Relation Between Phase Transition and Laser Irradiation Strength and Time Duration through Phase Patterning of $MoTe_2$

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An intriguing property displayed by transition metal dichalcogenides (TMDCs) known as polymorphism, is attractive for its application in future electronic devices. Molybdenum ditelluride ($MoTe_2$) is a TMDC with an energy difference of ~35 meV between its semiconducting 2H and metallic 1T' phases, which is considerably less than the homologous energy differences of other TMDC materials [1,2]. By taking advantage of this smaller energy difference, we were able to feasibly observe polymorphism within $MoTe_2$. In this study, we fabricated $MoTe_2$ field effect transistors, and used laser-driven phase patterning to induce property changes in desired areas of the semiconducting channel [3]. While previous studies have confirmed successful 2H-1T' phase transition at laser irradiated sites, we investigate the possibility of controlling semiconducting properties by controlling laser irradiation strength and time. We are particularly interested in p-n polarity and threshold voltage shifts (from normally-off to normally-on) of $MoTe_2$ upon phase patterning, as establishment of such relationships is essential for configuring electrical circuits within crystals of $MoTe_2$. Furthermore, we attempt to describe the mechanism behind the phase patterning induced phase transition. Although it is known that the formation of the Te-atom vacancy serves as the key origin for phase transition [3], the specific cause of this vacancy and other related causes of phase transition are still not confirmed. Realizing the previously stated relationships along with the driving mechanism of phase patterning opens the potential of fabricating circuit components, such as logic gates and transistors, with a uniform material.

[1] K. -A. N Duerloo, Y. Li, E. J. Reed, *Nat. Commun.* **5**, 4212 (2014)
[2] D. H. Keum *et al*., *Nat. Phys.* **11**, 482-486 (2015)
[3] S. Cho *et al*., *Science* **349**, 625 (2015)

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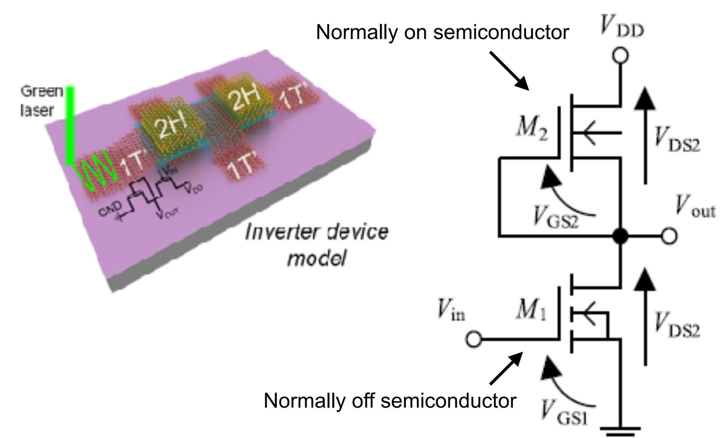
Introduction

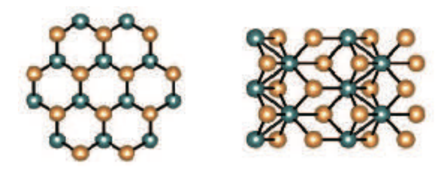
Background

- Fabrication of a monolithic integration circuit is desirable
- Requires different types of semiconducting and metallic areas

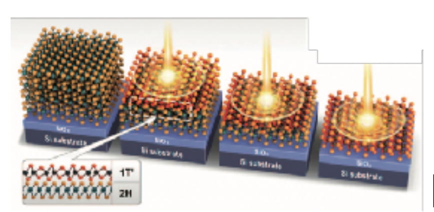


$MoTe_2$

- Displays polymorphsim (semiconducting 2H & metallic 1T' phases)
- Laser-induced phase patterning provides clean phase transition (free of chemical doping)



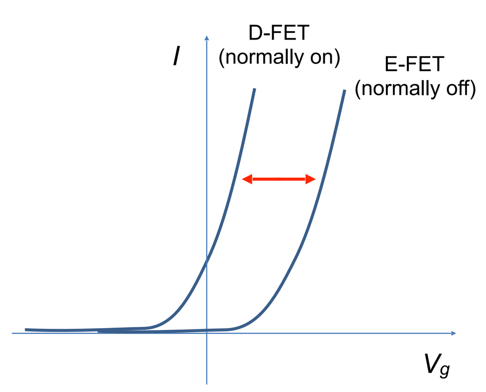
2H (top view) 1T' (top view) [1]



