Picosecond Laser Ultrasonic Measurements on the Thermal and Acoustic Properties of Transition Metal Dichalcogenides

Florence Binny ‘23, Kishan Patel ‘24, Clara Ross ‘23 and Prof. Brian Daly; Department of Physics & Astronomy

Introduction

Transition metal dichalcogenides (TMDs) are an emerging class of 2-D semiconductor materials, with applications in electronics and nanoscale devices. We used ultrafast laser spectroscopy to examine the thermal and acoustic properties of three different TMDs: $MoSe_2$, WSe_2 and Bi_2Te_2Se.

Methodology

TMDs consist of 2D layers of strongly bonded atoms, with weak Van Der Waals forces holding the layers together. We used mechanical exfoliation to cleave layers off the bulk crystal and deposit flakes on silicon substrates. We produced thick crystals (~1 um), which would be the most sensitive for thermal measurements,[1] and thin crystals (~ 10s of nm) which would produce high ultrasonic frequencies on the order of 100 GHz.

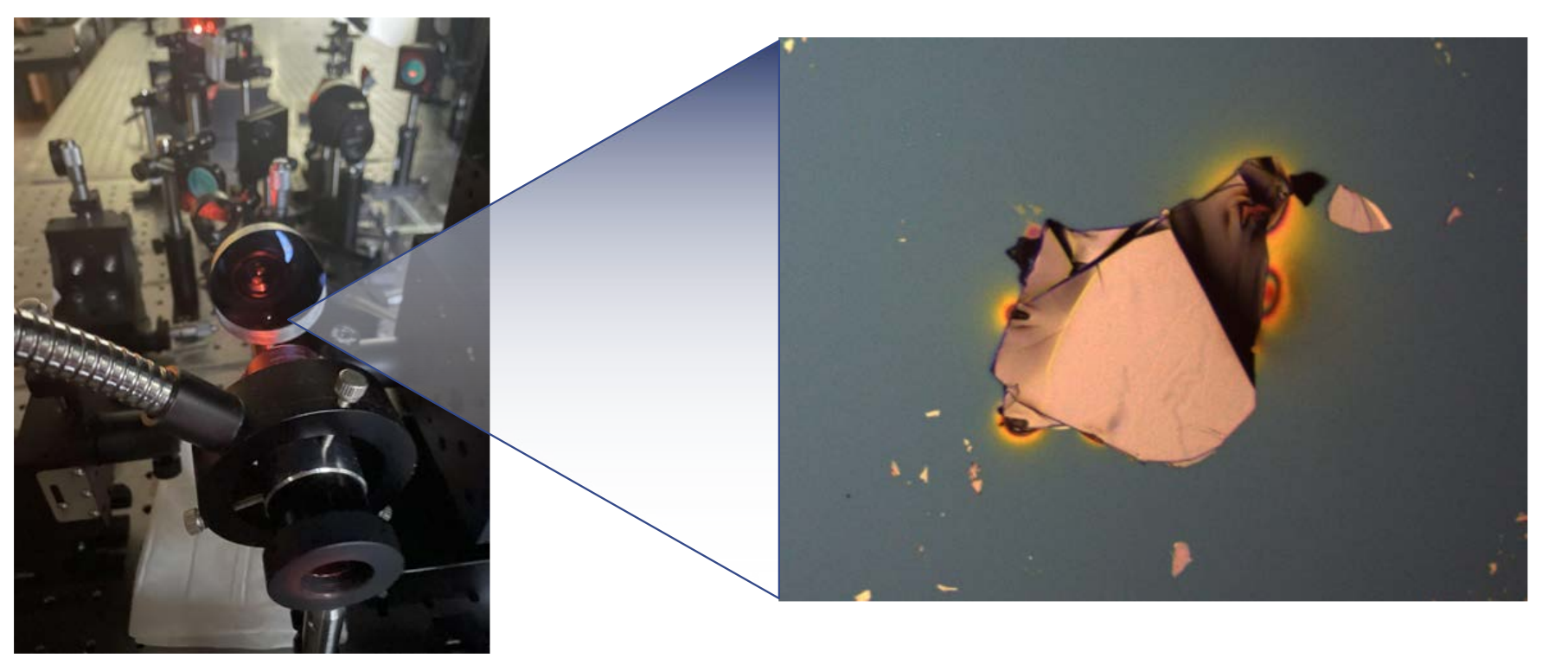


Fig. 1. A sample wafer in the optical setup (left), with a 10x magnified image taken with a Raman microscope of a 780 nm $MoSe_2$ crystal (right).

In order to obtain thermal data, we sputtered a layer of aluminum onto the wafer using a Denton Vacuum Sputter Unit. When a high voltage is applied to the vacuum chamber, a plasma is struck inside the chamber that causes individual atoms to be ejected from the aluminum target. We set the voltage to 150W and allowed the sputtering to run for 5 min in order to reach our target thickness of 70-90 nm[1].

