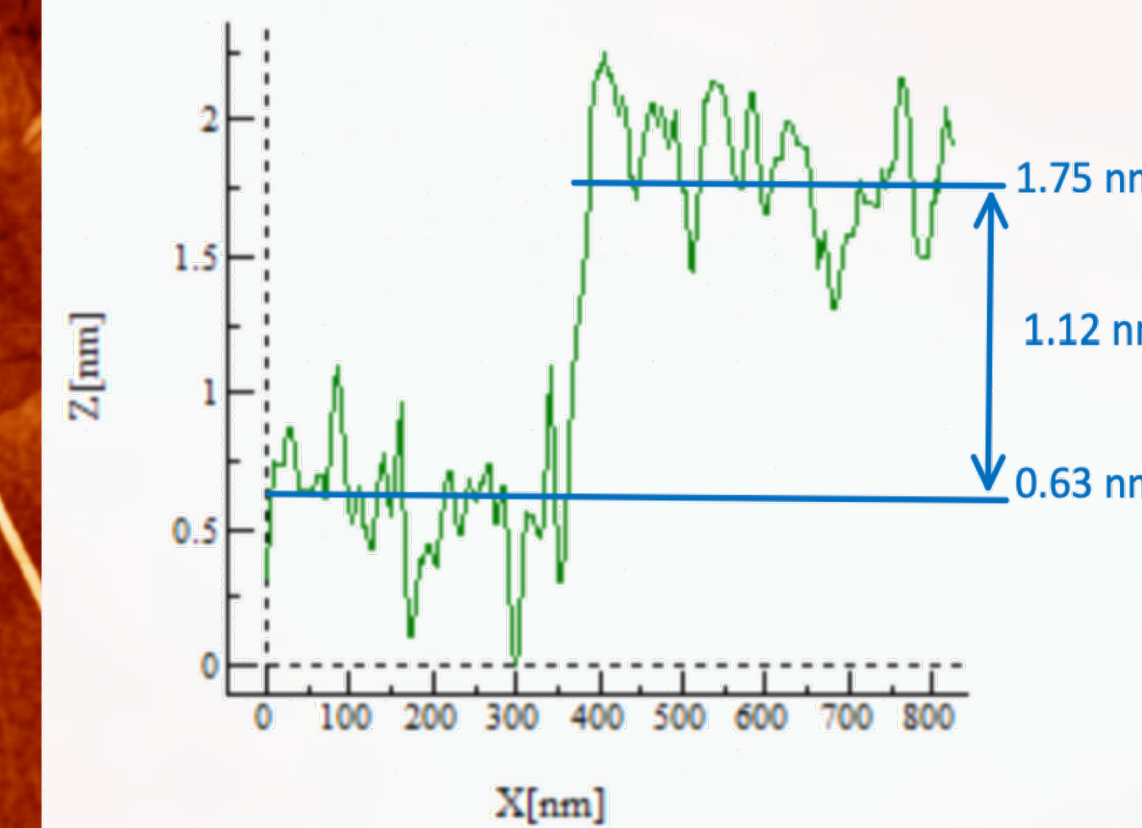
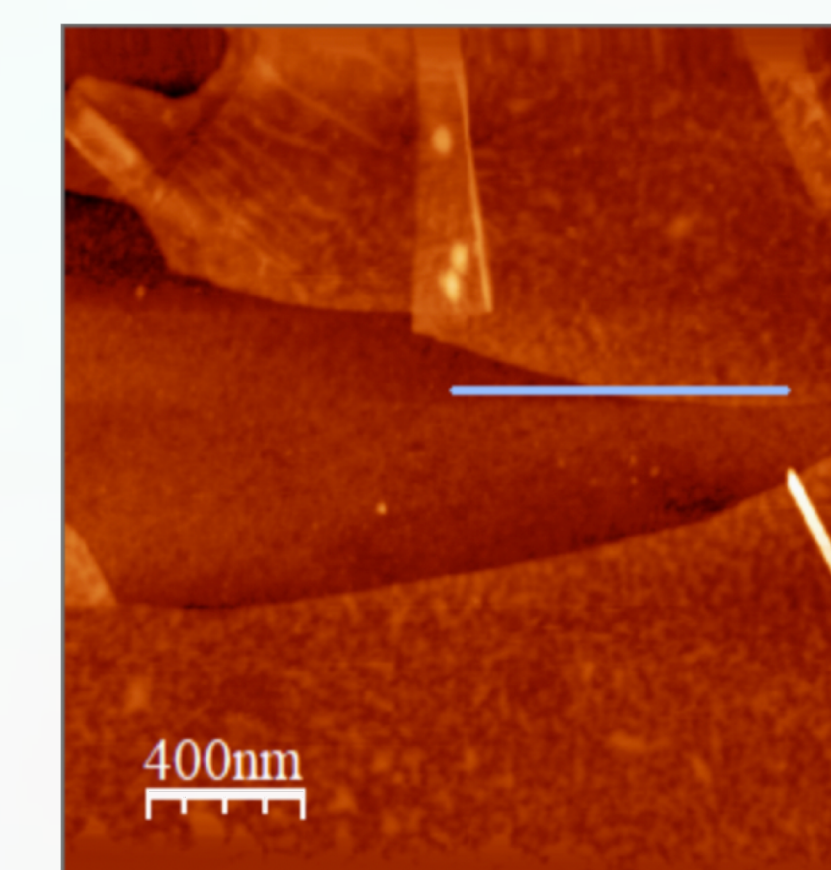
The MoS₂ crystal is held together by the van der Waals forces between the layers. Since the van der Waals forces are weak intermolecular forces, single-to-few layer MoS₂ sheets can be isolated by using a piece of tape to peel off the other layers.

