Characterizing MoS_2-Si p-n Heterojunction Using Laser Terahertz Emission Spectroscopy

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Atomically thin two-dimensional (2D) materials demonstrate markedly different properties from their bulk (3D) counterparts, which could lead to interesting applications for optoelectronic and electronic devices. Advancements in the creation of these 2D semiconductor materials have expedited the fabrication of a variety of 2D-2D and 2D-3D van der Waals heterojunctions with novel properties compared to those of typical covalently bonded semiconductor junctions. However, the characteristics of 2D-3D semiconductor junctions have not yet been extensively studied and are therefore not well understood. In this study, we examined the emission of terahertz radiation from a heterojunction created with n-type monolayer MoS_2 and p-type bulk Si using laser terahertz emission spectroscopy. The results of this study will provide new insight into the nature of the MoS_2-Si p-n junction energy states (e.g., band alignment and bending) as well as allow us to better understand how the properties of 2D-3D junctions differ from those of conventional 3D-3D junctions.

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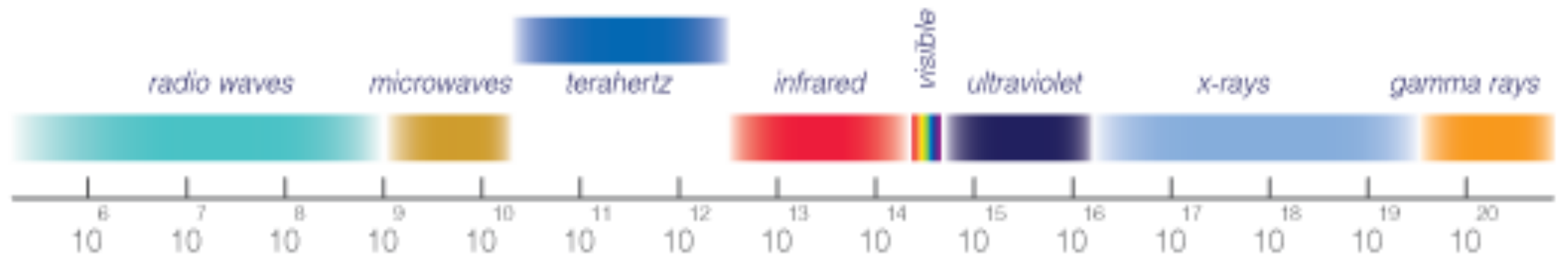
Introduction

The "Terahertz Gap"

- Spectral region 0.3 – 3.0 THz (1 mm - 100 μm)



- Final frontier for improving optoelectronic and electronic devices
  - Low energy usage

Atomically thin two-dimensional (monolayer/2D) materials differ significantly from bulk (3D) counterparts

- Van der Waals bonds (2D) vs. covalent bonds (3D)
- MoS_2 characteristics
  - Direct band gap of 1.8 eV (2D) vs. indirect band gap of 1.3 eV (3D)
  - Stable charge exciton state at room temperature (2D)
- Unique applications for optoelectronic and electronic devices