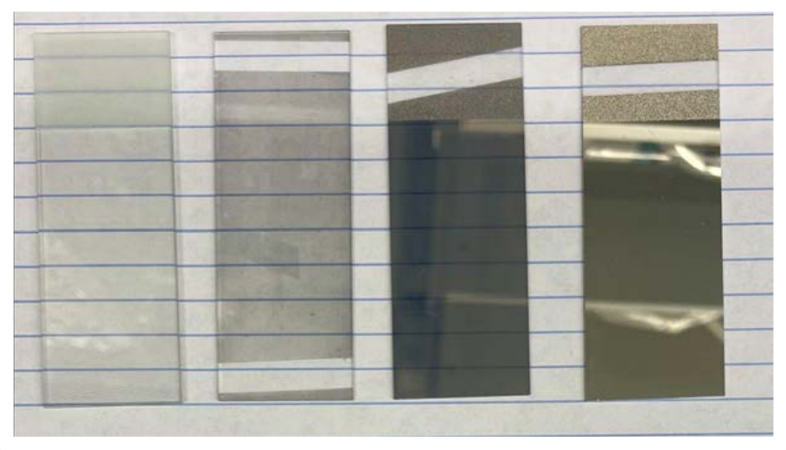


Fig. 2. Sputtering aluminium onto glass sides for increasing lengths of time corresponds with increasing film thicknesses

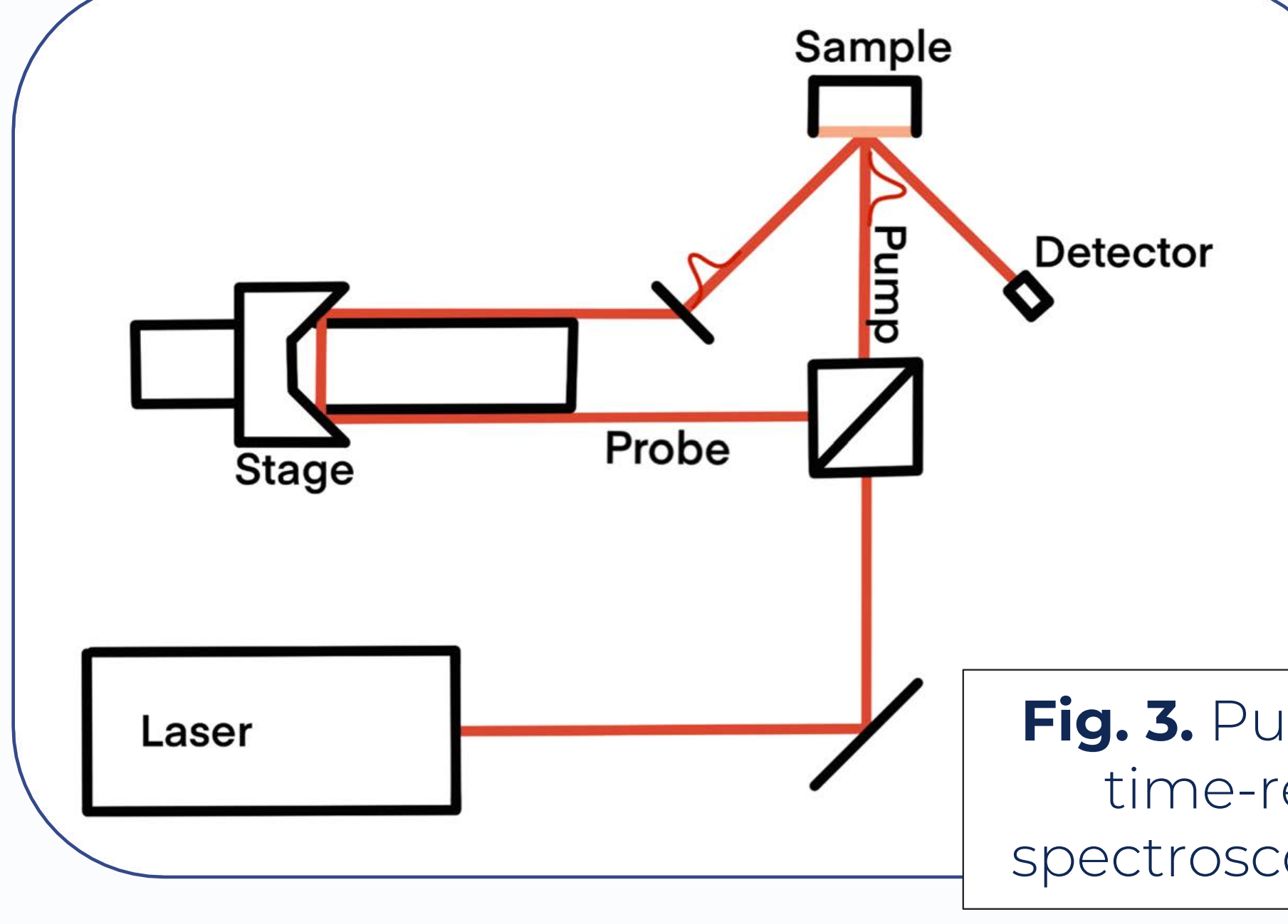


Fig. 3. Pump-probe time-resolved spectroscopy set up.

