Transition Metal Dichalcogenides (TMD) as Strain Sensors in Pump-Probe Experiments

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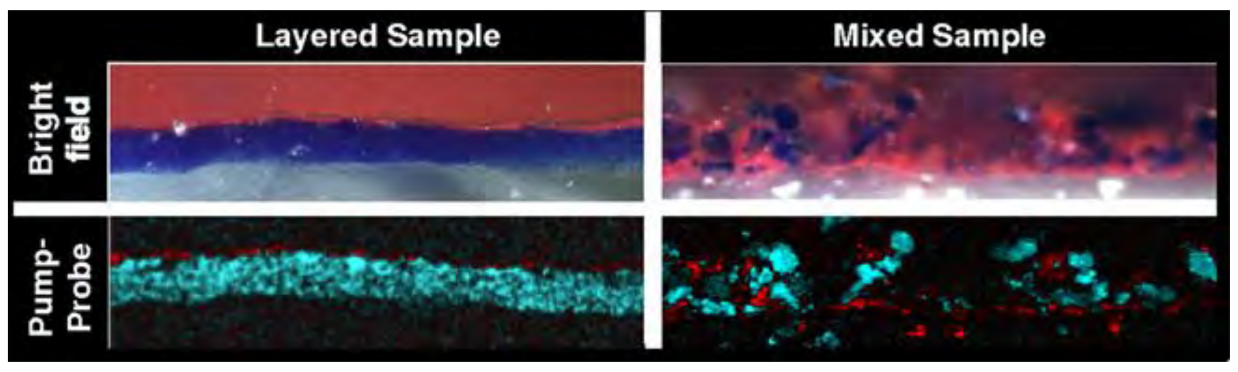
Introduction

Imaging a sample with both spatial and temporal resolution is one of the capabilities of the Ultrafast Pump-Probe Experiment. This method allows us to see how a sample behaves on a picosecond timescale. Moreover, it can be potentially nondestructive and allows for label-free imaging. One of its application are for historians to study paint pigments in old paintings without changing composition or destroying the pigments (Figure 1) [1].



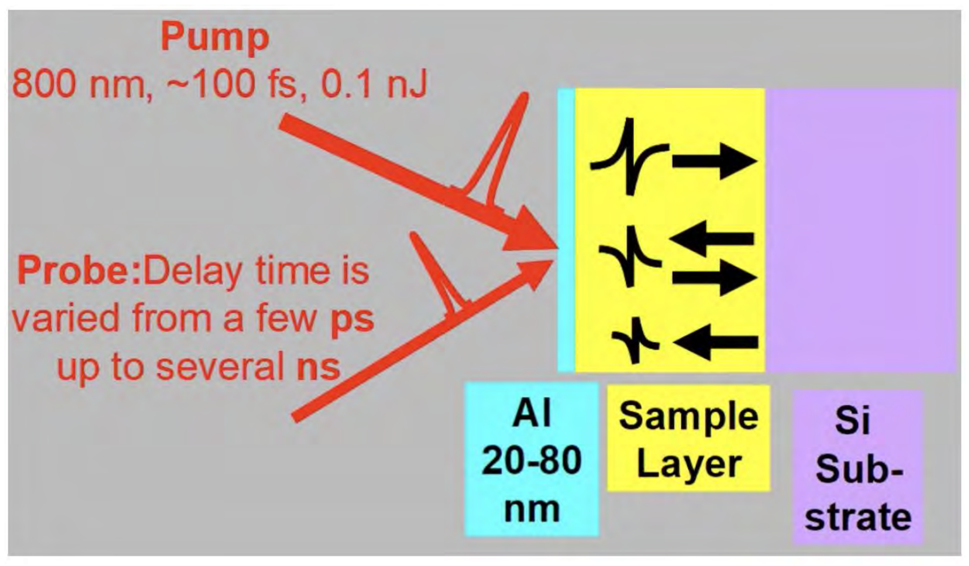


Figure 1. (Top) Highlighting pigments Quinacridone Red (false-colored red) and Ultramarine Blue (false-colored cyan) by using pump probe experiment. Scale: 365 x 90 μm [1]
Figure 2. (Bottom) An ultrafast laser excites acoustic phonons in the aluminum sample, altering the reflectivity at the surface. This change in reflectivity is measured by a probe laser [2].

The experimental setup of a typical pump-probe experiment is depicted above (Figure 2). The change in reflectivity data is used to create an image of the sample. However, the resolution of those images is limited by noise and attenuation present in the experiments due to the substrates used in the setup.

