WSe_2 Thin-Film Growth by Molecular Beam Epitaxy and Electric Double-Layer Transistor Implementation

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In the past, transition metal dichalcogenides (TMDCs) have been widely studied for their bulk-form applications as semiconductors, with an indirect bandgap in the near-infrared spectral range. More recently, however, there has been a surge in interest towards TMDCs, with a new focus on thin films and monolayers instead. In monolayer form, TMDCs (like WSe_2) have direct bandgaps in the visible spectral range and display photoluminescence of up to four orders of magnitude greater than in their bulk counterparts.[1] This allows for many novel applications in devices like FETs, LEDs, sensors, and even photovoltaic solar cells. While there are many different methods to synthesize and fabricate TMDC films, including, but not limited to, mechanical exfoliation, liquid exfoliation, and chemical vapor deposition, molecular beam epitaxy (MBE) is a bottom-up method that has greater potential for scalability in industry and is capable of producing large uniform crystals on the millimeter scale. To demonstrate the viability of MBE-grown films, we grew both multilayer and monolayer WSe_2 films by MBE on various substrates. Sapphire, SiC, and mica were chosen for their atomically smooth surfaces, and SiO_2 and $SrTiO_3$ were chosen for their potential uses as back-gate dielectrics in electronics. Characterizing the film with x-ray diffraction and Raman spectroscopy, we then selected the highest quality films for fabrication in an electric double-layer transistor, measuring the resulting transport characteristics using a Physical Property Measurement System (PPMS®). By examining substrate-dependent MBE film growth quality, we hope to spur on and expand the field of future 2D TMDC research.

[1]Wang, Q. H., Kalantar-Zadeh, K., Kis, A., Coleman, J. N., & Strano, M. S., *Nature Nanotech.* **7**, 699–712 (2012).

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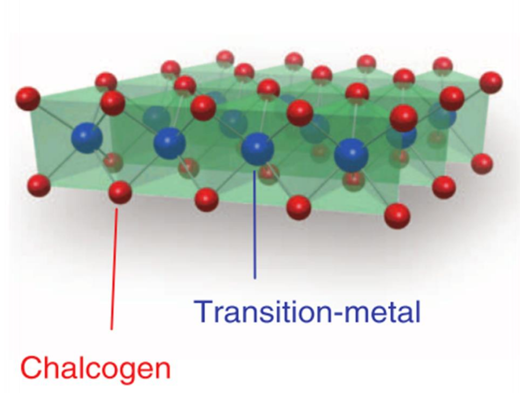
Introduction

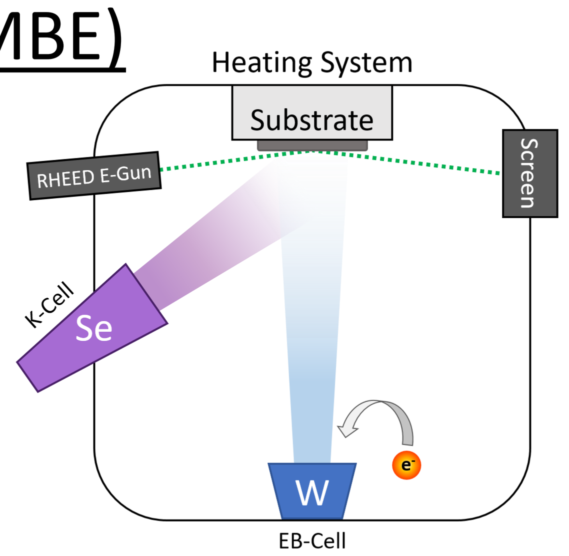
Transition Metal Dichalcogenides (TMDCs)



- Two-dimensional layered material
  - Direct band gap in monolayer form
  - WSe_2 TMDCs have **promising optical applications**
    - Ambipolar transistors
    - Photoluminescence
    - Solar cells

Molecular Beam Epitaxy (MBE)

- Bottom-up growth method
  - **Layer-by-layer** deposition
  - Can produce **large-area, high-quality films** on the mm-scale
  - Introduces **scalability** in industry



