**WSe₂ 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 WSe₂) 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 WSe₂ films by MBE on various substrates. Sapphire, SiC, and mica were chosen for their atomically smooth surfaces, and SiO₂ and SrTiO₃ 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.

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Introduction

Transition Metal Dichalcogenides (TMDCs)

- Two-dimensional layered material
- Direct band gap in monolayer form
- WSe₂ 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

Film Growth

Reflection High Energy Electron Diffraction (RHEED)

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

Substrate dot pattern

MBE Growth

Film streak pattern

RHEED oscillation for 10L WSe₂ film on Al₂O₃

Multilayer Films

X-Ray Diffraction, RHEED Rotation & AFM Analysis

- Gives information about the crystal structure uniformity

Conclusions

- Successfully fabricated WSe₂ multilayer crystal on SiO₂ & SrTiO₃
  - Proof-of-concept for direct growth on back-gate dielectrics
- Discovered that SiC is an even better substrate than Al₂O₃ for WSe₂
  - 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 SiO₂/SrTiO₃
- Fabricate an electric double-layer transistor from a film grown on SiC/Mica

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