Determine the MoS₂ Flake Thickness

Optical microscope, atomic force microscopy (AFM), and Raman spectroscopy methods were used to determine the flake thickness.



Optical image of MoS₂ flakes on SiO₂. The dark rectangular blue area is the single layer MoS₂. Brighter colors are the thicker flakes. The optical microscope is a quick way to estimate the flake thickness. Scale bar is 20 microns.

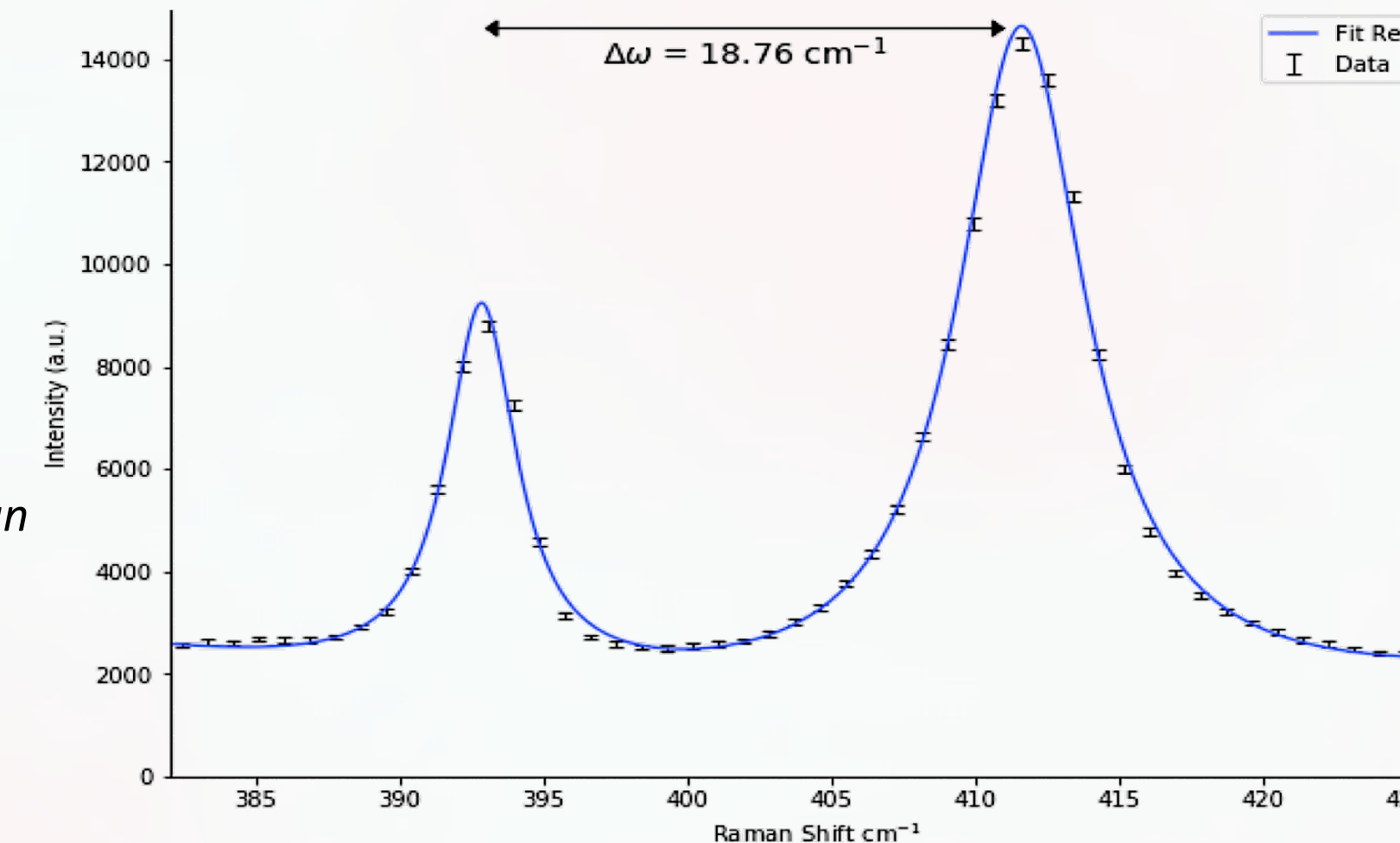


AFM data of MoS₂ on SiO₂ and its height profile. AFM scans the sample surface and record the surface topographies.

Raman spectroscopy works by detecting the energy lost to vibrations in the crystals.

- Vibrations serve as the fingerprint for the materials.
- Vibrations are sensitive to strain, therefore strain can be detected by observing the frequencies shift