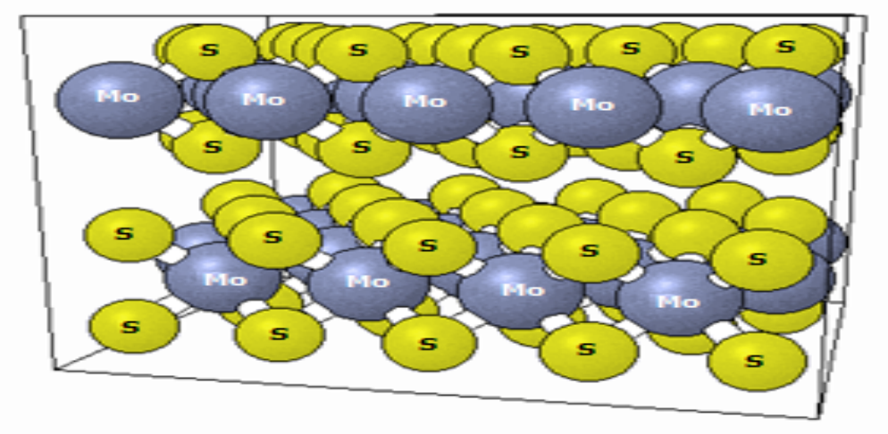


Fig. 1: Atomic structure of MoS_2

Fig. 2: Bulk MoS_2 sample

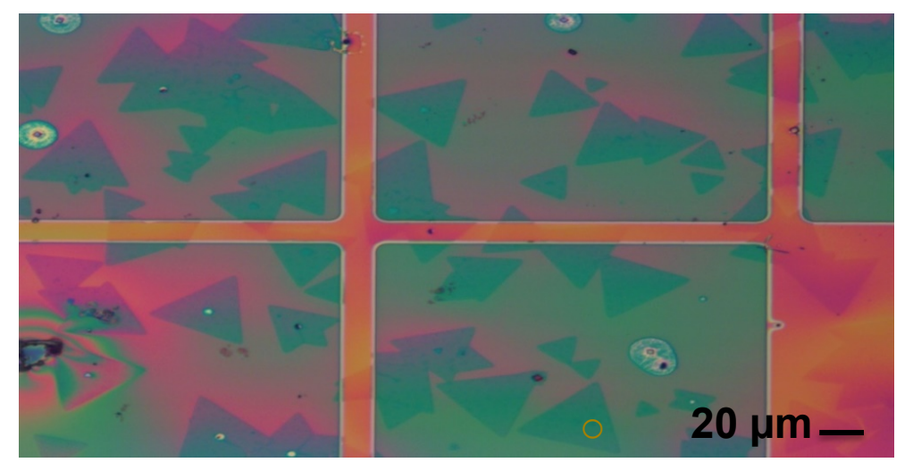


Fig. 3: Monolayer MoS_2 sample

Objectives

Investigate 2D-3D heterojunction MoS_2-Si

- n-type (electron majority carrier) monolayer MoS_2 and p-type (hole majority carrier) bulk Si

Gain new insight into the nature of the MoS_2-Si p-n junction energy states

- Band alignment
- Band bending

Understand how the properties of 2D-3D junctions differ from those of conventional 3D-3D junctions