A Coherent Ti:Sapphire laser generates a stream of picosecond laser pulses, which is split into two beams: pump and probe. When incident on the sample, the pump beam causes rapid thermal expansion and produces acoustic waves in the crystal lattice, while a time-delayed probe beam measures the changes in reflectivity.

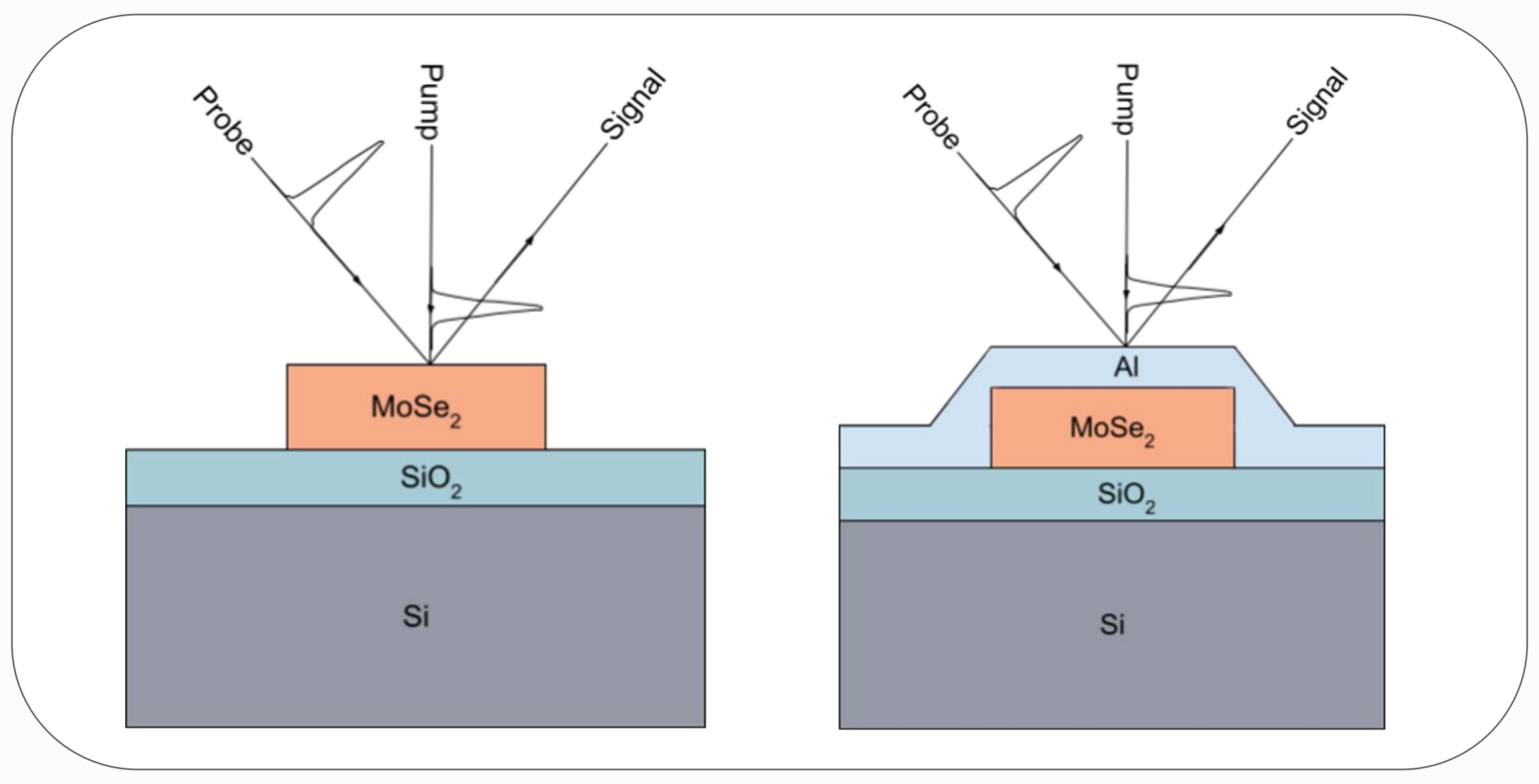


Fig. 4. Vertical cross-section of the material setup for collecting acoustic data (left) and thermal data (right).

Acoustic Measurements

We obtained acoustic data on flakes of $MoSe_2$ and WSe_2 of varying sizes, from 30 to 2300 nm thick. The graphs below are given for a 780 nm $MoSe_2$ flake. WSe_2 gave very similar results.