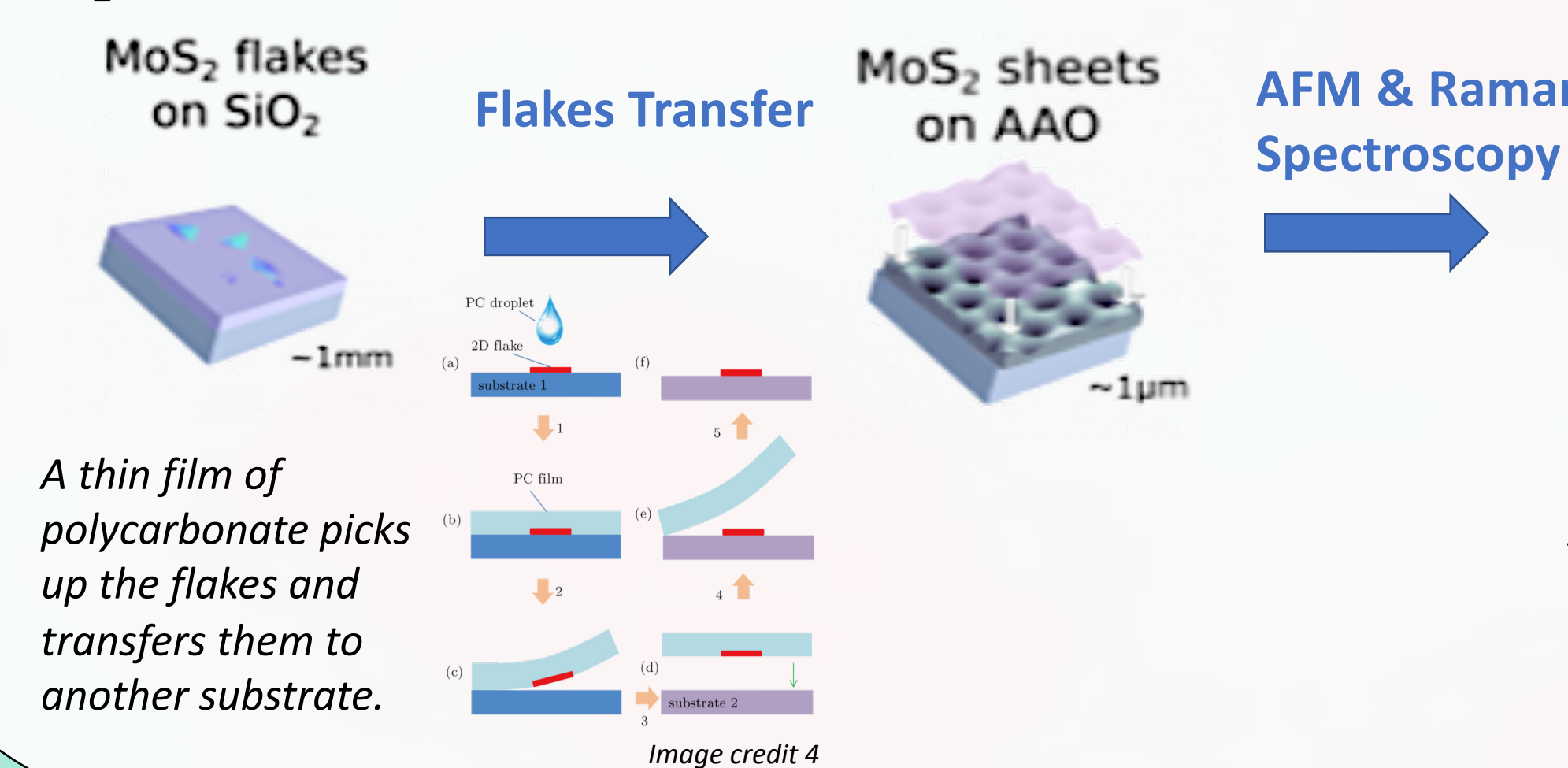
Raman spectroscopy data fitted to Lorentzian distribution. $\Delta\omega = 18.76 \text{ cm}^{-1}$.