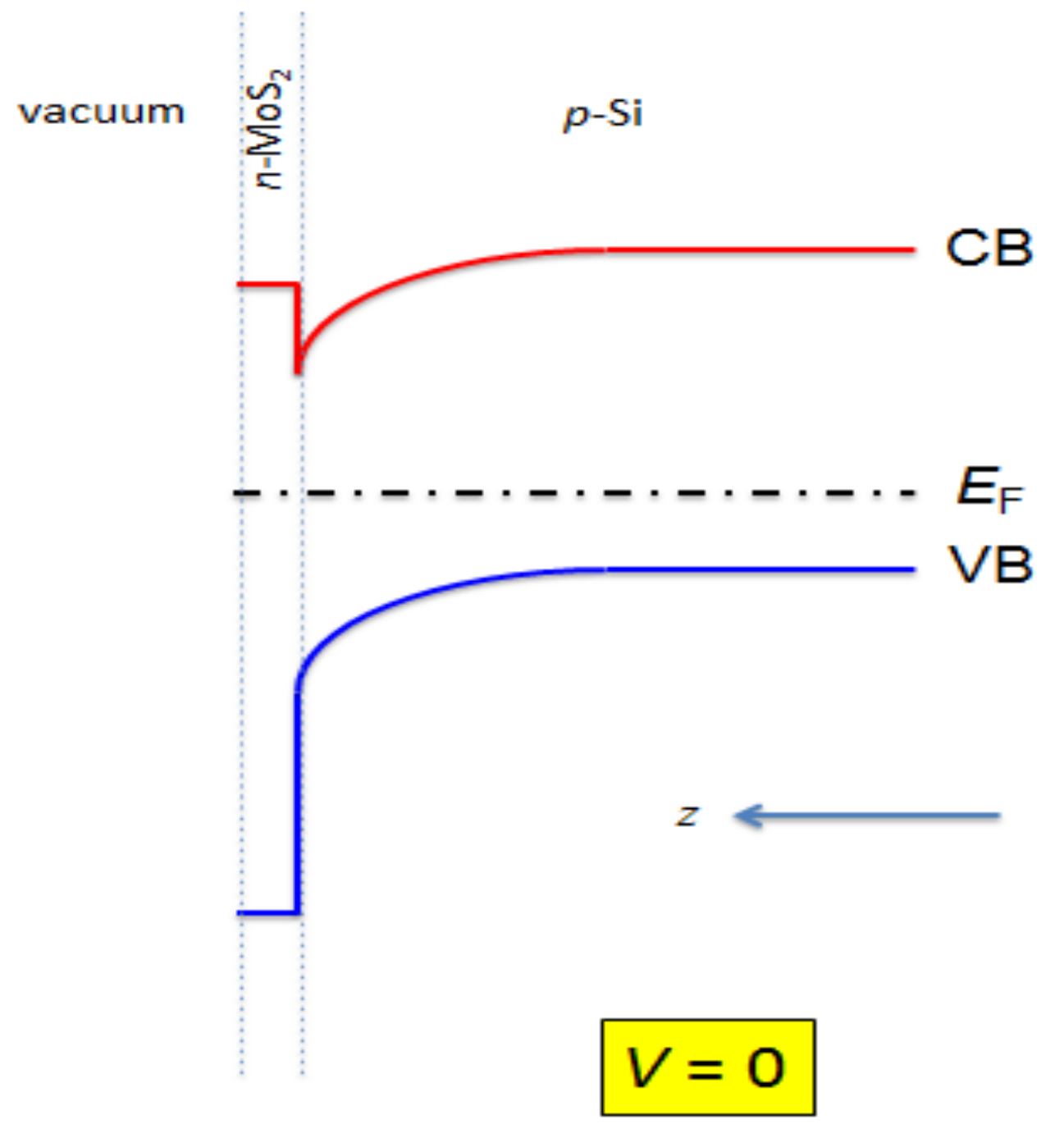


Fig. 4: Band diagram of MoS_2-Si heterojunction[1]

Methodology

Laser Terahertz Emission Spectroscopy and Imaging

- Sensitive to electric fields in MoS_2-Si heterojunction
  - Map out distribution of electric fields (band bending)

Optical Imaging

- Determine resolution of system
- Optimize alignment of system in order to perform terahertz imaging

Methodology

Terahertz Imaging

- Evaluate terahertz emission from MoS_2 p-n heterojunction

Raman Microscopy and Spectroscopy

- Monitor the deterioration of MoS_2 p-n heterojunction and categorize different materials within the sample