This summer remote URSI allowed us to perform literature research on possibility of incorporating TMDs (Transition Metal Dichalcogenides) into a pump-probe imaging experiment to improve the resolution. TMD's optical properties are known to change under stress and we hope to capture that strong change caused by laser induced stress [5]. We investigated what type of TMDs to use and how many layers of TMDs to use.

Methodology from the Literature

Strain sensors

We investigated how strain sensors are used to produce images, and how these images can be improved by changing the transducer material. We found that a better quality image would come from a transducer that is more sensitive to strain, and has a larger change in reflectance when hit with strain pulses. In other words, the material would amplify the strain signal, which reduces the problem of attenuation and noise in the imaging process. The sensitivity to strain of a material is known as a strain gauge factor. For transition metal dichalcogenides, the strain gauge factor is very high, with TMD gauge factors being around 10x higher than metals like aluminum [3]. There is limited research on the gauge factor of TMDs measured from the change in reflectance of the sample. Therefore, more experimentation is needed to determine which TMD would be most sensitive and appropriate to use in a strain sensing experiment. While there is not a lot of confirmation from other experiments, some studies suggest that bilayer and trilayer TMDs are more sensitive than monolayers to strain, and are easier to produce [3].

Different TMD Properties

Not every TMD is capable of being a strain sensor. Most of the candidates for TMDs have formula MX_2, where M is the transition metal and X is the dichalcogenide.

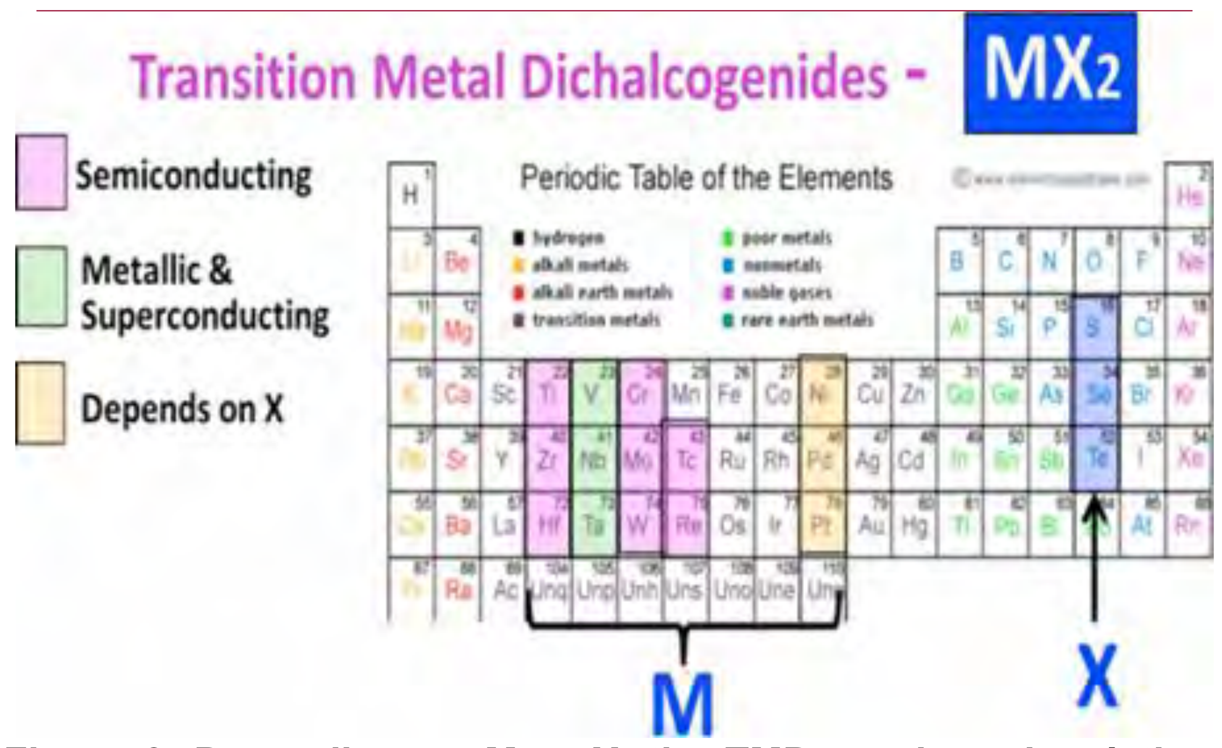


Figure 3. Depending on M or X, the TMD can have insulating, conducting or semiconducting characteristics [5].