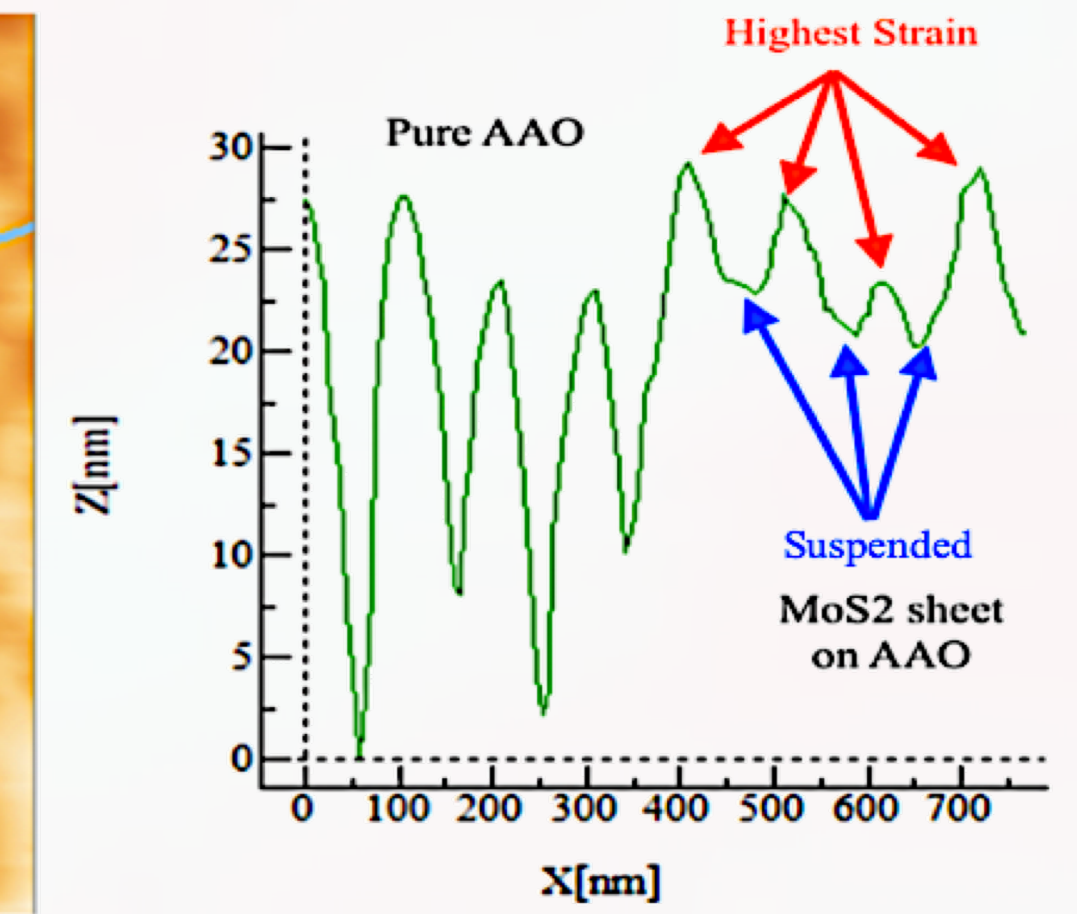
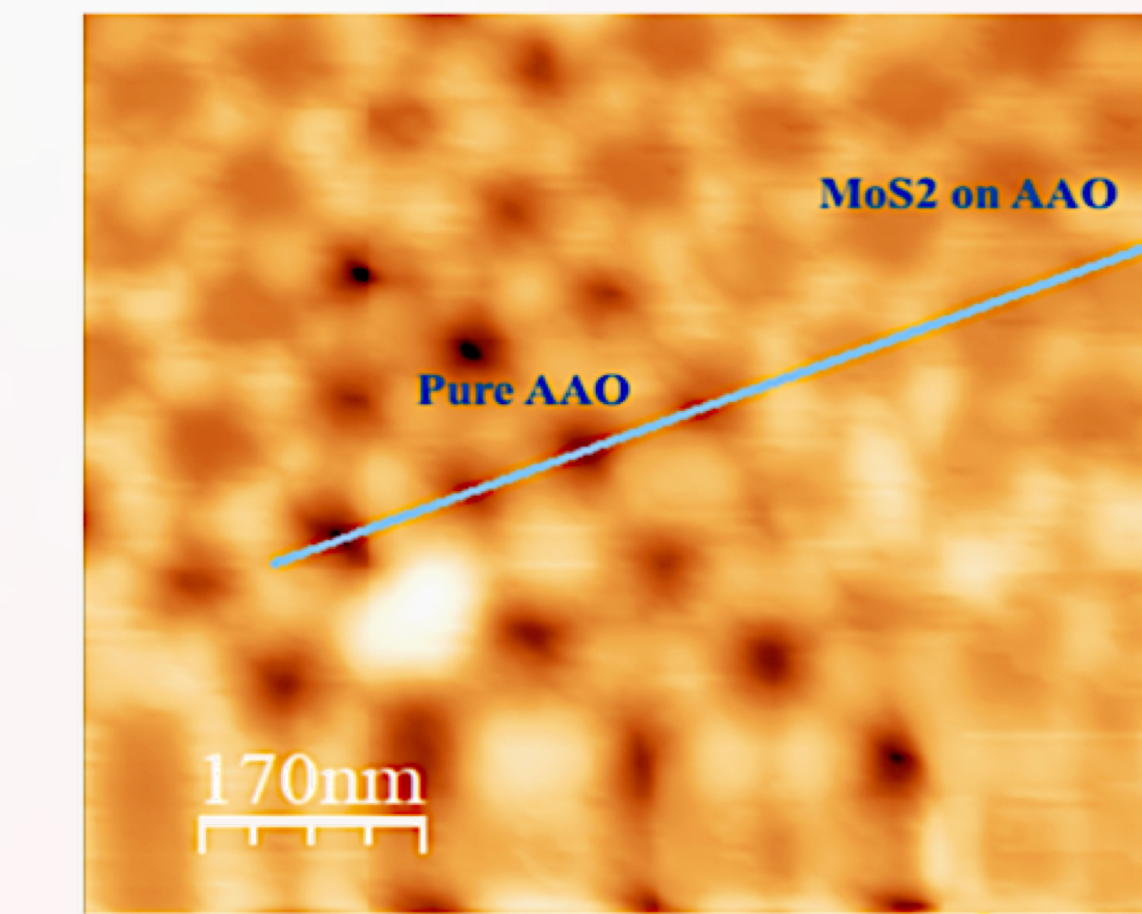
The AFM data and Raman data are consistent to single layer MoS₂, with ~1 nm thickness and frequencies difference within 17-19 cm⁻¹ range.