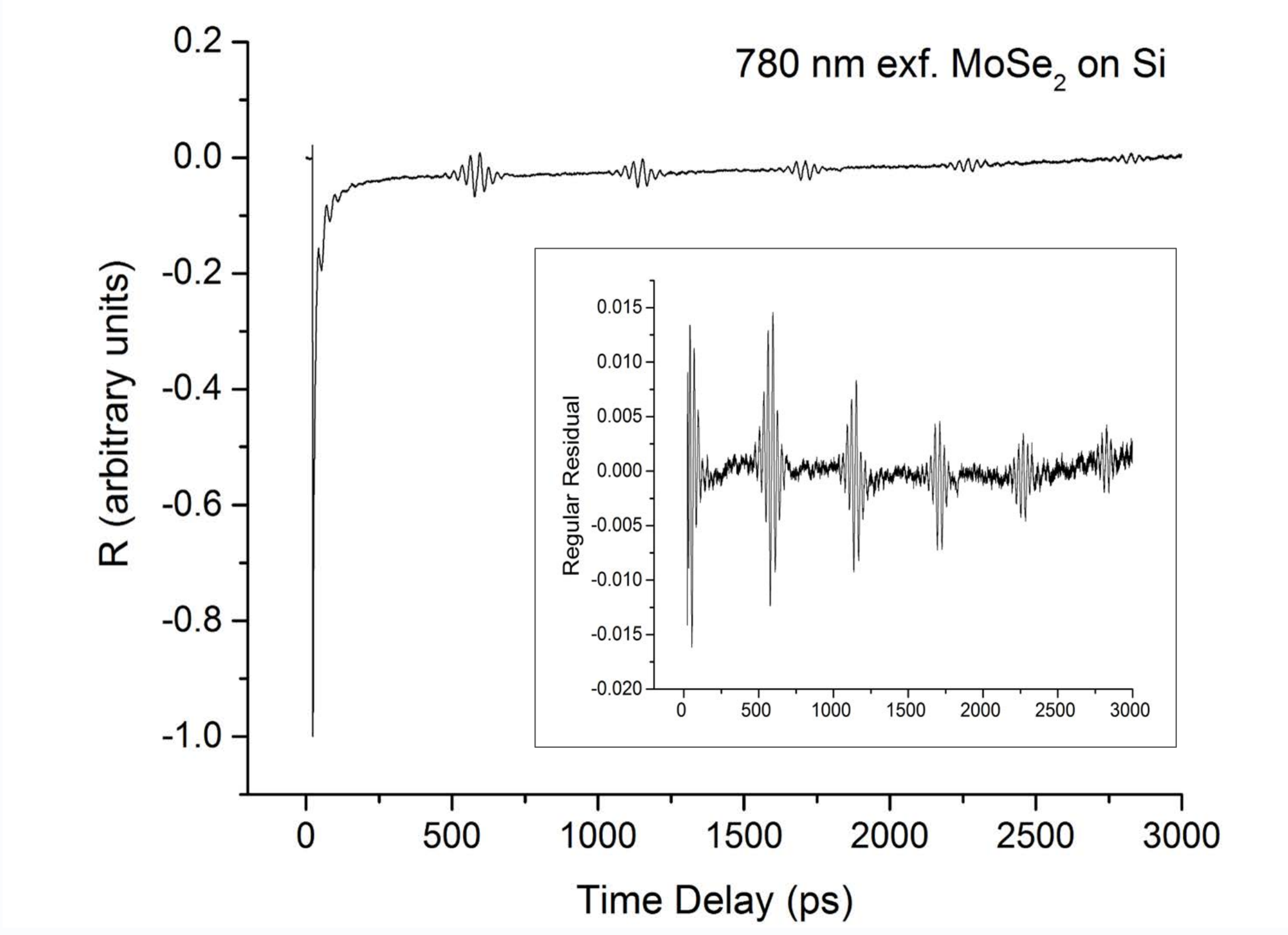


Fig. 5. Acoustic data with residual