For our purposes, we want semiconducting TMDs since they have desirable bandgaps. Monolayer semiconducting TMDs have a direct bandgap and multilayer TMDs have an indirect bandgap. In other words, as we increase the number of layers of TMDs, TMDs are less sensitive to light [5].

We also looked at how TMDs behave in a pump-probe experiment. A published paper from Korea used a pump-probe experiment to study WSe_2 vibrations. These vibrations can be quantized by specific frequency also known as phonon. Under Raman spectroscopy, WSe_2 can have but are not limited to A_{1g}, E_{2g}, B_1, LA(M) and S modes. All these modes represent different frequencies in relation to different directions of motion.

When they measure the transmissivity of WSe_2, they were only able to see certain phonon modes. In monolayer, WSe_2 displays LA(M) and A_{1g} modes (Figure 4a). In bilayers, WSe_2 displays A_{1g} and B_1 modes (Figure 4b). Interestingly, A_{1g} and E_{2g} have comparable strength in Raman scattering spectra, yet E_{2g} does not appear in this experiment. S mode is also not seen in any of the layers (Figure 4c).

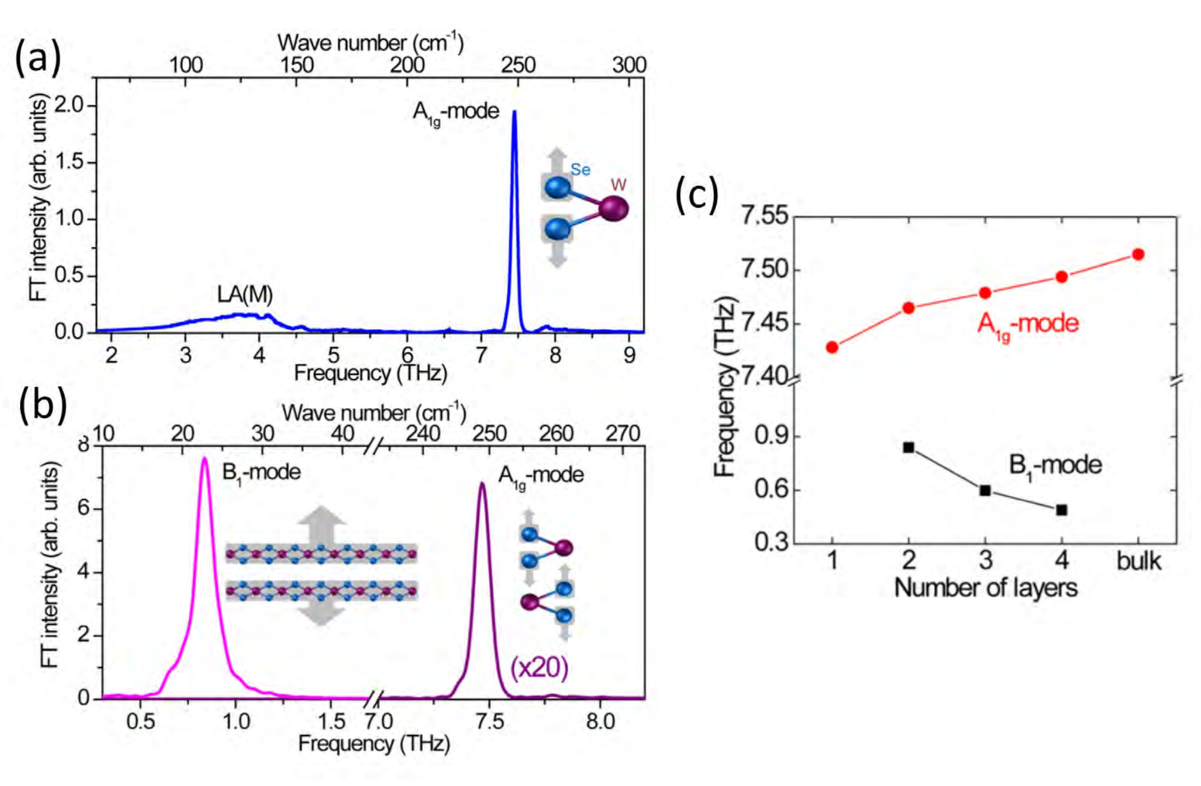


Figure 4. Fourier Intensity of (a) monolayer WSe_2 and (b) bilayer WSe_2. (c) Peak frequency of A_{1g} and B1 mode for each layer. Notice there is no B_1 mode for monolayer. [4]

Our preferable mode for WSe_2 is B_1 mode (~0.6 THz) since our pump-probe experiment at Vassar College is not sensitive enough to detect A_{1g} mode (~7.5 THz). Since B_1 mode does not appear in monolayers, using bilayer WSe_2 in pump-probe experiment shows the most promise.

