$MoSe_2$ Thin-Film Growth by Molecular Beam Epitaxy and Electrical Double Layer Transistor Implementation

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Atomically layered semiconducting transition metal dichalcogenides (TMDs) have attracted recent attention in the field of 2D materials due to their thickness-dependent band gaps, which become direct in the monolayer limit, ideally suited for optoelectronic device applications. However, mechanical exfoliation, a widely-used method for thin-film fabrication, is unsuitable for industrial application. An alternative method, molecular beam epitaxy (MBE), can produce high-quality and large-area (mm-range) films with controllable thickness. Here, we strive to demonstrate the viability of MBE as a means of TMD thin-film fabrication by presenting an electrical double layer transistor (EDLT) that utilizes MBE-grown $MoSe_2$ and its resulting transport measurements. EDLTs are specialized field effect transistors that rely on an electrochemical phenomenon and have been able to achieve ambipolar operation in similar TMDs.[1] We selected MSe_2 (M = W, Mo) as the materials of focus due to their semiconducting properties that make them appropriate for EDLT integration. $MoSe_2$ and WSe_2 are also notable TMD materials because of their promising optical properties and previously observed electroluminescence.[2,3] We grew $MoSe_2$ films by MBE and characterized them by atomic force microscopy and x-ray diffraction to confirm their quality. We then fabricated an EDLT that incorporates $MoSe_2$ and measured its transport characteristics using a Physical Property Measurement System (PPMS®). The optimization of TMD thin-film growth by MBE can greatly improve the efficiency of 2D TMD research efforts and introduce scalability in device fabrication.

[1]Y. Zhang, J. Ye, Y. Matsuhashi, and Y. Iwasa, Nano Lett. **12**, 1136 (2012).
[2]Y. J. Zhang, T. Oka, R. Suzuki, J. T. Ye, and Y. Iwasa, Science **344**, 725 (2014).
[3]M. Onga, Y. Zhang, R. Suzuki, and Y. Iwasa, Appl. Phys. Lett. **108**, 073107 (2016).

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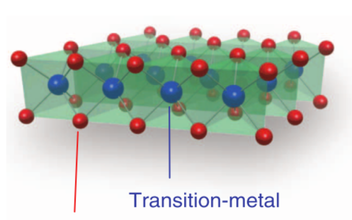
Introduction

2D Materials

Material	Structure	Band Gap (eV)	Property
Graphene		0	Semi-metal
h-BN		7.2 (indirect)	Insulator
TMD (MX_2)		0.6~2.3	Semiconductor

Transition Metal Dichalcogenides (TMD)



Ref. 2

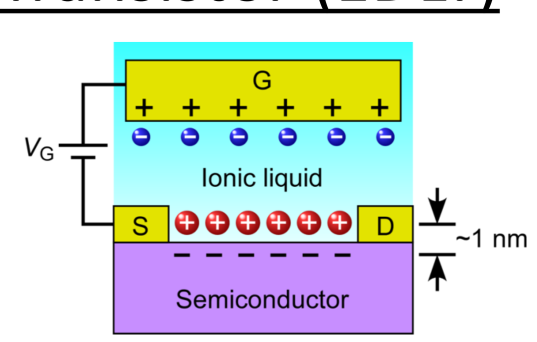
- Direct band gap in monolayer form
- MSe_2 (M = W, Mo) TMDs have promising optical applications
    - Ambipolar transistors[1]
    - Observed electroluminescence[2,3]
    - Solar cells[4]

Significance of Molecular Beam Epitaxy

- Cleaving is one of the most common ways to manufacture 2D materials
    - Not suitable for industry
- Molecular Beam Epitaxy (MBE) can produce **large-area, high-quality films**
    - Introduces scalability

Electrical Double Layer Transistor (EDLT)