[1]

Objectives

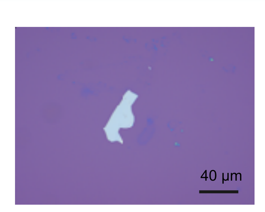
- Change 2H-$MoTe_2$ semiconducting properties through laser irradiation
- Investigate the mechanism behind laser-induced phase transition



FET Fabrication and Testing Process

1. Mechanical Exfoliation

- Multilayer flakes onto SiO_2/Si substrate



2. Electrode patterning

- Wire/metal mask method (n-type sample)
- Photolithography method (p-type sample)

3. Electrode deposition

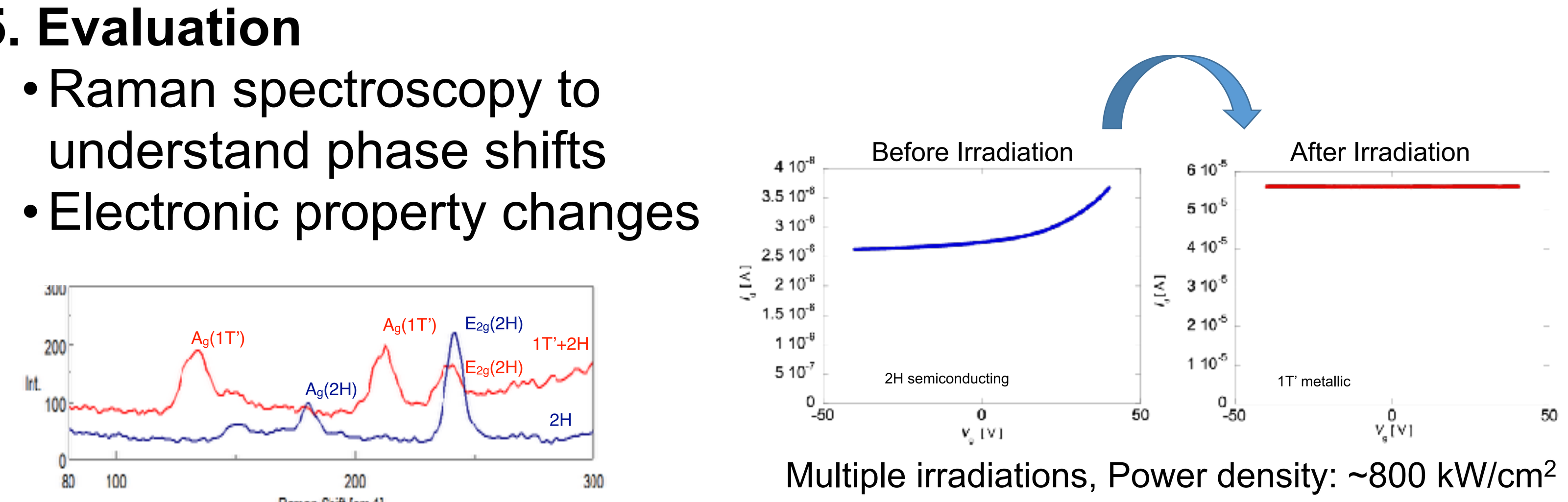
- Pd/Au (5/75 nm) top contact

4. Laser Irradiation

- Irradiate samples with 532 nm CW laser under various laser powers and times

5. Evaluation

