Photoacoustic Spectroscopy of Energy Gap in van der Waals Crystals

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Transition metal mono- and dichalcogenides consisting of layers bonded by weak van der Waals forces are extensively investigated due to their interesting electronic and optical properties. Materials such as $Mo(S,Se)_2$ and $W(S,Se)_2$ are indirect gap semiconductors in the bulk crystal form, while the size reduction to single atomic layer causes the indirect-direct gap transition verified experimentally by strong photoluminescence. Although most of the reported studies are based on optical characterization of direct excitonic transitions with emission-like methods, i.e. photoluminescence and Raman spectroscopy, measurements of indirect gap for some layered materials are still missing. Optical transmission and reflectance techniques often give inaccurate results of the absorption edge in bulk van der Waals crystals due to unwanted oscillations below the band gap.

In photothermal techniques such as photoacoustic (PA) spectroscopy the signal is generated due to the light absorption leading to nonradiative processes causing periodic pressure fluctuations inside the measurement cell. In this work we have determined indirect gap energies for various layered materials from room temperature PA spectra. In addition, photoreflectance spectroscopy was applied to elucidate blue-shifted direct optical transition energies, similarly as in the previously published work [1]. As a result we provide the experimental data of band gap energy values for both indirect and direct transitions in selected van der Waals crystals.

[1] J. Kopaczek, M. P. Polak, P. Scharoch, K. Wu, B. Chen, S. Tongay, and R. Kudrawiec, *J. Appl. Phys.* **119**, 23 (2016).