Field-Effect Characterization of Polymorphic Molybdenum Disulfide using Scanning Probe Techniques

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Molybdenum disulfide (MoS_2) is a two-dimensional polymorphic material known to exist in at least two different structures, 2H and 1T. In monolayer 2H form it is characteristic of an n-type direct gap semiconductor, while 1T exhibits metallic properties.[1] A thorough understanding of each form and how to convert from one to the other allows for the creation of efficient field effect transistors based on this material.[2] Single-crystal MoS_2 flakes are grown by chemical vapor deposition[3] and analyzed by scanning probe microscopy techniques including electrostatic force microscopy (EFM) and scanning gate microscopy (SGM). EFM detects the electrostatic variation across a surface, while SGM tracks changes in current. These methods were selected for their ability to detect local transport properties and confirm the presence of a Schottky barrier, the point of contact between a metal and semiconductor.[4] Other methods of analysis include tip-enhanced Raman spectroscopy, for the known peaks of 1T and 2H; and photoluminescence, for the difference in response between metals and non-metals. Since prior work suggests that a phase transition from 2H to 1T may be induced through electron beam (EB) irradiation,[1] crystals were partially exposed to EB irradiation. Electrical contacts are deposited on some samples, while others lack Cr/Au composites. Observation of EFM and SGM responses reveals distinct regions dependent upon EB exposure and consistent with the presence of separate metallic and semiconducting areas. These results confirm the capacity of EB exposure to control the electrical properties of MoS_2, important for the development of transistor technology from this material.

[1] Y.-C. Lin, *et al*., Nature Nanotech. **9**, 391 (2014).
[2] B. Radisavljevic, *et al*., Nature Nanotech. **6**, 147 (2011).
[3] Y. Zhan *et al*., Small **8**, 966-971 (2012).
[4] N. Aoki, *et al*., Appl. Phys. Lett. **91**, 192113 (2007).

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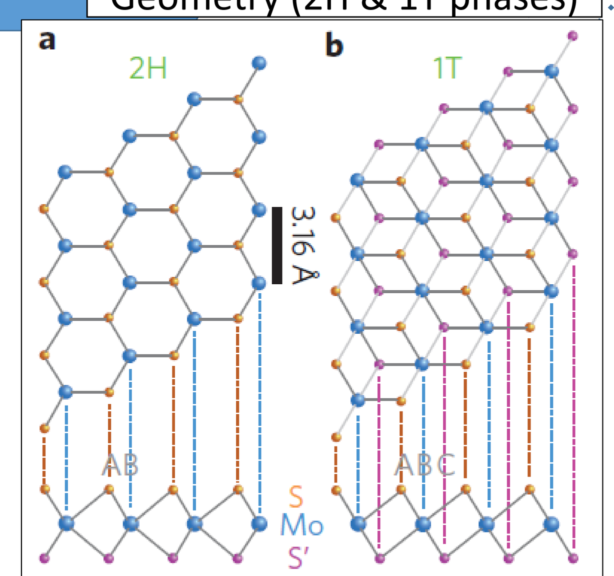
Introduction

Monolayer MoS_2 exists in at least two phases:

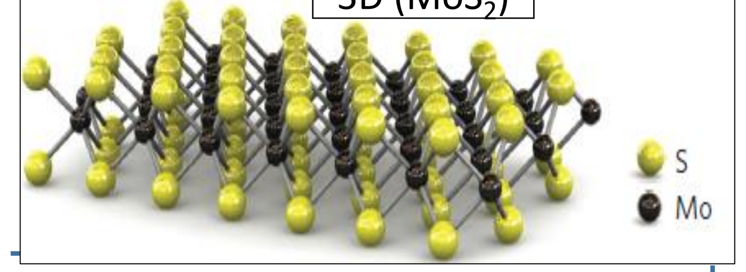
- **2H** – properties of n-type semiconductor
- **1T** – metallic characteristics

2H→1T phase transition may be possible with the use of electron beam (EB) irradiation. Samples **M03** and **M04** are attempts to confirm this

Geometry (2H & 1T phases)



3D (MoS_2)