- Easy method for characterization
- Specialized field effect transistor



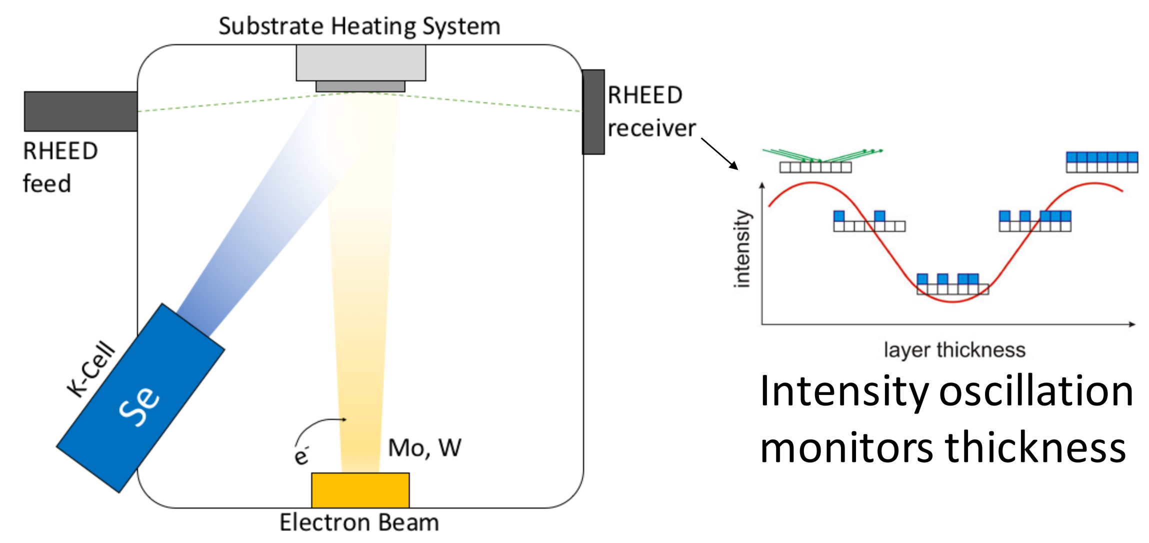
Objectives

- Achieve quality growth of MSe_2 (M = W, Mo) to demonstrate the viability of **molecular beam epitaxy (MBE)**
- Characterize film by atomic force microscopy and x-ray diffraction
- Learn fabrication methods for EDLT
- Take transport measurements for MBE-grown $MoSe_2$ EDLT

Methodology

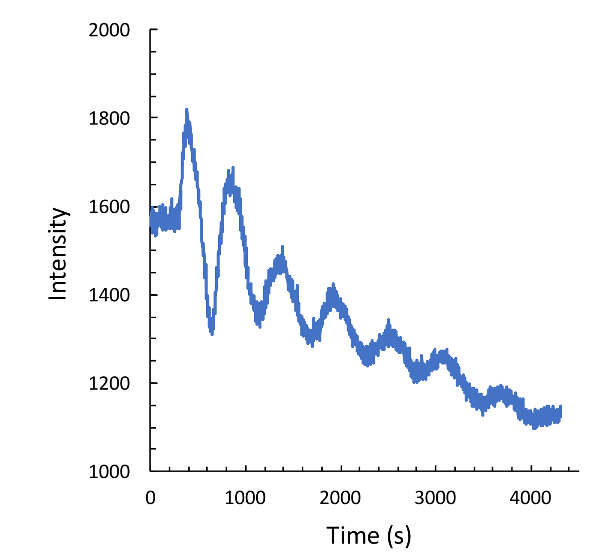
Film Growth

Molecular Beam Epitaxy



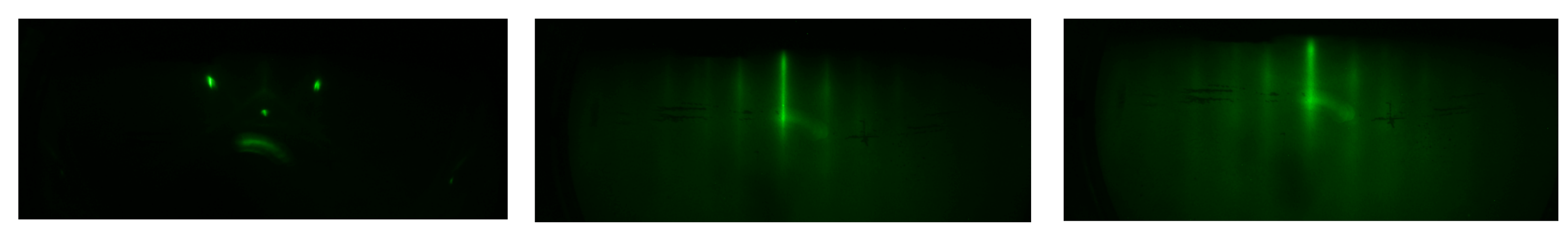
Intensity oscillation monitors thickness