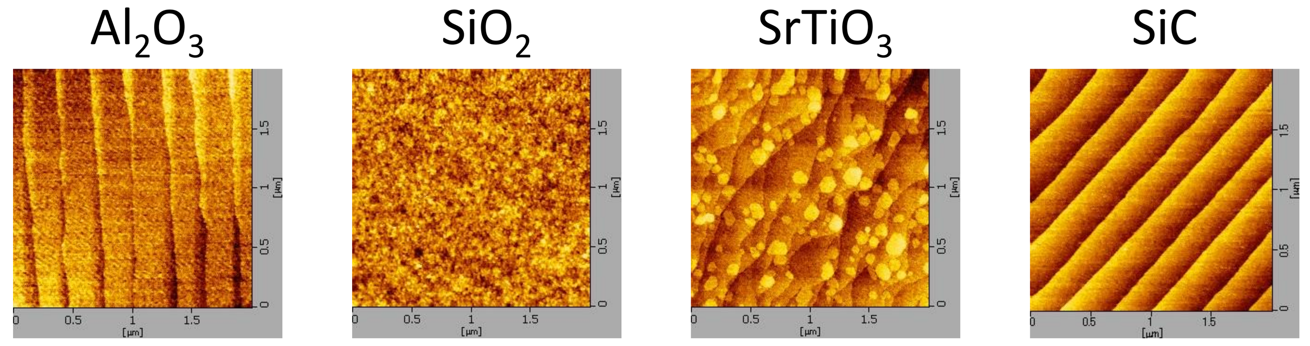
Motivation

- Achieve quality growth of multilayer and monolayer WSe_2 to **demonstrate the viability of molecular beam epitaxy**
- Grow on a variety of substrates to **improve film quality** (Al_2O_3, SiC, Mica) and **find suitable back-gate dielectrics** (SiO_2, $SrTiO_3$)

Substrates

Atomic Force Microscopy (AFM)

- Confirm the quality and roughness of substrate
  - Lower RMS → Smoother Surface



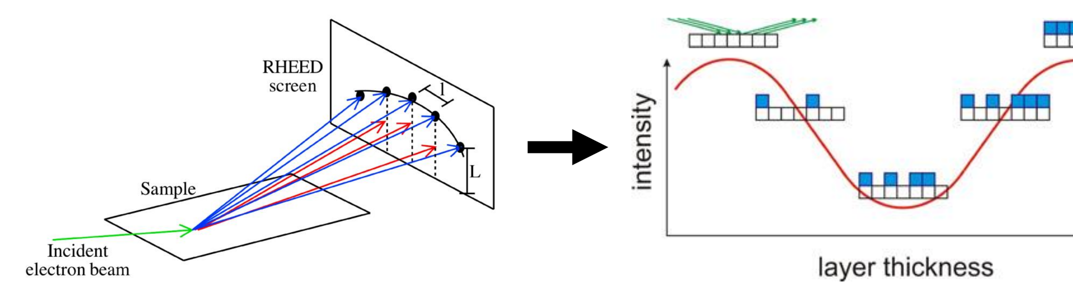
RMS = 7.474E-2 nm | RMS = 1.917E-1 nm | RMS = 1.733E-1 nm | RMS = 1.473E-1 nm

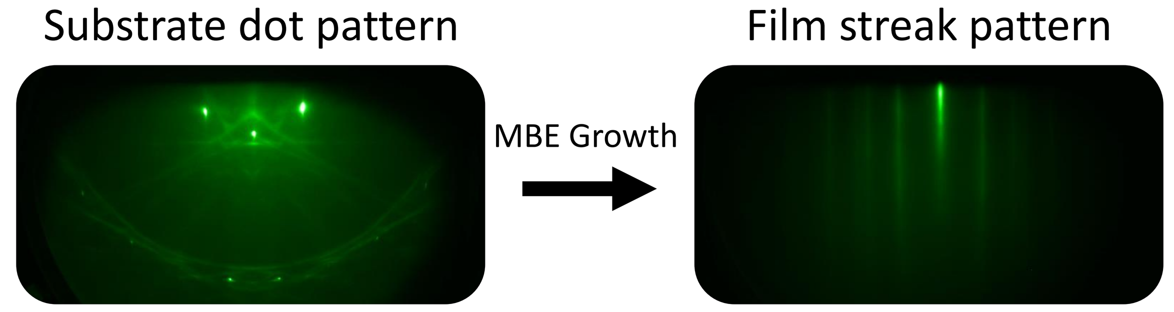
- Al_2O_3, SiO_2, and $SrTiO_3$ wafers were ultrasonically cleaned and then annealed at high temperatures
- Mica was cleaved and also used because of its atomically smooth surface