Methods

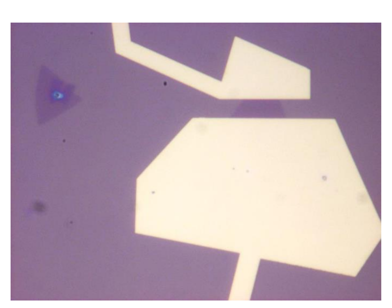
Chemical Vapor Deposition

Electron beam lithography/irradiation

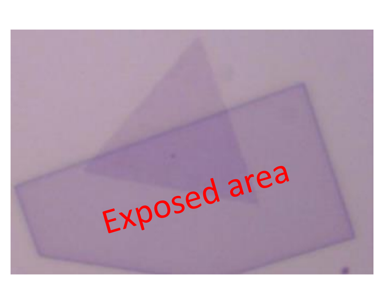
SPM: Scanning Probe Microscopy (AFM, EFM, SGM)

M03 M04

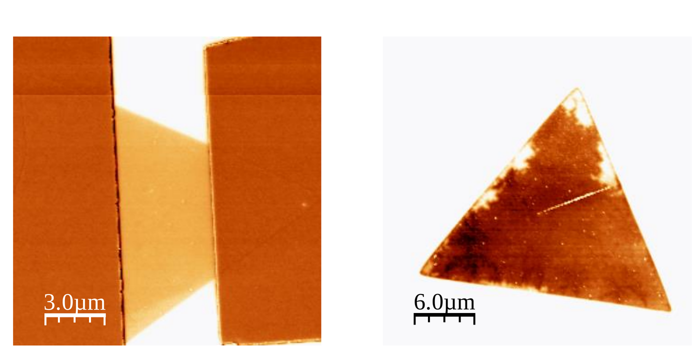
Sulfurization of MoO_3 films forms MoS_2 devices on SiO_2/Si substrate. Certain devices are selected to undergo EB irradiation/lithography



Cr/Au electrodes provide electrical contact



Cr/Au not deposited, leaving EB irradiated region



EFM Phase images

Why FET?

FET – Field Effect Transistor

MoS_2 is characterized by:

- High thermal stability
- No dangling bonds
- Bandgap of 1.3 eV in bulk (indirect), 1.8 eV in monolayer (direct)
- Enhanced mobility with dielectric

In transistors:

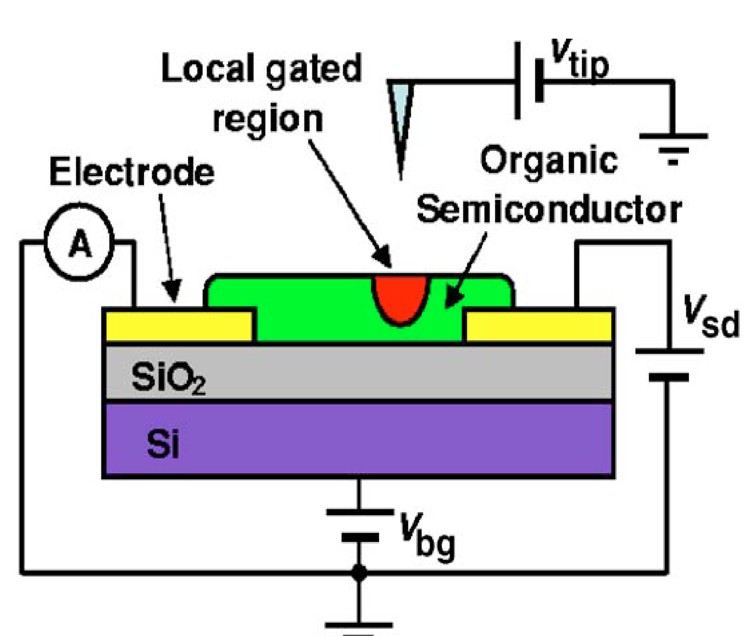
- Large (>10^7) on-off current ratio
- Good subthreshold swing (74mV/decade)
- 2H⟶1T transition potentially useful in achieving efficient electrical contacts from MoS_2

SPM Techniques

AFM: Atomic force microscopy
Uses van der Waals forces to image surface topography