Framework

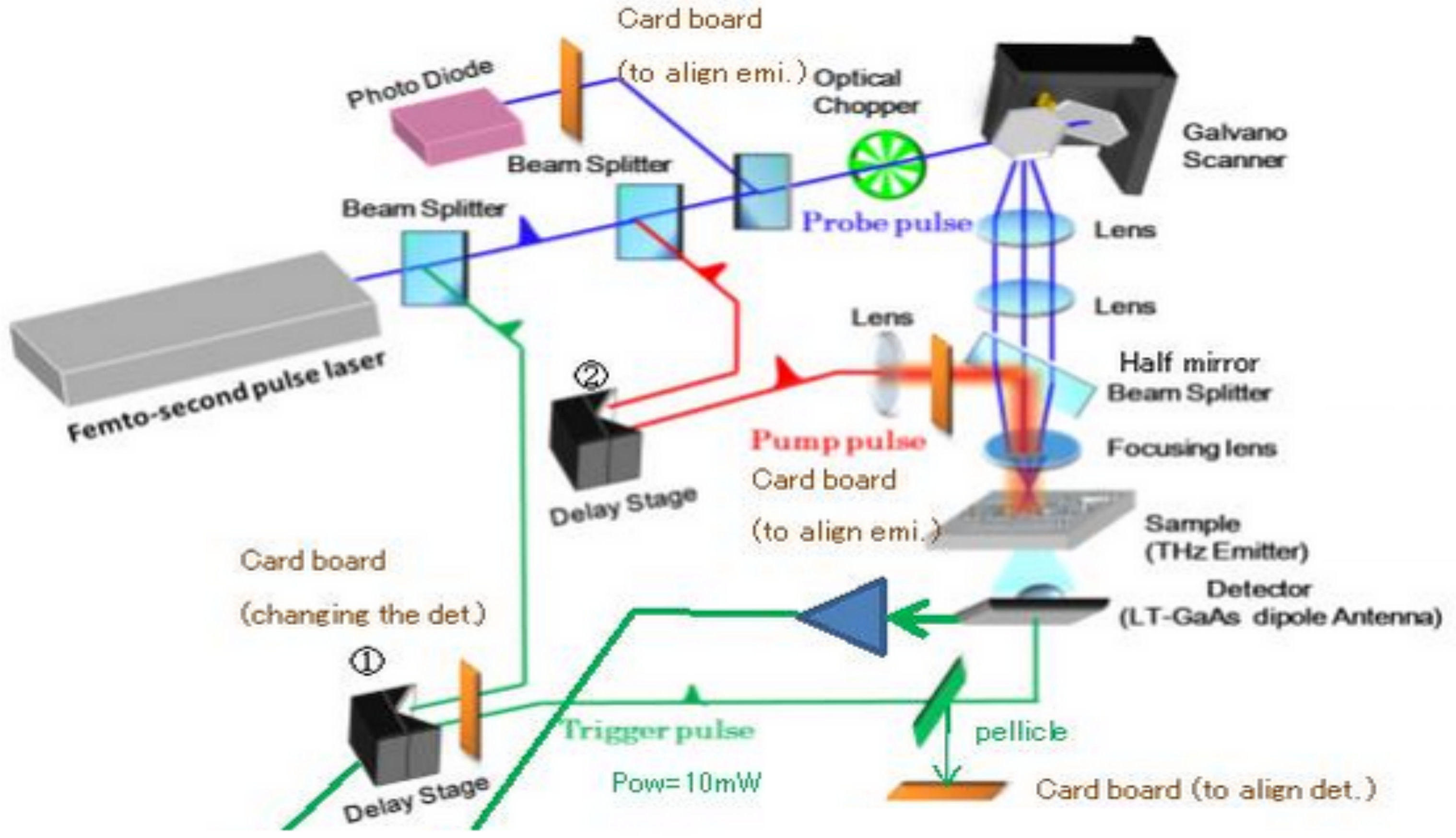


Fig. 5: Schematic of terahertz system setup

Results and Discussion