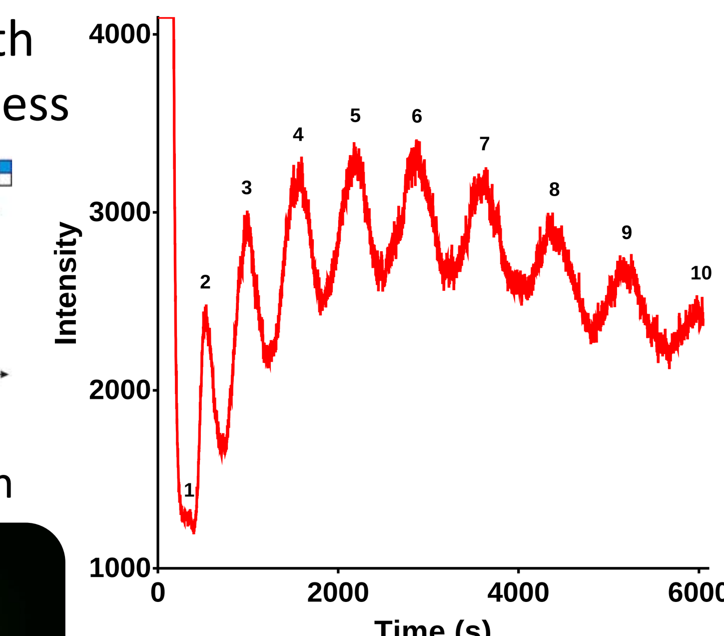
Film Growth

Reflection High Energy Electron Diffraction (RHEED)

- Probes the surface of the sample during growth
  - Uses intensity oscillations to monitor thickness







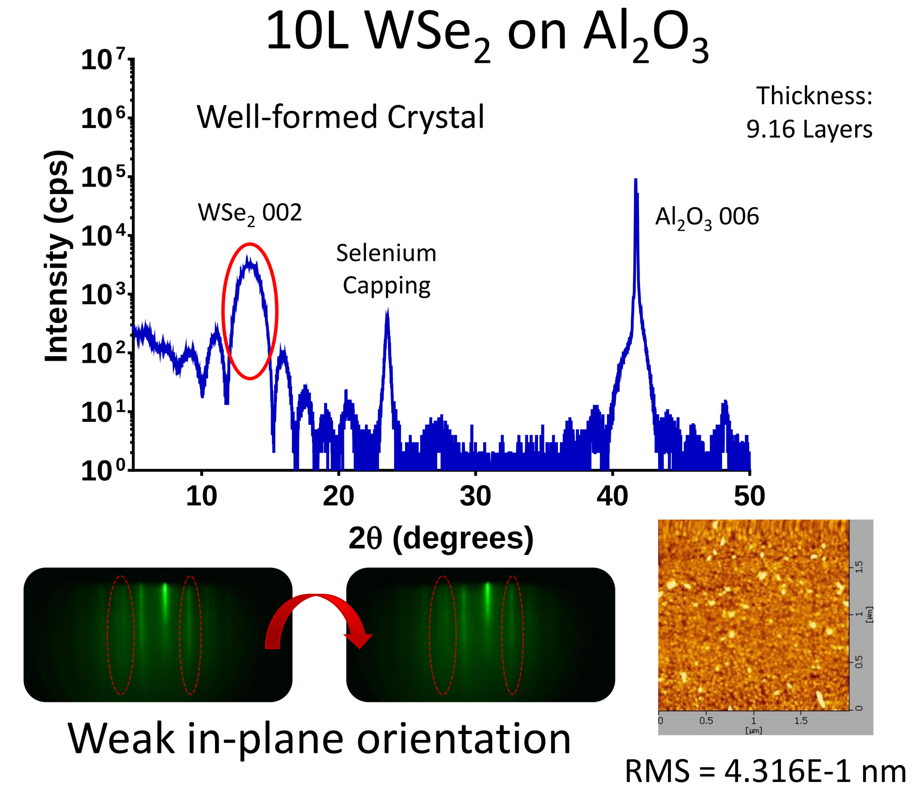
RHEED oscillation for 10L WSe_2 film on Al_2O_3