EFM: Electrostatic force microscopy
Maps surface potential difference

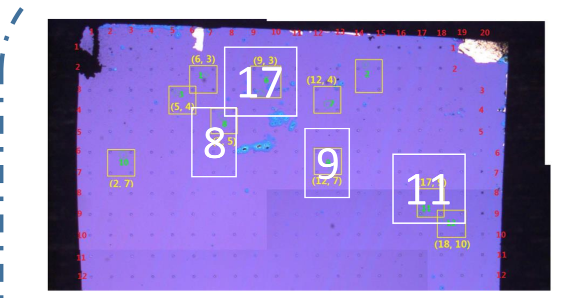
SGM: Scanning gate microscopy
Tracks changes in current



EFM/SGM + sample setup

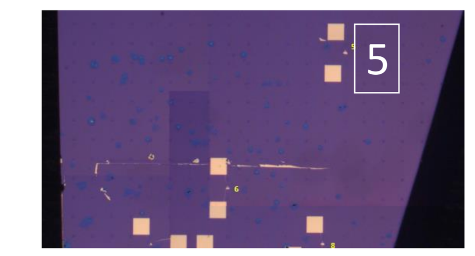
Results

M04

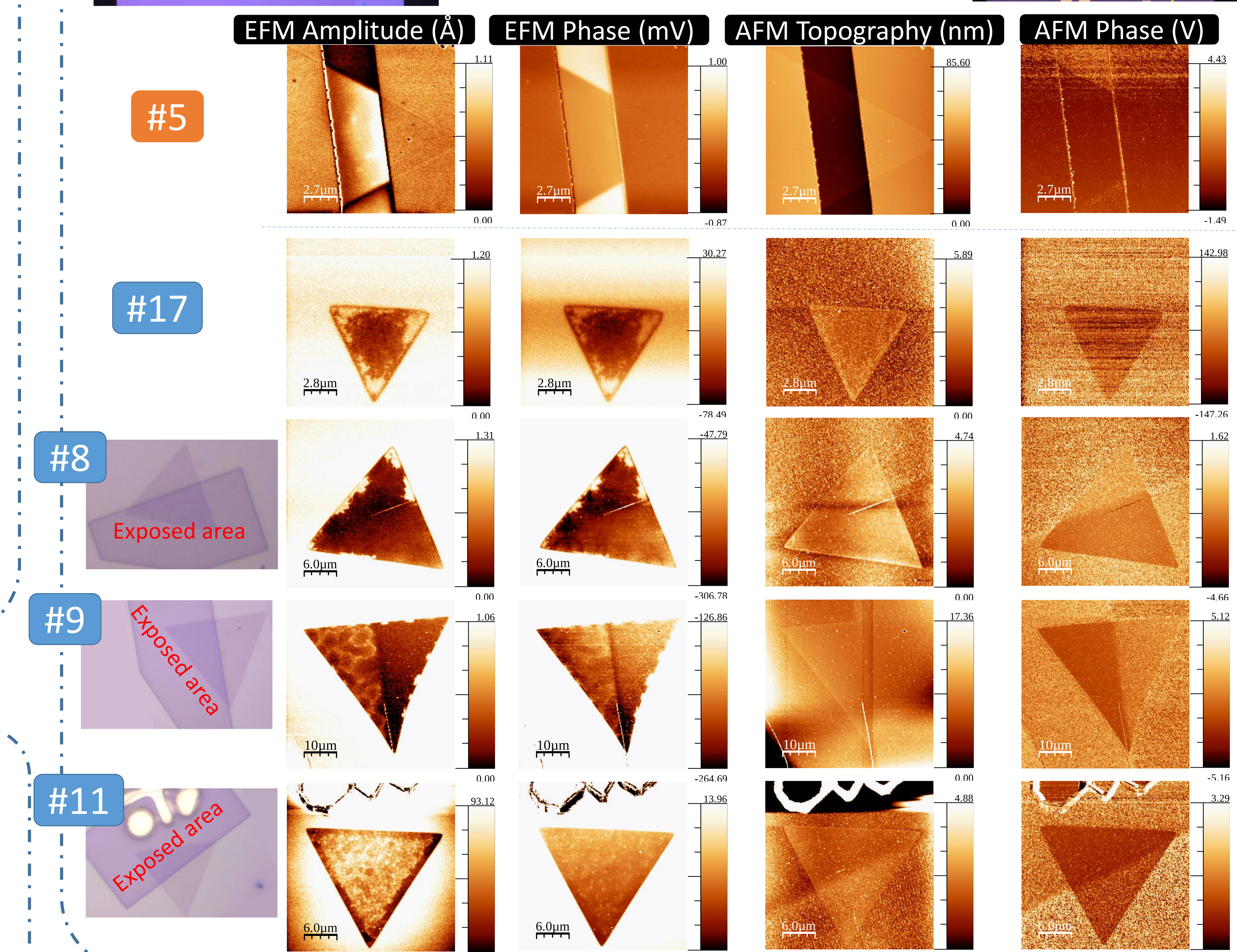


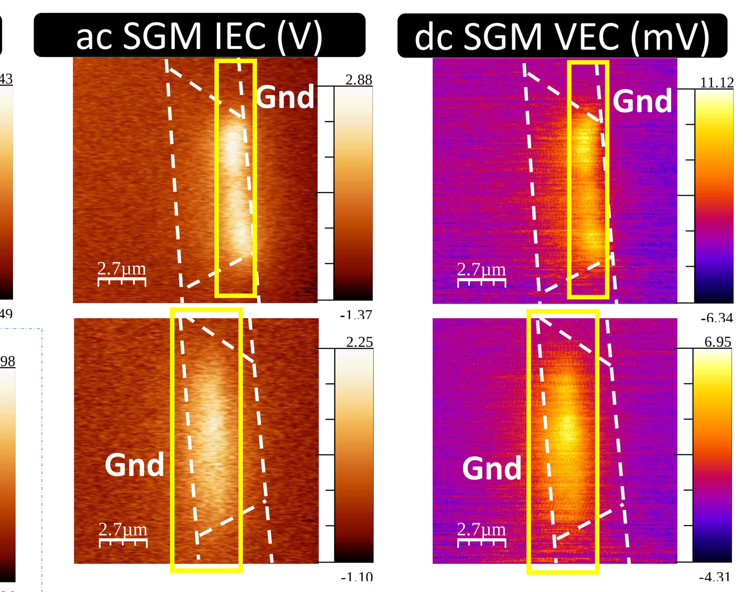
Imaged to determine if EB irradiation triggers 2H to 1T phase transition (as interpreted from past results)

M03



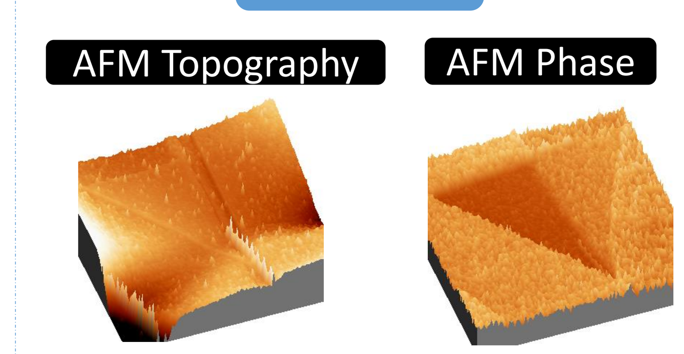
Imaged to confirm past results of distinct regions near EB lithographed regions





Schottky barrier - point of contact between metals and semiconductors

M04 #9



3D image of M04 #9

Discussion

- #5 may show the Schottky barrier between electrodes and MoS_2 channel
- Bright spots in EFM images of #8 and #17 could be regions where charge has gathered
  - Strong electric fields expected at corners
- Distinct regions along exposed area in EFM images #9 suggest two different materials
  - May be semiconductor and metal
- #11 may show the growth of a second layer of MoS_2
- Different color in AFM Phase suggests residual resist
- **EB irradiation may contribute to 2H⟶1T phase transition**

Future Work

Further tests to confirm phase transition:

- Raman spectroscopy
- Photoluminescence
- SGM imaging

Experimental analysis following

- Creating field-effect transistor from MoS_2 (possibly as both semiconductor and electrode)

References
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