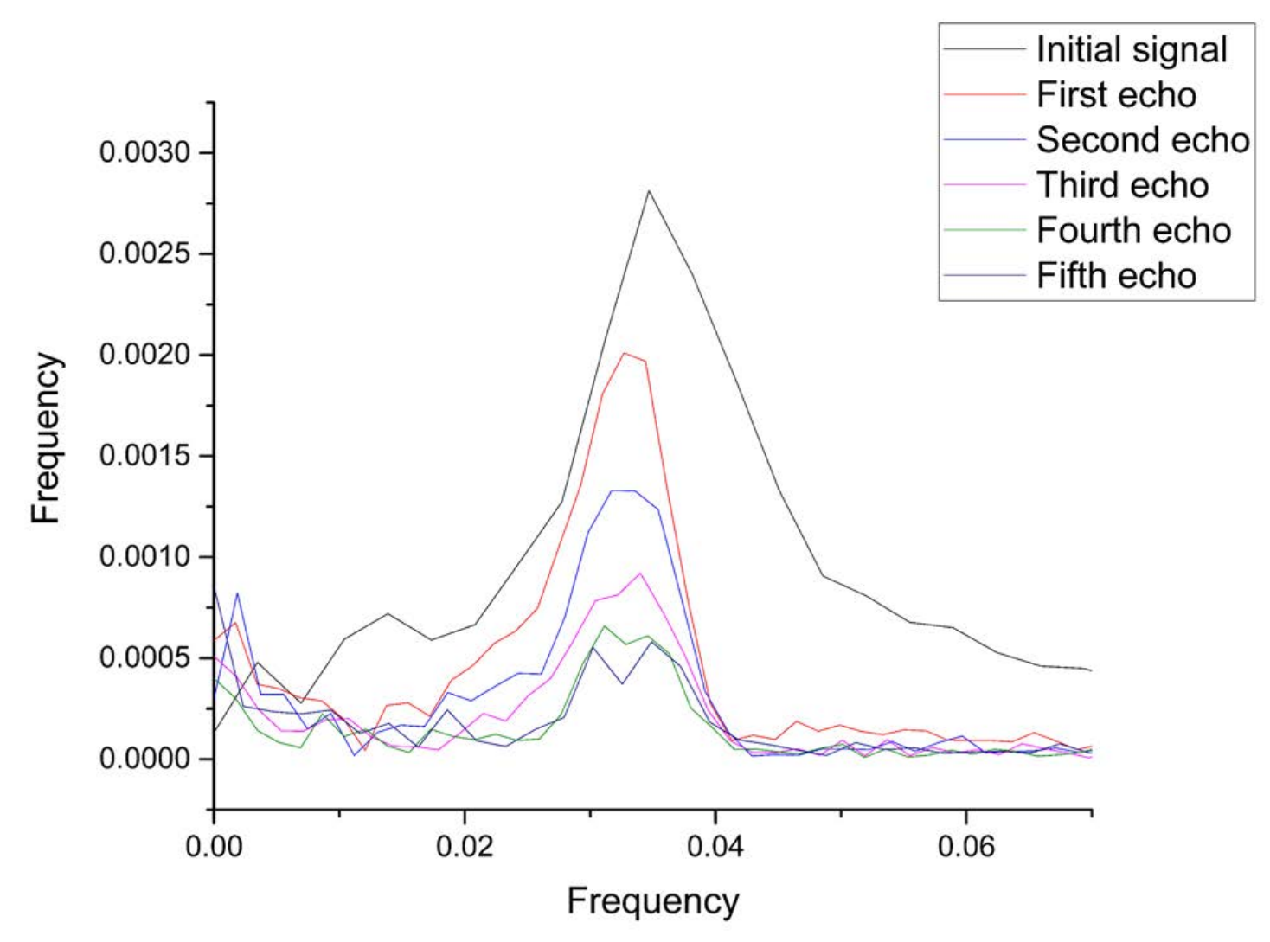
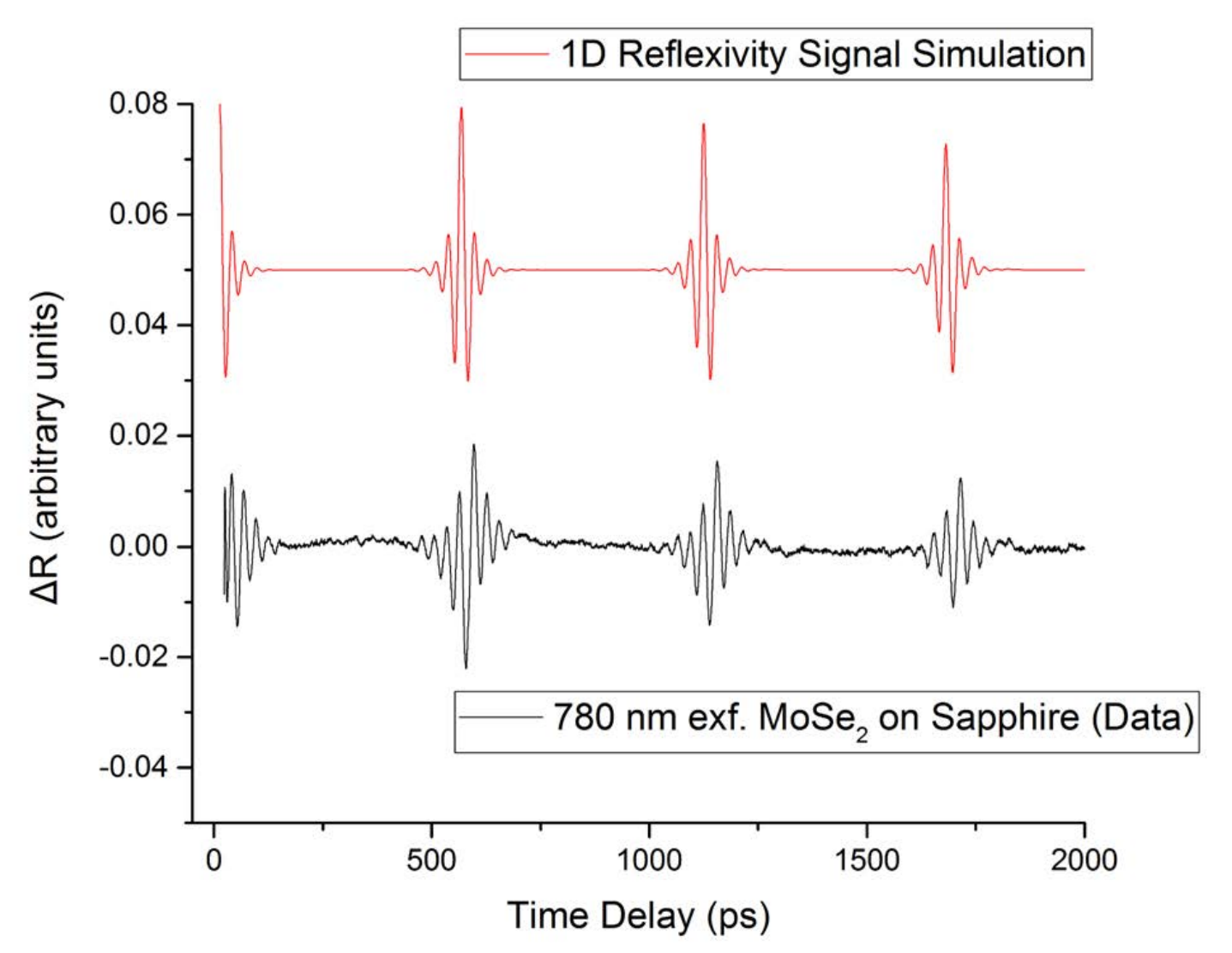


