Growth and Transfer of 2D Semiconductors and Heterostructures

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Abstract:

Physical vapor transport (PVT) was utilized to grow two-dimensional (2D) semiconductors that can be used in devices such as transistors, LEDs, and solar cells. Molybdenum diselenide ($MoSe_2$), which is in the transition metal dichalcogenide (TMDC) family, was the main semiconductor grown during this study. Limited numbers of papers have been released in which $MoSe_2$ monolayer crystals have been grown via PVT. In this study, $MoSe_2$ and other TMDC thin flakes are grown onto a SiO_2 on silicon substrate in a high-temperature furnace using PVT. Monolayer crystals were distinguished and characterized by optical imaging, photoluminescence measurements, and atomic force microscopy. By spin-coating poly(methyl methacrylate) (PMMA) onto the growth substrate, we were able to transfer the as-grown samples successfully. The PVT methods explored in this study can be further developed to create either lateral or vertical heterostructures between different monolayers.

Introduction:

Two-dimensional (2D) semiconductors have been studied extensively in recent years, as their 2D nature can make semiconductor properties easier to control. Along with their unique characteristics, 2D semiconductors are more flexible and cheaper to produce than traditional semiconductors [1]. Following the exfoliation of graphene that won the Nobel Prize in 2010, further methods of creating 2D semiconductors were developed to improve semiconductor yield and accelerate production of viable results [1]. Graphene, lacking a naturally existing band gap, began to be looked past for use in electronic devices due to the necessity of a band gap [1, 2]. Transition metal dichalcogenides (TMDCs) are 2D materials with an existing band gap having electrical properties that can improve upon graphene. Exfoliation via the Scotch tape method has proven successful for the creation of monolayer TMDCs, however the process is also time-consuming and yields few viable 2D semiconductors quickly [2]. PVT has emerged as a new technique for synthesizing 2D materials in a more time-efficient manner.

PVT involves the use of a high-temperature furnace to deposit crystalline monolayer materials onto a substrate. TMDCs have a hexagonal lattice with the form MX_2 ("M" being a transition metal and "X" a chalcogenide) [3]. Molybdenum diselenide ($MoSe_2$) and tungsten diselenide (WSe_2) are two TMDCs explored due to their ideal band gap for electronic circuit applications. $MoSe_2$ in particular has a direct band gap of 1.5 eV as well as a drastic photoluminescence change when in monolayer form, making it suitable for use in LEDs and solar cells [2]. Finding a consistent method for creating monolayer TMDCs can have various useful electronic applications.

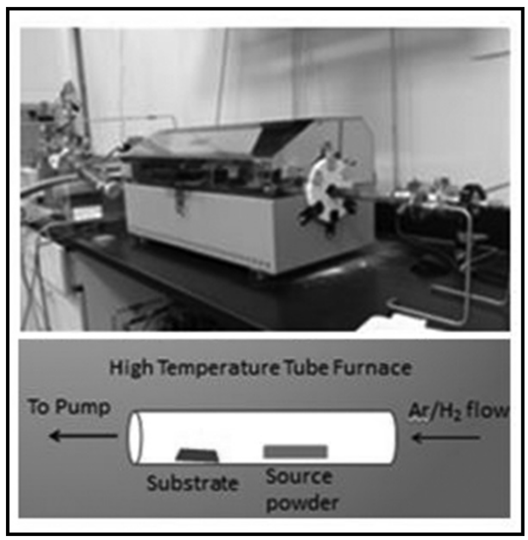

Figure 1: (a) PVT furnace setup used to grow TMDCs. (b) Diagram of setup within furnace

Methods:

Using the setup shown in Figure 1, monolayer $MoSe_2$ was grown. A mixture of $MoSe_2$ and MoO_3 powder was placed inside the furnace as the source. SiO_2 on an Si substrate was placed upstream from the source powder in a temperature gradient. The furnace was steadily heated to a growth temperature of between 830 and 900°C at 100 millitorr. Once the maximum

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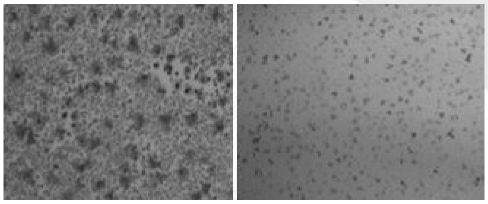

Figure 2: (a) Monolayer and bilayer $MoSe_2$ growth. (b) Monolayer triangular growth.

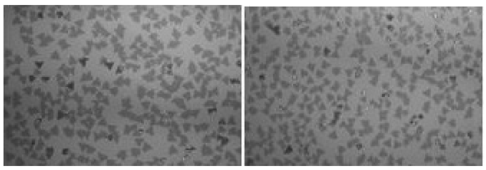

Figure 3: (a) Pre-transferred growth. (b) Post-PMMA transferred growth on new substrate.

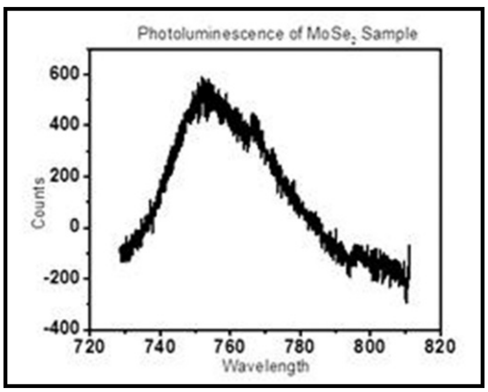

Figure 4: PL Spectrum of $MoSe_2$ sample.

temperature was reached, argon and hydrogen gas were flown for five minutes at 70-100 sccm and 10-27 sccm, respectively. Following the growth period, the furnace was steadily cooled to room temperature.

Monolayer $MoSe_2$ was successfully grown, however results were inconsistent. Photoluminescence (PL) measurements verified the presence of monolayer crystals; however the PL peak was shifted from an expected $MoSe_2$ peak. Crystalline triangles of monolayer $MoSe_2$ were found at multiple parameters, but results were not repeatable. We attributed the PL peak difference to crystalline impurity due to growth parameters not being optimized.

Improving upon growth parameters will lead to more reliable results that can vastly improve upon exfoliation with regard to monolayer yield. Increasing the triangle size will also improve our ability to use monolayer $MoSe_2$ in devices.

Monolayer TMDC growth was transferred off the growth chip by spin-coating PMMA and etching in 1 M KOH solution. A thin film of PMMA containing growth was transferred onto a new substrate and cleaned with a series of solvent baths. Although optical microscopy verified the success of PMMA transfer, AFM images exposed impurities in transferred growth. In the future, dry transfer methods will be explored that cause less damage to the growth.

Conclusions and Future Directions:

Monolayer $MoSe_2$ was successfully grown, however results need to be replicated to make these 2D semiconductors viable. Triangular crystals need to be optimized so that they are large enough for utilization in devices, as $MoSe_2$ has highly attractive electronic properties. With the development of successful monolayer growth, establishment of an effective dry transfer technique can help create vertical heterostructures between TMDC monolayers that are necessary for devices. Similarly, using PVT and known parameters for other TMDCs, lateral heterostructures may be grown between 2D materials with similar lattice structures [3], which would create a 1D quantum wire with interesting electronic properties [4].

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