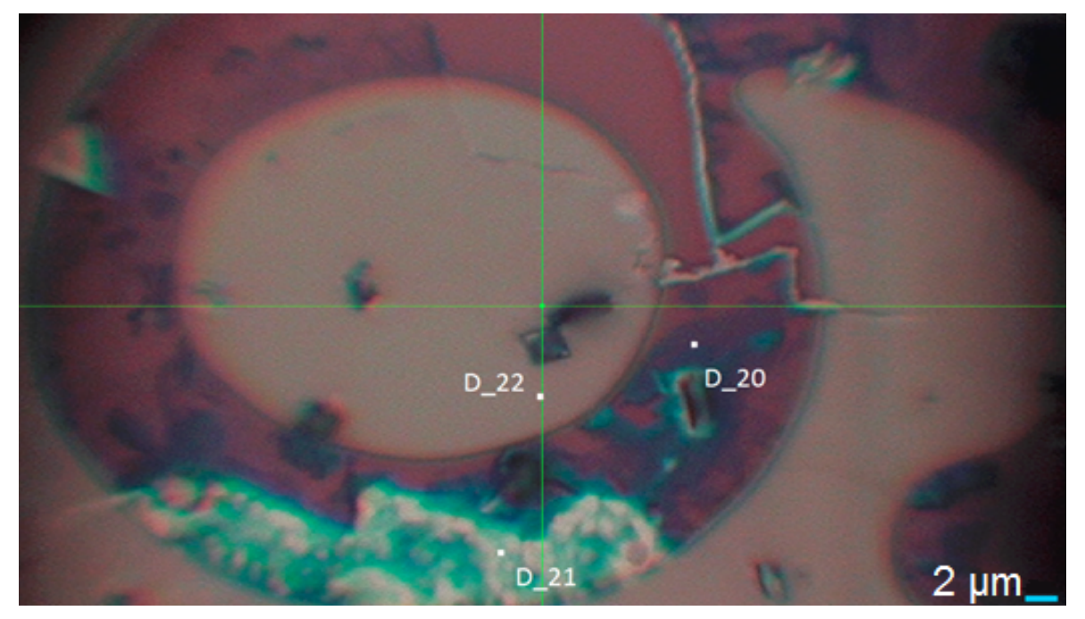
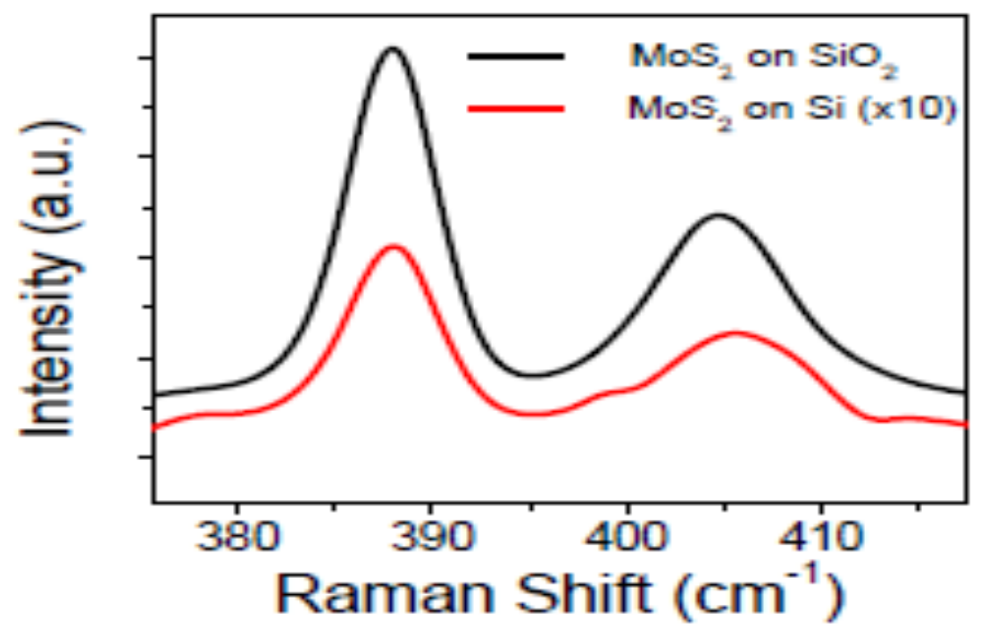
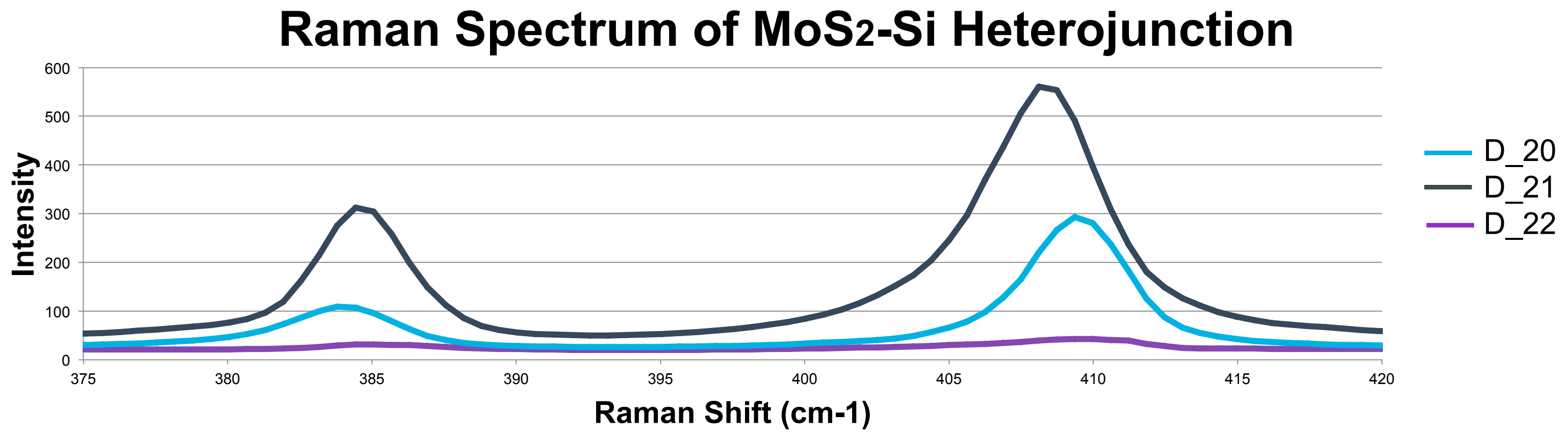