Fig. 6. Fourier transforms of individual acoustic signals display attenuation, as successive signals are reduced

Fig. 7. Residual of the data plotted with an *rt6* simulation of the experiment.



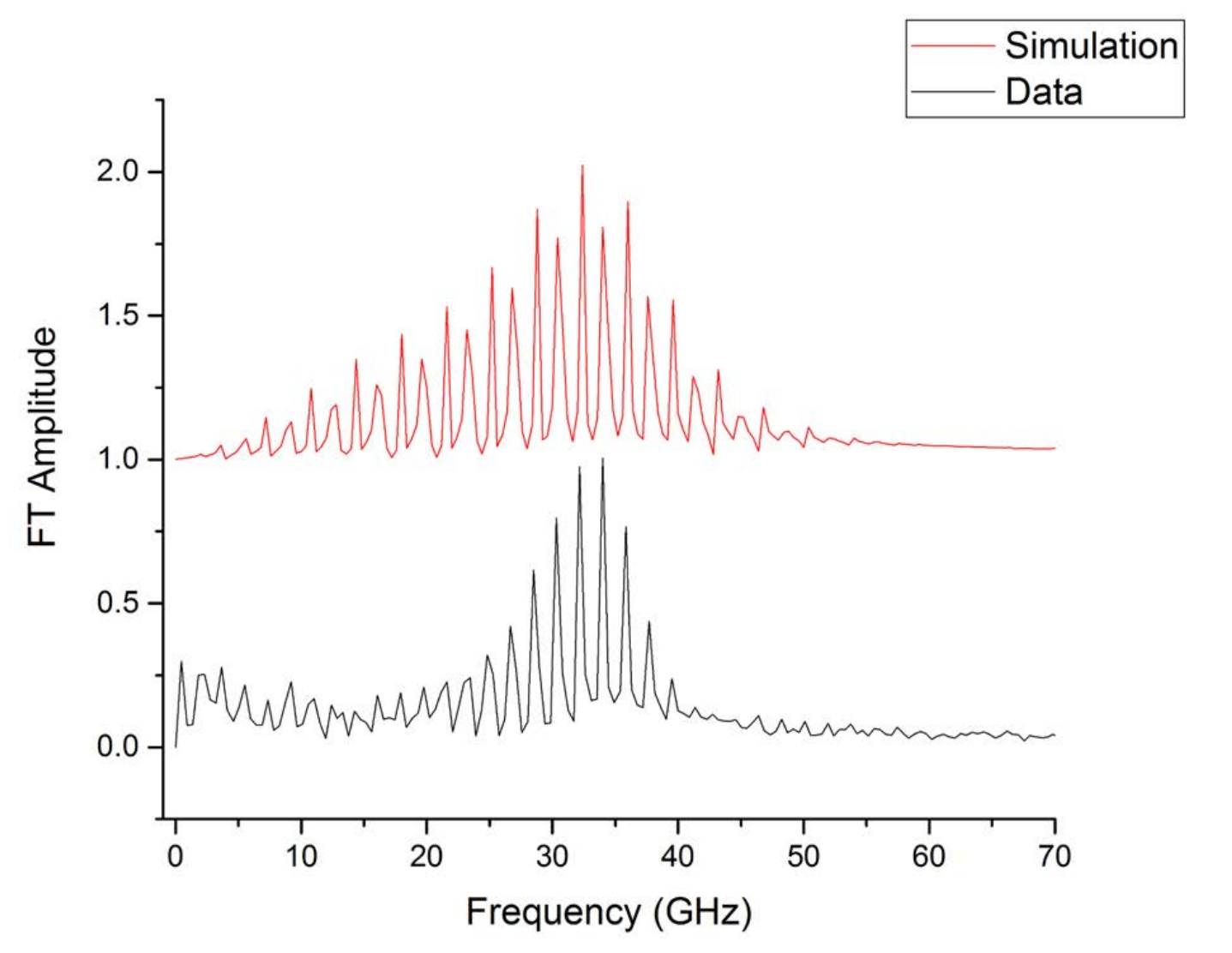


Fig. 8. Fourier transform of the data plotted with an *rt6* simulation of the experiment.

The time between successive transient signals is determined by the acoustic wave round trip time through the sample, directly proportional to thickness. A Fourier transform frequency comb can also be used to calculate the thickness of the