RHEED: Reflection High Energy Electron Diffraction



RHEED oscillation for $MoSe_2$ film #2

RHEED Images
- These images are used to determine the intensity



Substrate dot pattern
- Before growth

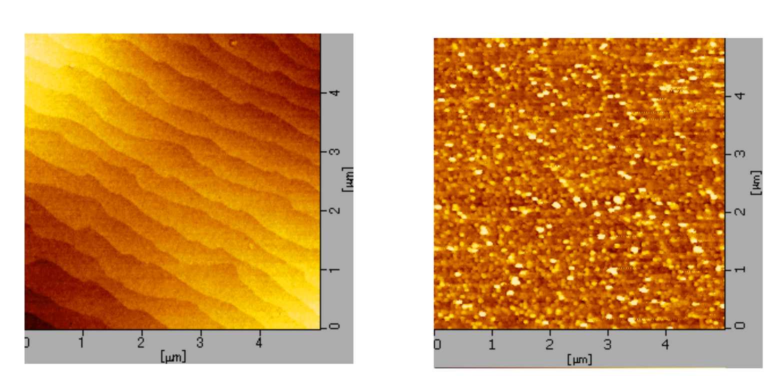
Streak pattern appears
- After first annealing

Streak pattern intensifies
- After second annealing

Film Analysis

Atomic Force Microscopy

Taken before and after film deposition by MBE
- Confirm quality of substrate and growth
- Smaller RMS → less surface roughness



