MoS$_2$ Bandgap and Photoluminescence

Name: Kenny Chan  
Email: chankenny900@gmail.com  
Glen A. Wilson Class of 2016  
University of Southern California - Department of Electrical Engineering

Introduction

Molybdenum disulfide (MoS$_2$) in its chunk form functions as a semiconductor with an indirect bandgap. The characteristics of this material have been explored and its practicality has been discovered. Due to the indirect bandgap of chunk MoS$_2$, its electrical uses are limited and exhibits weak optical properties. As a result, it is commonly used as a simple dry lubricant or catalyst and has very little application in electrical engineering.

However, with the discovery of graphene's structure, a layer of carbon atoms, scientists began to show interest in creating and examining different types of monolayer materials and fullererenes. When reduced to a monolayer sheet, MoS$_2$ becomes a semiconductor with a direct bandgap. This expands the practicality of MoS$_2$ in electrical components. A direct bandgap allows for greater photoluminescence and improved electrical conductivity, making MoS$_2$ an effective material in sensitive photodetectors and other optoelectrical devices. Controlling and studying the bandgap of MoS$_2$ at different levels of thickness could provide more future applications for the material in upcoming technology.

The research conducted aimed to find trends within the bandgap and photoluminescence of MoS$_2$ at different levels of thickness. Monolayer, bilayer, and trilayer MoS$_2$, along with natural bilayer and folded bilayer MoS$_2$, were tested and compared in order to observe changes in bandgap and peak intensity of light emitted.

Objectives & Impact of Professor's Research

MoS$_2$ was tested using Raman Spectroscopy, and the resulting photoluminescence was recorded as data. The data were studied in order to find trends within the bandgap and photoluminescence of MoS$_2$ at different levels of thickness. Monolayer, bilayer, and trilayer MoS$_2$, along with natural bilayer and folded bilayer MoS$_2$, were tested and compared in order to observe changes in bandgap and peak intensity of light emitted. This research demonstrates that MoS$_2$ can be a potential material in applications such as photodetectors, optoelectronics, and other future technologies.

Materials and Methods

Throughout the research process, many skills were required:

- A strong background in chemistry was required to understand the concept of photoluminescence. For example, the ability to material to release its own light emission after being excited by an external source of energy, such as photons, was explained by using the Bohr Model's quantized energy levels of electrons. This also helped to explain the definition of a bandgap, which is the energy gap between the valence and conduction bands of an atom.

- We used our understanding of standing waves and energy at quantum levels from physics in order to conceptualize the difference between direct and indirect bandgaps. Direct bandgap materials can emit light with the same energy as it absorbed from the incident light source, while indirect bandgap materials need a change in density in order to emit light. We also derived the direct proportionality between the conduction band edge, the valence band edge, and the wavelength of the photoluminescence using our knowledge of physics. This relation was used in our conclusion and helped to explain the trends observed in our research.

How This Relates to My STEM Coursework

Our study on the photoluminescence and bandgap of ultrathin MoS$_2$ applied many of the STEM standards:

- Science, specifically in physics and chemistry, was applied in the conceptualization of the basic principles behind the research. As explained in the previous section, a combination of chemistry and wave physics explained the phenomenon of photoluminescence in direct and indirect bandgap materials. These two subjects also played a role in the proposed explanation of the effect observed in our experiments. As a result, we successfully determined conclusions about the relationship between a material's thickness and emitted light intensity.

- Advanced lab equipment and technology were used to collect data that would be impossible for humans to gather manually. Learning how to operate technology in a lab is an essential component of the STEM curriculum, and in our research, we used a Renishaw Raman Microscope along with its accompanying WiRE software to collect all of our data (figure 1.4).

- Our study focused mainly on electrical engineering. By learning more about the photoluminescence of MoS$_2$, we aimed to expand the opportunities to create smaller, more efficient, and more complex electrical components. Optoelectronics, such as sensitive photodetectors and variable transistors, will benefit greatly by having a new material to add to their complexity.

- Mathematics was applied in order to calculate and measure the results from the Raman Spectroscopy. However, in this situation, most of the calculations were performed by the WiRE software. The results were compiled into graphs that were used in order to accomplish our goal.

Acknowledgements

This research was a great experience for me and my fellow peers. Although most of the information was sophisticated and advanced, it was beneficial and helped me decide what field I wanted to study. The program provided many resources and connections that taught me more about the subject of my research. Improved my understanding of physics and chemistry. It also introduced me to technology that I had previously been unaware of, giving me experience using advanced lab equipment that a high school can not provide.

Skills Used

- A strong background in chemistry was required to understand the concept of photoluminescence. For example, the ability to material to release its own light emission after being excited by an external source of energy, such as photons, was explained by using the Bohr Model's quantized energy levels of electrons.

- We used our understanding of standing waves and energy at quantum levels from physics in order to conceptualize the difference between direct and indirect bandgaps. Direct bandgap materials can emit light with the same energy as it absorbed from the incident light source, while indirect bandgap materials need a change in density in order to emit light. We also derived the direct proportionality between the conduction band edge, the valence band edge, and the wavelength of the photoluminescence using our knowledge of physics. This relation was used in our conclusion and helped to explain the trends observed in our research.

- Advanced lab equipment and technology were used to collect data that would be impossible for humans to gather manually. Learning how to operate technology in a lab is an essential component of the STEM curriculum, and in our research, we used a Renishaw Raman Microscope along with its accompanying WiRE software to collect all of our data (figure 1.4).

- Our study focused mainly on electrical engineering. By learning more about the photoluminescence of MoS$_2$, we aimed to expand the opportunities to create smaller, more efficient, and more complex electrical components. Optoelectronics, such as sensitive photodetectors and variable transistors, will benefit greatly by having a new material to add to their complexity.

- Mathematics was applied in order to calculate and measure the results from the Raman Spectroscopy. However, in this situation, most of the calculations were performed by the WiRE software. The results were compiled into graphs that were used in order to accomplish our goal.

Future Plans and Advice

This research has given me a greater understanding of the work involved in actual college research and the importance of this involved in the field of electrical engineering and 2D materials. As a result, I plan to apply to a multitude of colleges in computer or electrical engineering—such as the University of Southern California or Stanford—to gradually expand my knowledge. In the distant future, I hope to one day be able to conduct my own research at a university, similar to my own experiences at USC. This summer internship was a great experience for me and my fellow peers. Although most of the information was sophisticated and advanced, it was beneficial and helped me decide what field I wanted to study. The program provided many resources and connections that taught me more about the subject of my research, improved my understanding of physics and chemistry. It also introduced me to technology that I had previously been unaware of, giving me experience using advanced lab equipment that a high school can not provide.

Acknowledgements

Dr. Han Wang  
Huan Zhao  
Emerging Photoluminescence in Monolayer MoS$_2$  
Dr. Katie Mills  
Liping Wang  
Leo Slow