- Raman spectroscopy to understand phase shifts
- Electronic property changes

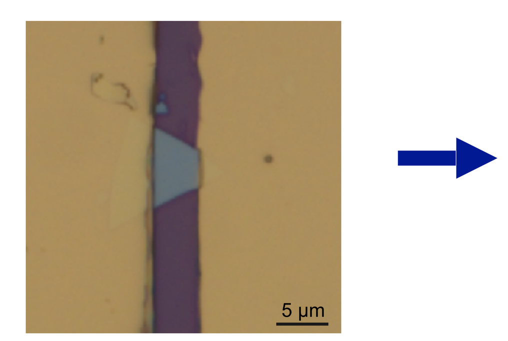


Multiple irradiations, Power density: ~800 kW/cm²

Results

A. Control of Semiconducting Properties

Photolithography FET sample



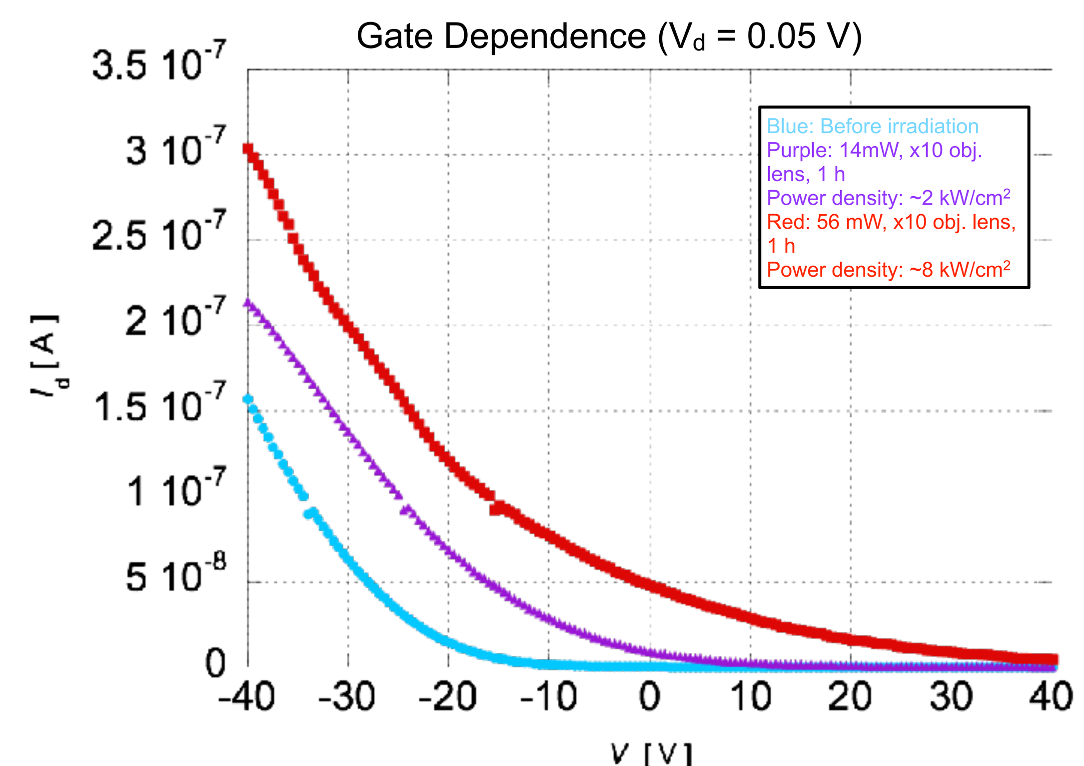
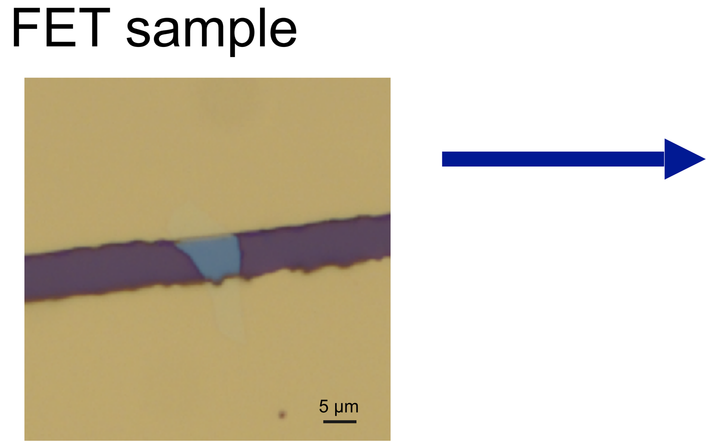


Fig. 1. Able to shift threshold voltage (from normally off to normally on) with a weaker laser power density

B. Irradiation Time Dependence

Photolithography FET sample



Irradiation conditions
Laser power: 14 mW
Objective lens: x10
Power density: ~2 kW/cm²
Irradiation time: 1~1000 minutes