crystal, as frequency spacings are approximately $(2d/v_L)^{-1}$, inversely proportional to sample thickness d. We used v_L sound velocities from literature for $MoSe_2$ (2800 m/s)[2], WSe_2 (2500 m/s)[2], and Bi_2Te_2Se (2300 m/s)[3].

Bi_2Te_2Se Results

Bi_2Te_2Se is a semiconducting topological insulator for which many properties remain unexplored. The signals contain fewer oscillations than $MoSe_2$ and WSe_2, revealing strong light absorption properties.

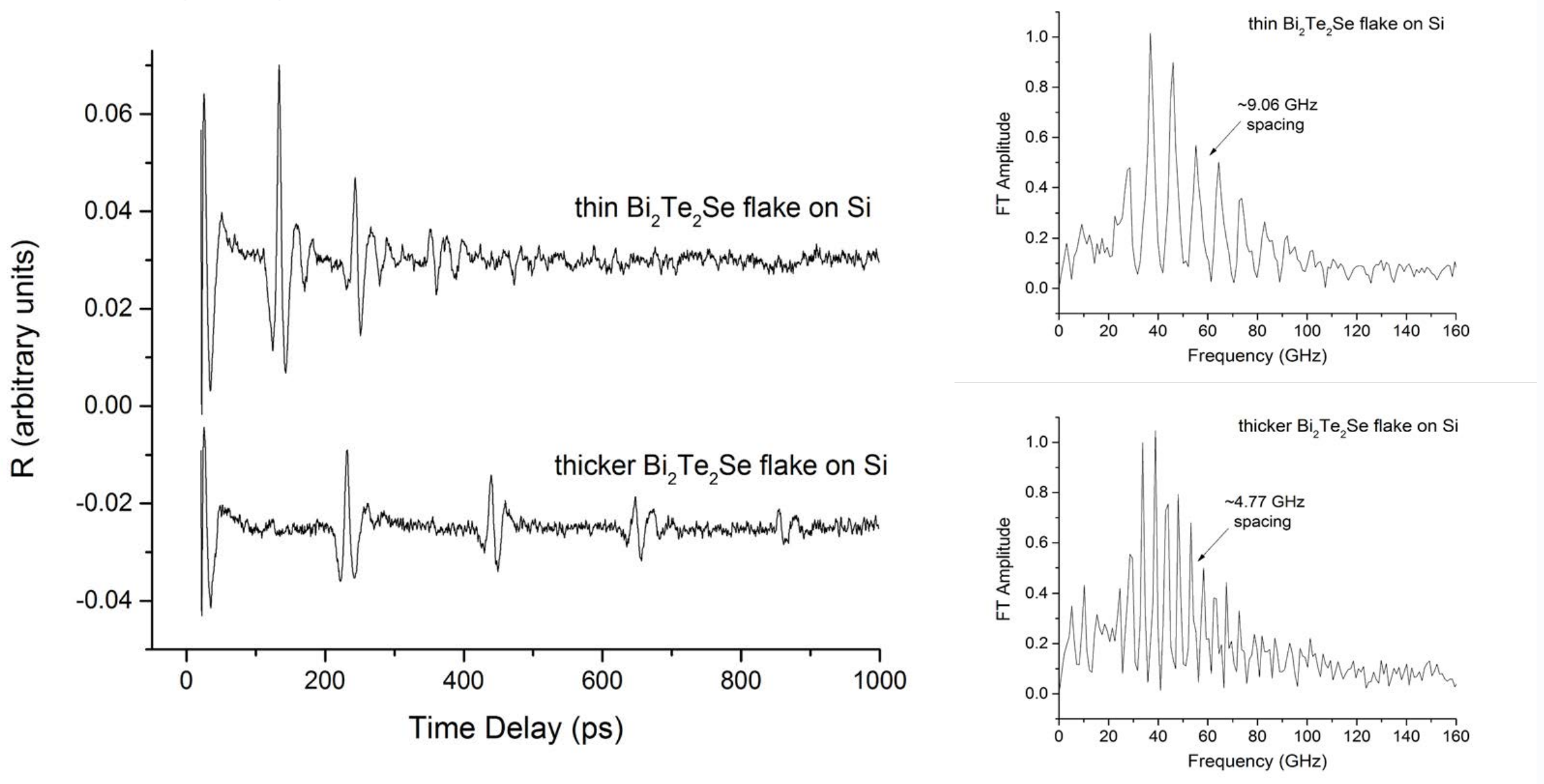


Fig. 9. Exponential fit residuals (left) and FFTs (right).