Multilayer Films

X-Ray Diffraction, RHEED Rotation & AFM Analysis

- Gives information about the crystal structure uniformity

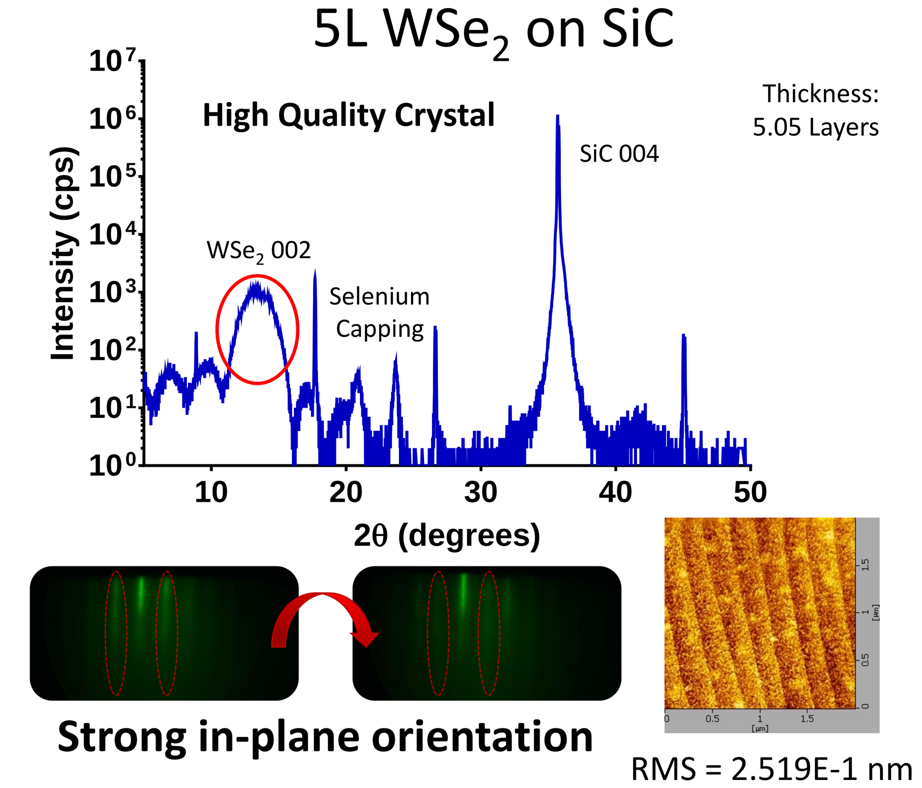
10L WSe_2 on Al_2O_3



Weak in-plane orientation

RMS = 4.316E-1 nm

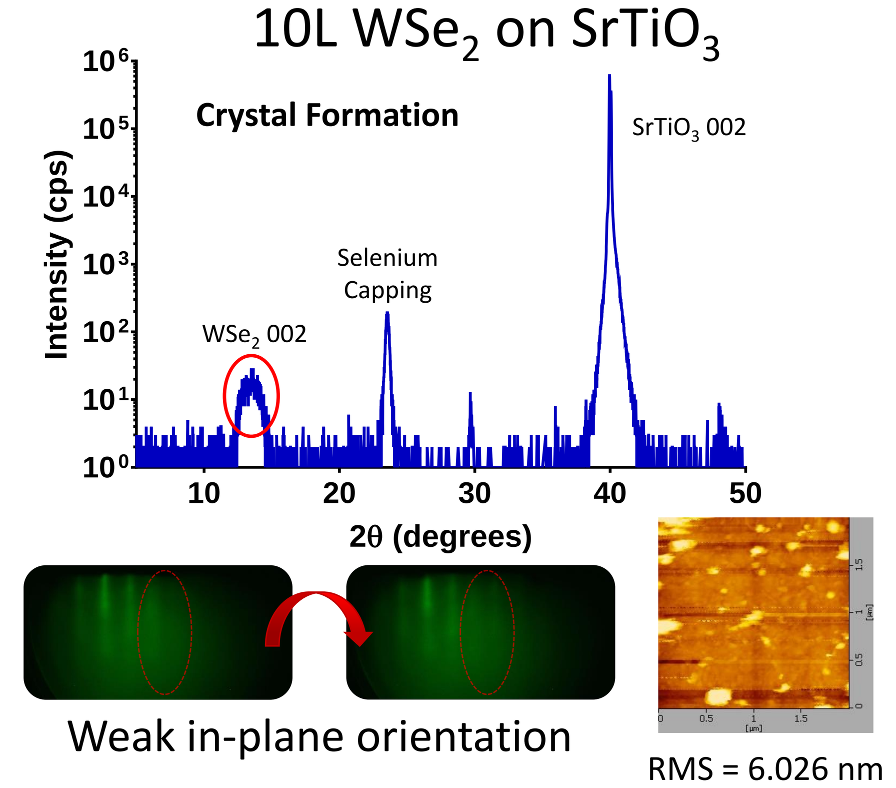
5L WSe_2 on SiC



Strong in-plane orientation

RMS = 2.519E-1 nm

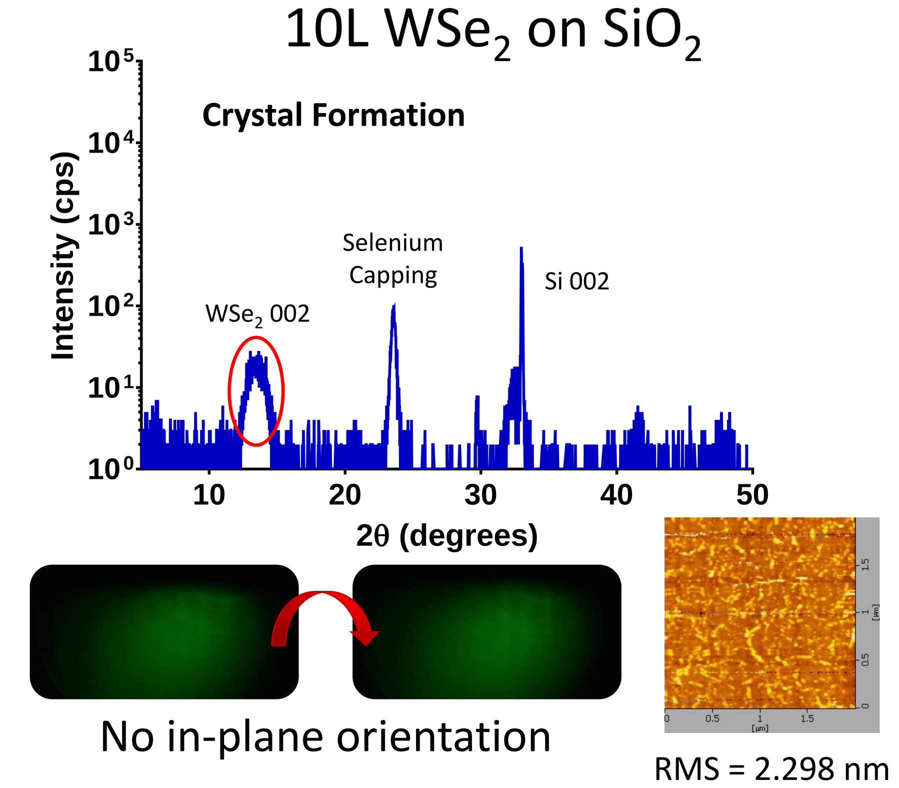
10L WSe_2 on $SrTiO_3$



Weak in-plane orientation

RMS = 6.026 nm

10L WSe_2 on SiO_2



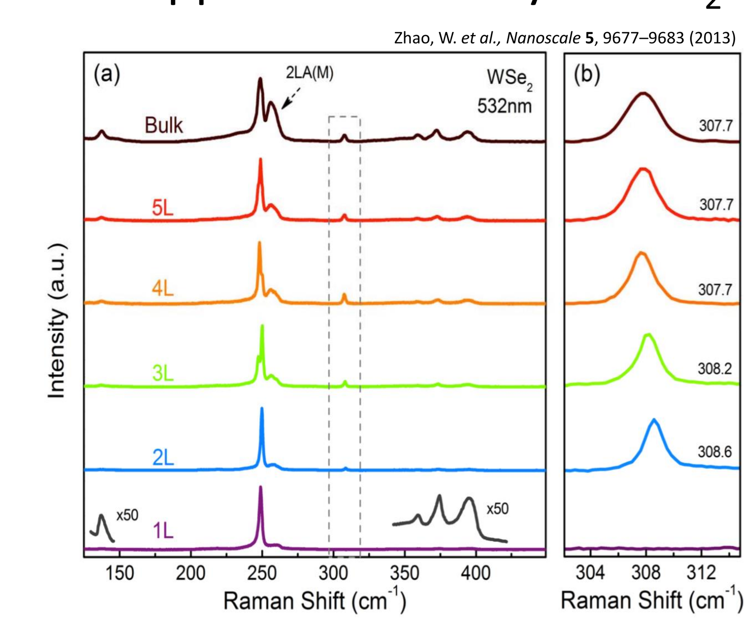
No in-plane orientation