Fig. 6 (left): Raman spectroscopy sampling areas of MoS_2-Si with PMMA removed

Fig. 7 (right): Previously found Raman peaks of MoS_2 on silicon and silicon dioxide[1]





D_20 and D_21 have Raman peaks characteristic of monolayer and bulk MoS_2 respectively
D_22 has Raman peaks characteristic of silicon only

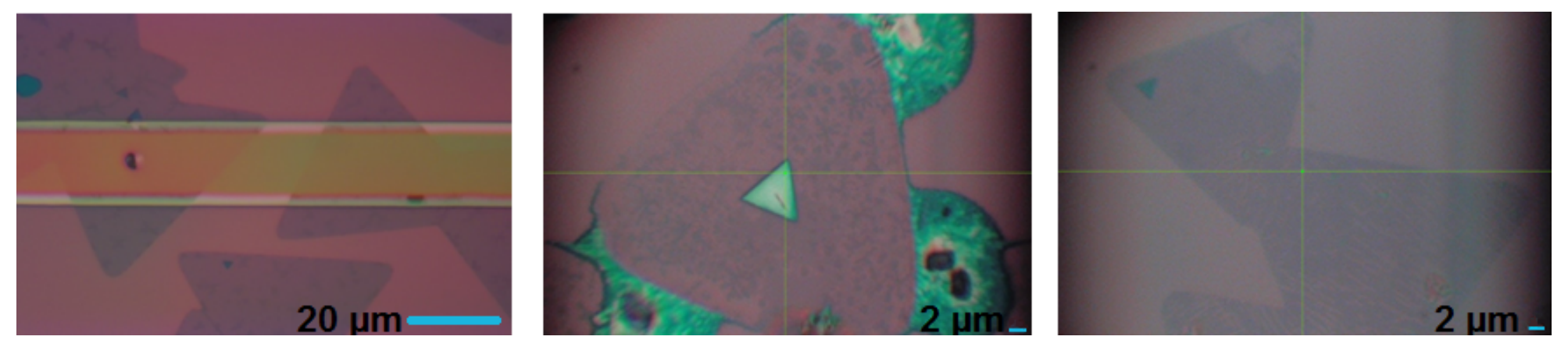


Fig. 8: Furthermost left image is of the sample freshly prepared. The other two images are of the sample one month later. All images are magnification X100. The furthermost right two images were acquired using Horiba XploRA ONE Raman microscope.