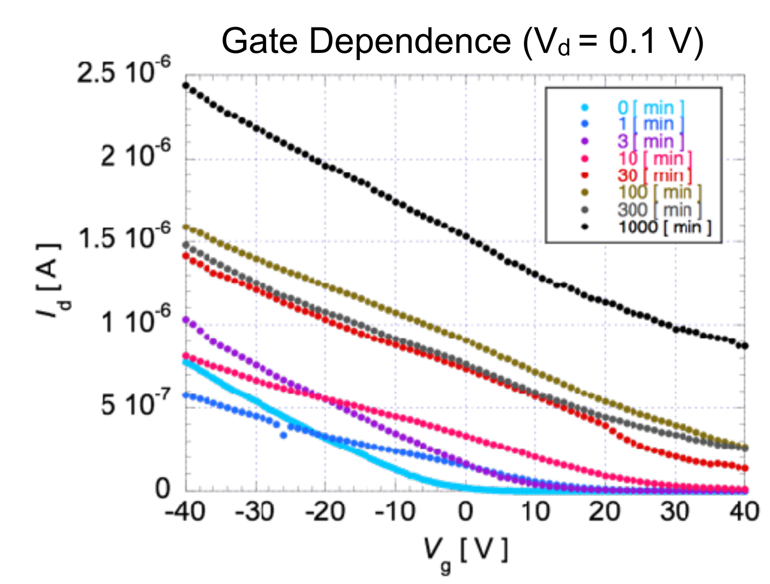


Fig. 2. Gate dependences of the sample after 0, 1, 3, 10, 30, 100, 300, and 1000 min of laser irradiation

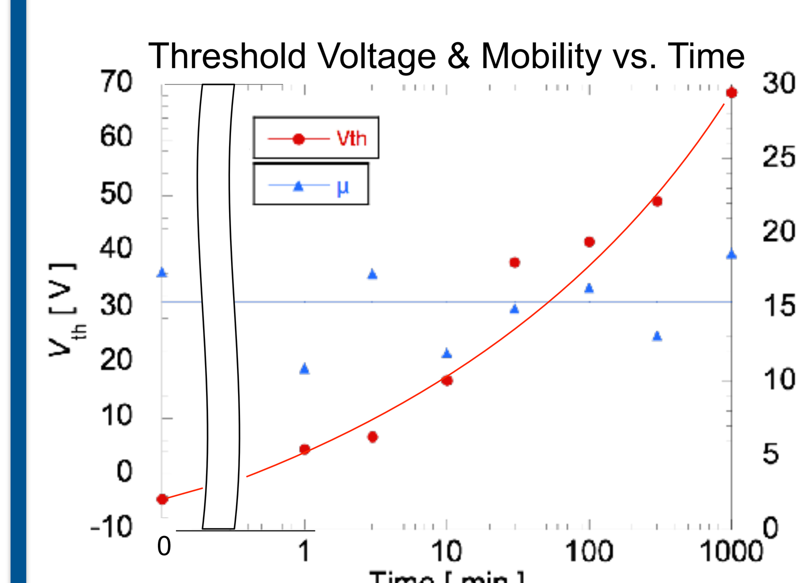


Fig. 3. Observed increases in threshold voltage with no significant change in mobility

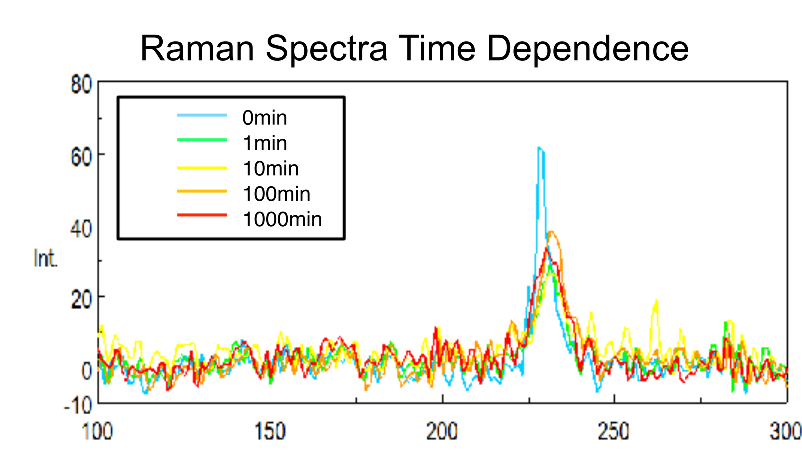
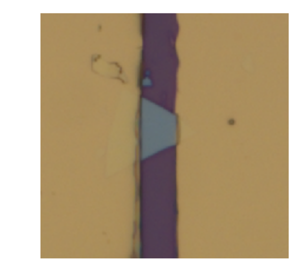