Induce Strain and Characterizing Strain

MoS₂ is transferred onto the AAO substrate to deform its lattice.



Results



- Successfully transferred MoS₂ flakes onto the AAO substrate.
- An average of 0.30% tensile strain was calculated based on the AFM data showing the contact areas between the MoS₂ and substrate.
 - Strain is modeled by a sphere with 50 nm radius. The strain obtained is the average over the top hemisphere described by the equation (1)⁵.

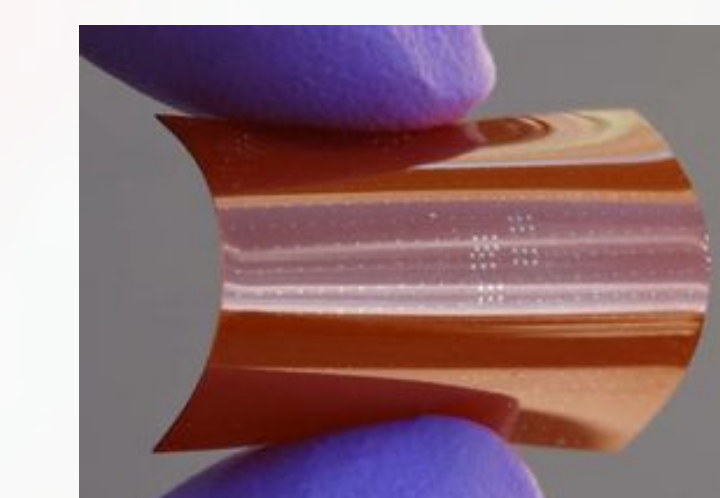
$$\epsilon = \frac{\sqrt{2Rs}}{\sqrt{Rs+z}} - 1 \quad (1)$$

- Suspended MoS₂ regions supported the hypothesis that MoS₂ is suspended over the valleys.

Future Work

- Prepare MoS₂ sheets larger than 1 μm to perform Raman spectroscopy.
- Employ advanced computation model to account for the induced strain by the force interactions between sample and substrate.
- Studying the effects of strain and suspension on the local conductivity in MoS₂ by using conductive-AFM.
 - The Conductive-AFM can probe the local electronic properties in the nanoscale regime.

This project demonstrated the ability to induce strain at the nanoscale, which will enable us to study and tune the electronic properties in 2-D materials that may find applications in next-generation electronics.



Flexible MoS₂ transistor that out performed existing model.

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