5 µm topographical image of Sapphire substrate

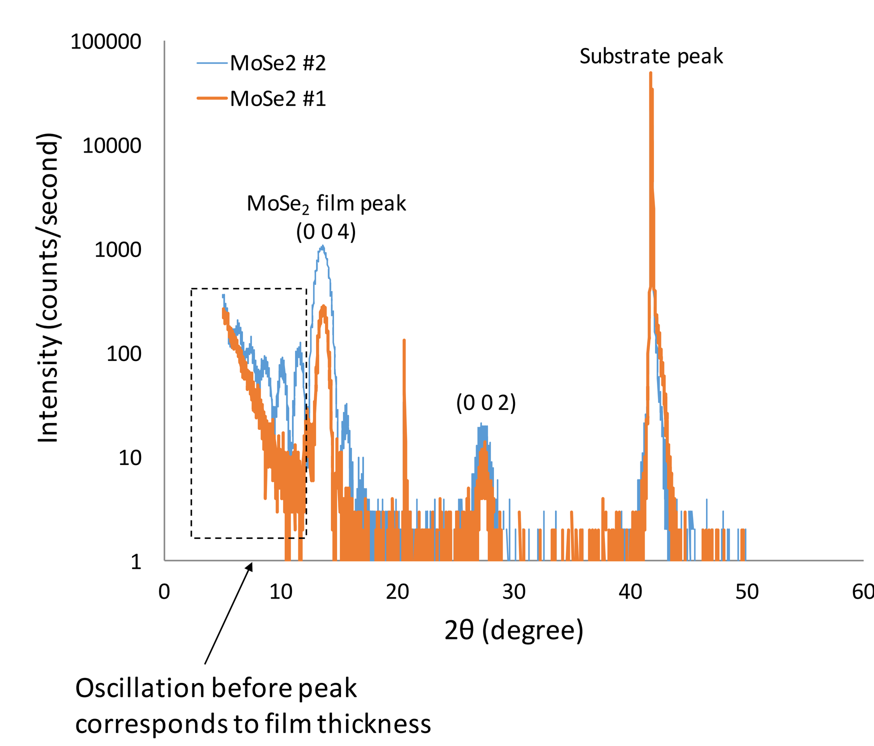
RMS = 0.295 nm

5 µm topographical image after deposition of $MoSe_2$

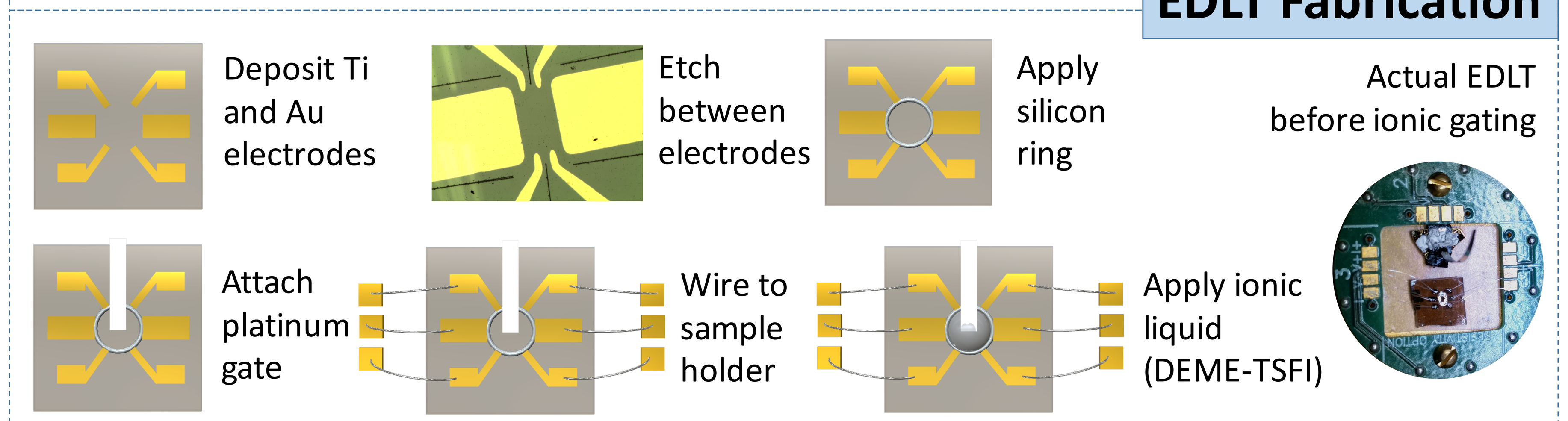
RMS = 1.99 nm

X-Ray Diffraction

- Gives information about the crystal structure



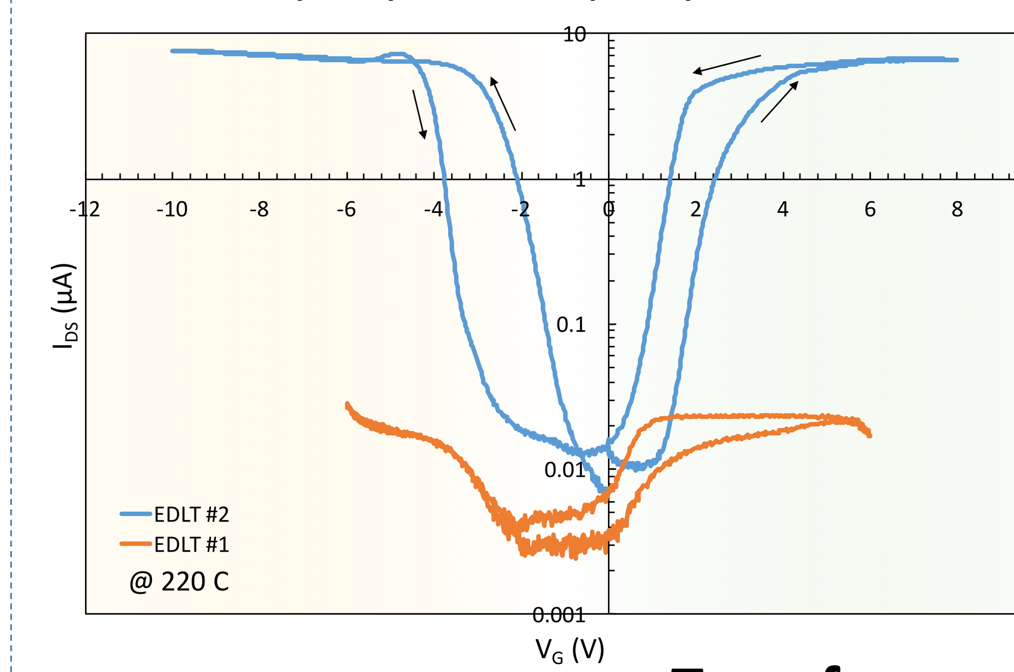
EDLT Fabrication



Transport Characteristics

EDLT Analysis

Measured by Physical Property Measurement System (PPMS)



Transfer curve

Mobility

$MoSe_2$ EDLT #1:
$\mu_{Electron} \approx 0.05\ cm^2/Vs$
$\mu_{Hole} \approx 0.01\ cm^2/Vs$

$MoSe_2$ EDLT #2:
$\mu_{Electron} \approx 2\ cm^2/Vs$
$\mu_{Hole} \approx 8\ cm^2/Vs$

- **Ambipolar operation** – tunable to be n-type and p-type
- Some hysteresis apparent– due to ionic movement

Conclusion

- Ambipolar operation achieved twice in MBE-grown $MoSe_2$ EDLTs
    - Also once in MBE-grown WSe_2
    - Believed to be first observation of this
- Film quality highly impacts device performance
- Testament to the viability of MBE for improving TMD device fabrication

Next Steps

- Further optimize MBE process
    - Especially monolayer growth
- Attempt to reproduce electroluminescence previously observed in WSe_2[2] and $MoSe_2$[3] with MBE-grown films

References

- [1]Y. Zhang, J. Ye, Y. Matsuhashi, and Y. Iwasa, Nano Lett. **12**, 1136 (2012).
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- [3]M. Onga, Y. Zhang, R. Suzuki, and Y. Iwasa, Appl. Phys. Lett. **108**, 073107 (2016).
- [4]A. Pospischil, M. M. Furchi, and T. Mueller, Nat. Nanotechnol. **9**, 257 (2014).

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