Fig. 4. E_{2g} peaks at ~270 cm^{-1} (characteristic of 2H-$MoTe_2$) with broadening curves and slight blueshift

C. Threshold Voltage Shifts of p & n Samples



Photolithography FET (p-type)

Wire/Metal mask FET (n-type)

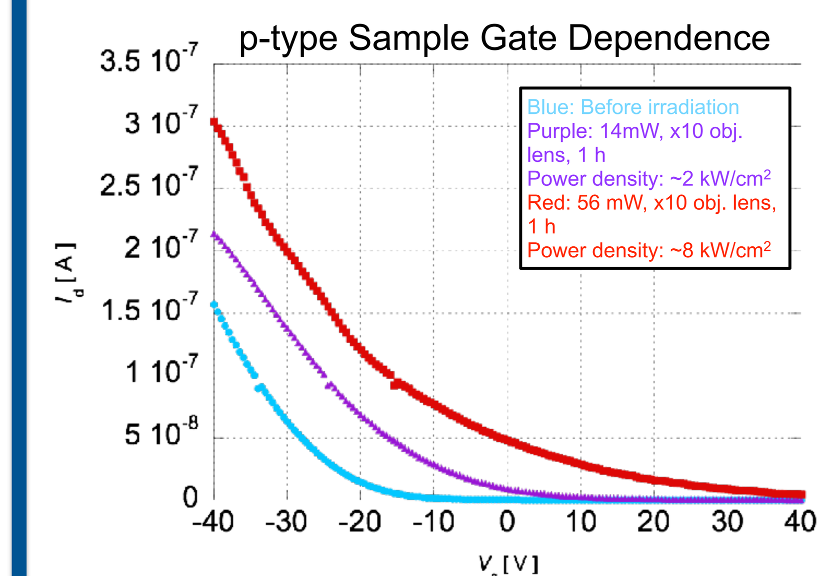


Fig. 5. p-type sample became more p-type-like upon laser irradiation

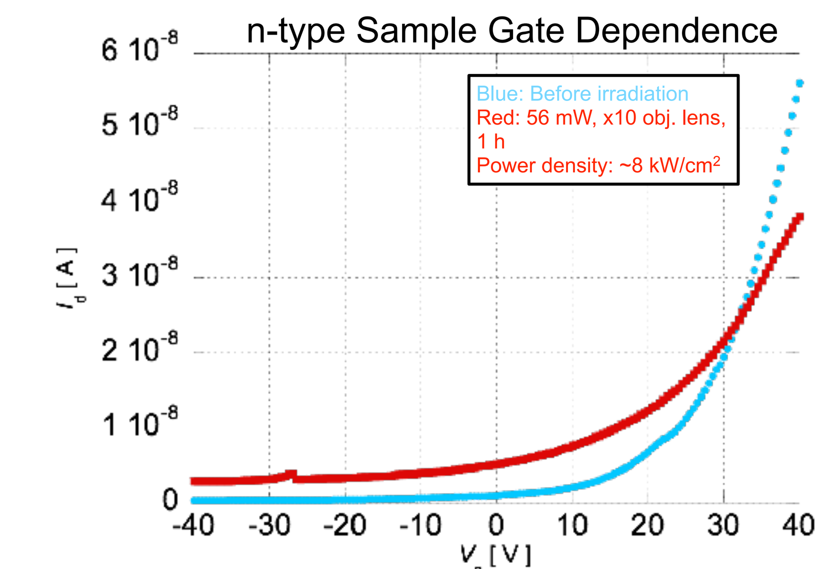


Fig. 6. n-type sample became more n-type-like upon laser irradiation

Discussion

- Successfully changed 2H-$MoTe_2$ semiconducting properties by using a weaker laser power density
- Observed systematic shifts in threshold voltage with increasing irradiation time
- Raman spectra broadening suggests irradiation induced Te-atom defects which is in agreement with previous studies
- Consistent threshold voltage shifts of p & n type samples suggests band gap narrowing (strains within the crystal)

Future work

- Identify the induced strains associated with $MoTe_2$ phase change (tensile or compressive) through further Raman spectra, band gap measurements, and simulation
- Explore the reversibility of 2H-1T' phase transition by studying the effects of $MoTe_2$ heat annealing
- Investigate the possibility of switching a sample's characteristics from p-type to n-type and vice versa

References
[1] S. Cho *et al.*, *Science* **349**, 625 (2015)

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