Conclusion/Recommendation

Since this summer was a remote literature search, we did not end up performing experimental research. However, we can recommend using bilayer WSe_2 in a pump-probe experiment since there is published work on it. Additionally, this recommendation is supported by the strain gauge factor data we found. 2D TMDs all have a high strain gauge factor, and would produce better quality images than an aluminum transducer. While a monolayer TMD would work as a strain sensor, a bilayer TMD would be more effective. Additionally, monolayers are more difficult to produce, so we recommend using a bilayer TMD for a future experiment. We are excited in incorporating TMD in our setup because current spatial resolution of pump-probe experiment is limited.

In addition, our collaboration with Penn State University allowed us to learn about nanofabrication. Like URSI, Penn State University's REU program was remote. We participated in live demonstrations of the staff using nanofabrication devices to produce a transistor on a 4 inch wafer. The demonstrations include wafer characterization, metal contact deposition, atomic layer deposition, and many more processes to characterize and etch the transistor.

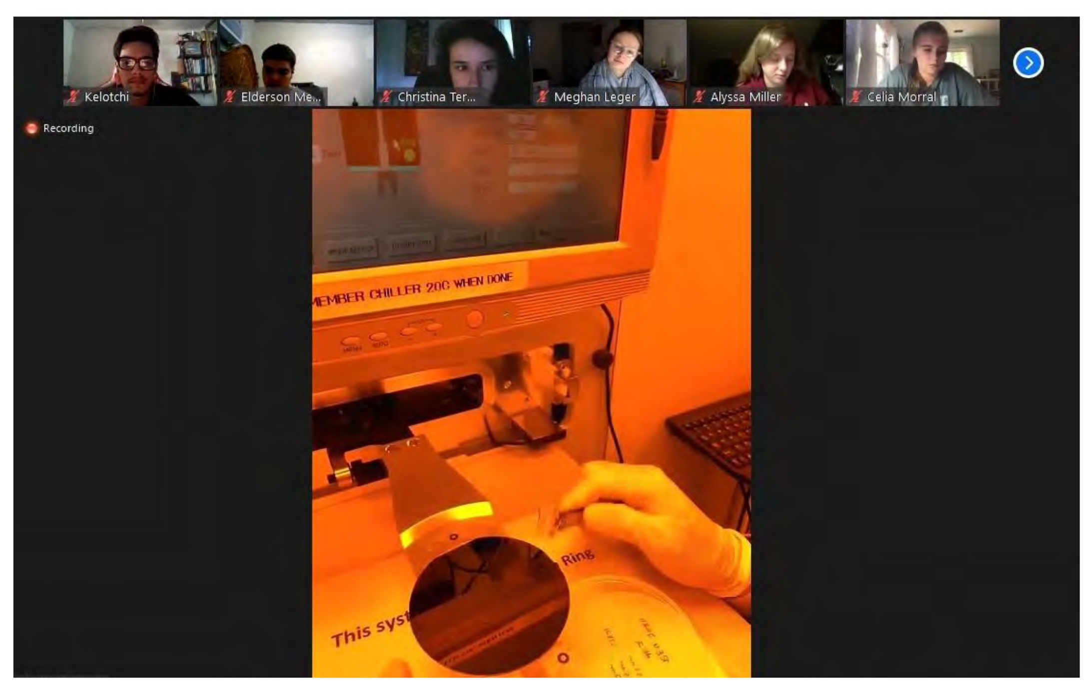


Figure 5. Screenshot from a virtual lab demonstration showing the transistor that was produced over the summer.

Acknowledgements + References

We would like to acknowledge Vassar's Undergraduate Research Summer Institute, Kathleen Gehoski (Penn State University), Dr. Ronald Redwing (Penn State University), and Susan Painter (Vassar College). The authors also acknowledge the support of National Science Foundation award number DMR-1709521 "RUI: Acoustic Phonons in Nanostructures: Surface Waves, Thermal Transport, and Imaging." This study was also funded by The Pennsylvania State University Two-Dimensional Crystal Consortium – Materials Innovation Platform (2DCC-MIP) which is supported by NSF cooperative agreement DMR-1539916.

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