RMS = 2.298 nm

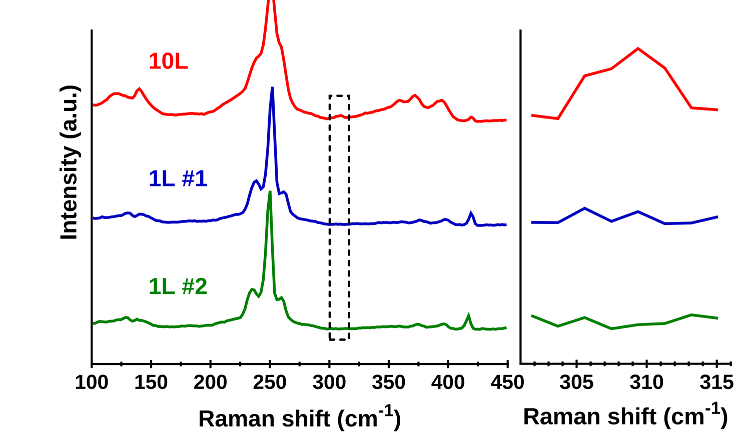
Monolayer Films

Raman Spectroscopy

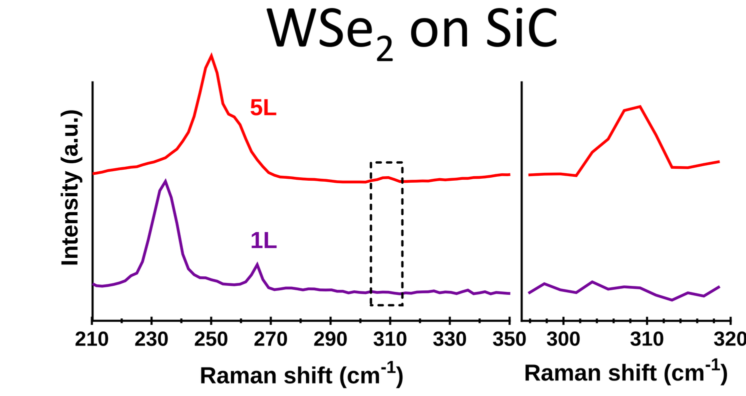
- Chemical fingerprint to confirm WSe_2 monolayer growth
  - Per literature, peak at 308 cm^{-1} should disappear in monolayer WSe_2



WSe_2 on Al_2O_3



WSe_2 on SiC



- Confirmation of **successful WSe_2 monolayer growth** on AL_2O_3 and SiC substrates

Conclusions

✓ Successfully fabricated WSe_2 multilayer crystal on SiO_2 & $SrTiO_3$
  - Proof-of-concept for **direct growth on back-gate dielectrics**

✓ Discovered that **SiC is an even better substrate than Al_2O_3** for WSe_2
  - May be because of smaller lattice mismatch

✓ Demonstrated the **viability of monolayer TMDC growth by molecular beam epitaxy**

Future Work

- Further optimize MBE process to produce higher quality films
- Attempt to produce photoluminescence in monolayer films
- Fabricate a back-gate transistor from a film grown on SiO_2/$SrTiO_3$
- Fabricate an electric double-layer transistor from a film grown on SiC/Mica

Acknowledgements

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