Thermal Conductivity

After depositing an Al film on the wafer, we repeated pump-probe spectroscopy with a probe time delay to 5000 ps.

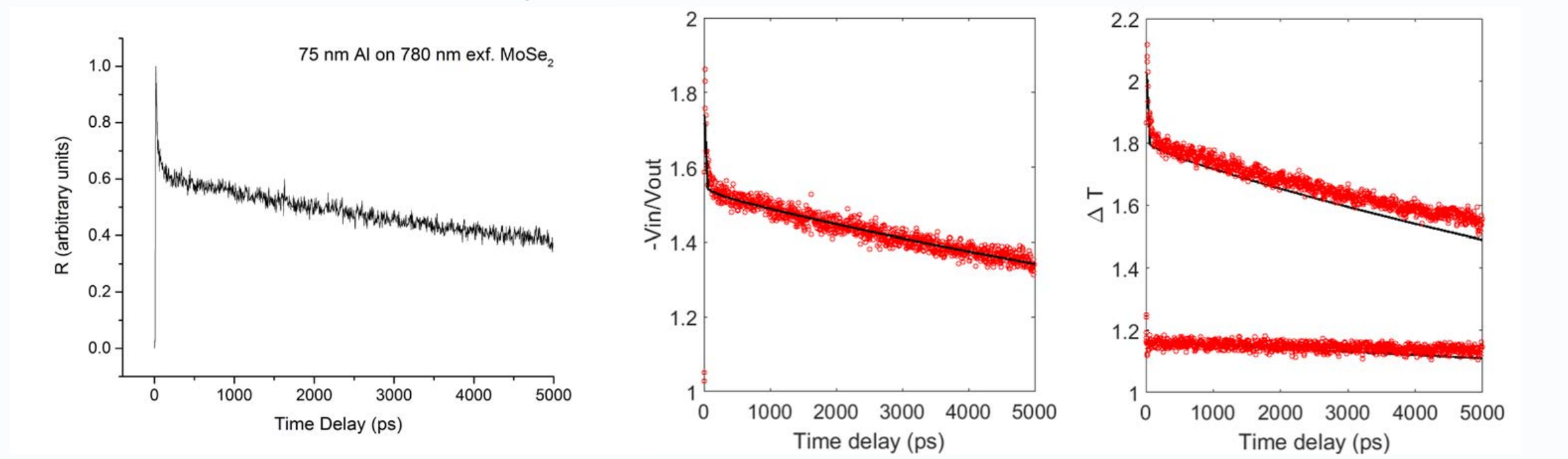


Fig. 10. (a) Thermal data of 780 nm $MoSe_2$ **(b)** Curve fit using Cahill *TDTR* software [4] using constraints for 5 layers: Si substrate, SiO_2, soft layer simulacrum, 780 nm $MoSe_2$, and 75 nm Al film.

The TDTR simulation predicted unreasonable values for soft layer thickness and $MoSe_2$ thermal conductivity. This may be from issues in the experimental setup and/or constraints used in the simulation. Future research will involve re-optimizing the laser setup and continuing simulations to obtain values for the thermal conductivity of $MoSe_2$, WSe_2, and Bi_2Te_2Se.

Acknowledgements

We would like to acknowledge Vassar’s Undergraduate Research Summer Institute as well as Seng-Huat Lee and Ronald R Redwing atPenn State University

References

[1] Manzella, Emma. Using Matlab Simulations to Study Heat Flow in Thin Films. URSI Summary

[2] E. Thompson, et. al., Picosecond laser ultrasonic measurements of interlayer elastic properties of 2H-MoSe2 and 2H-WSe2, Materials Today Chemistry, Volume 18, 2020, 100369, ISSN 2468-5194, https://doi.org/10.1016/j.mtchem.2020.100369.

[3] Rashid, et. al. (2019). Phonon transport and thermoelectric properties of semiconducting Bi 2 Te 2 X (X = S, Se, Te) monolayers. Physical Chemistry Chemical Physics. 21. 10.1039/C8CP05793A.

[4] Cahill, David. “Cahill Research Group,” *Cahill Research Group*, cahill.matse.illinois.edu.

Scan Me! →

UNDERGRADUATE RESEARCH SUMMER INSTITUTE