Results and Discussion

Current alignment and resolution of system

- Photoconductive antenna

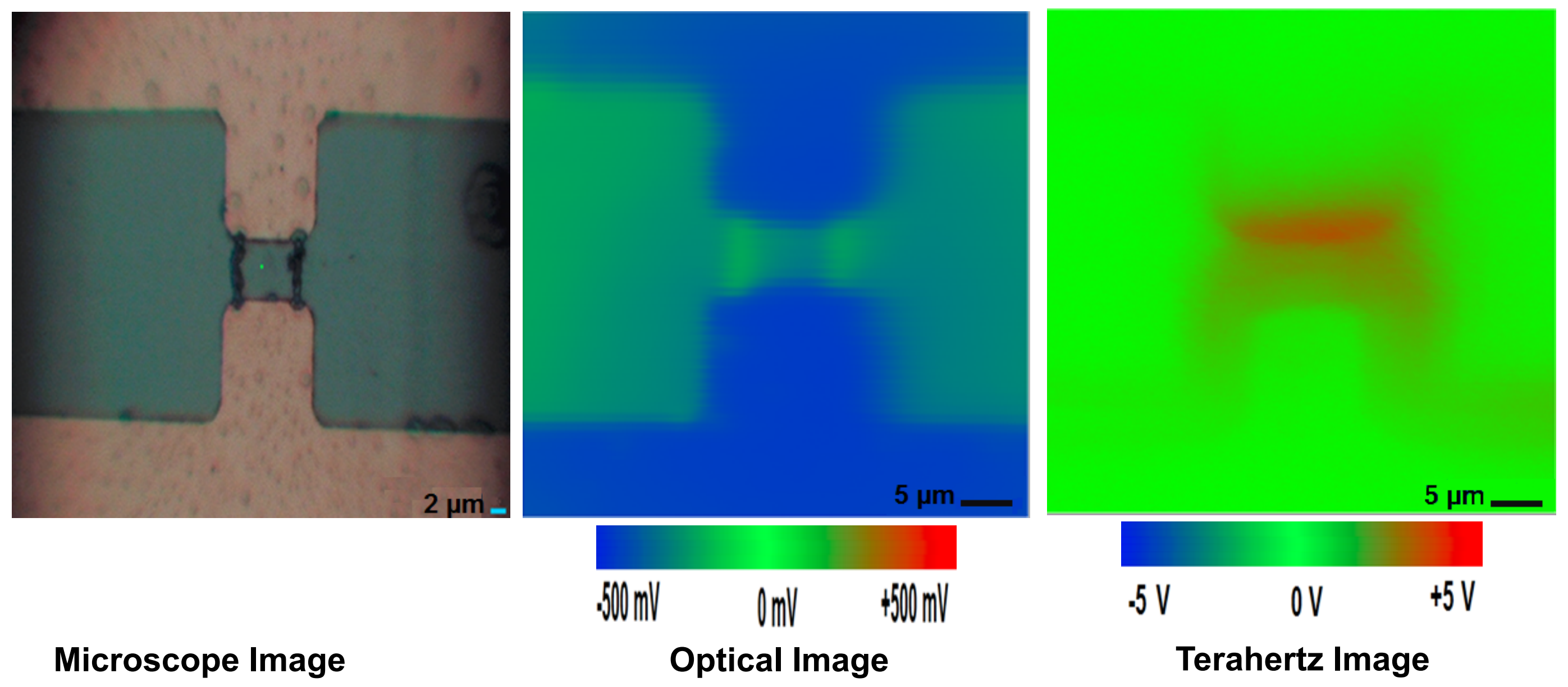
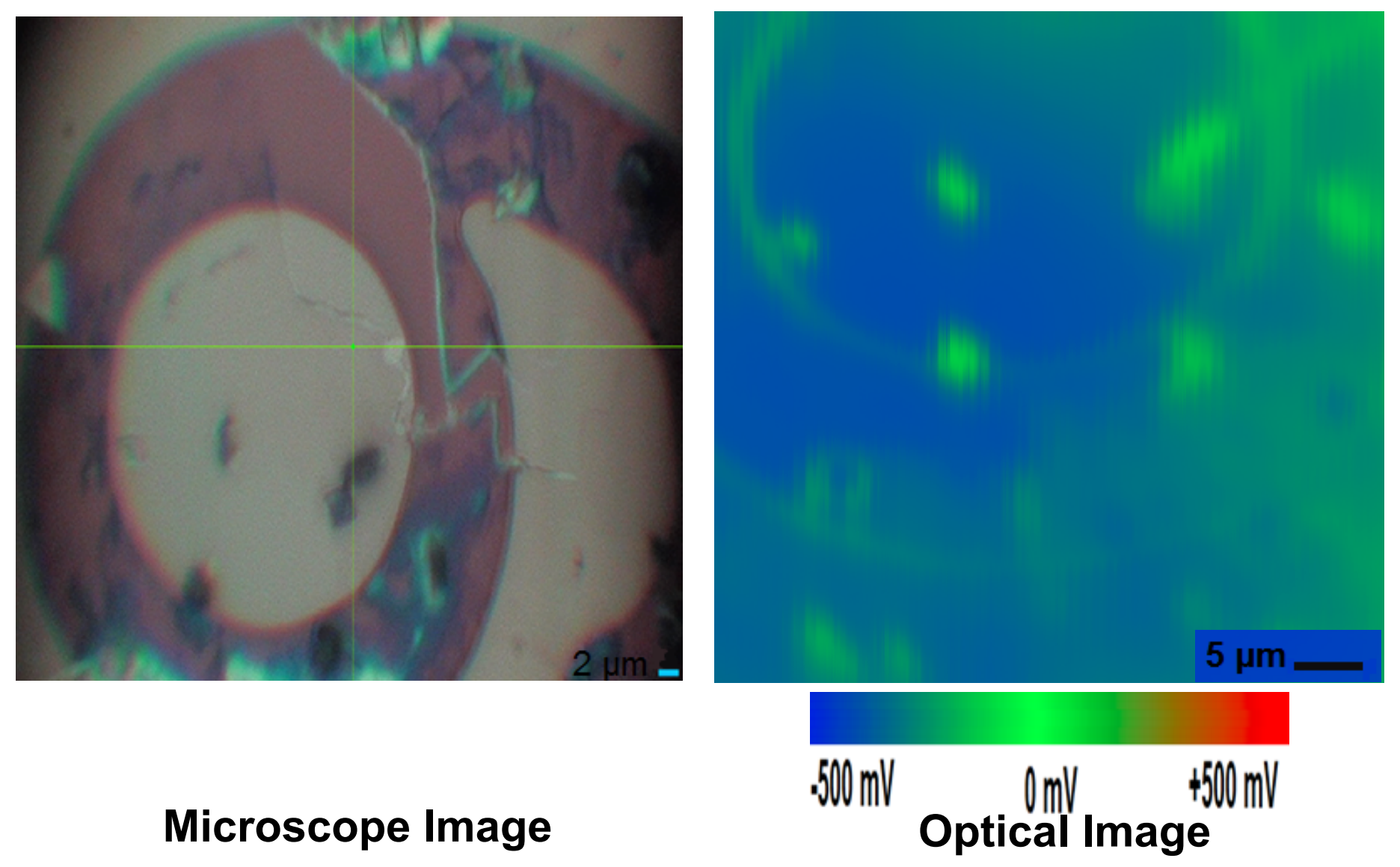


Image of photoconductive antenna is distinguishable



Optical image can discern outline of number

- However, cannot detect monolayer Raman spectroscopy-confirmed MoS_2 (D_20) on "9"
- Resolution is not good enough for terahertz imaging

Conclusions and Future Work

Finer tuning will be required to achieve higher quality optical and terahertz images

- Currently resolution is ~5 μm
- Resolution up to ~1 μm achievable

Delay the deterioration of p-n heterojunction

- Determine the thickness of resultant bulk MoS_2 layers
- Understand why oxidization of silicon results in apparent conglomeration of MoS_2

Reference

[1] Bo Li et al., in preparation

Acknowledgments

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