Synthesis, Device Fabrication, and Characterization of Two-Dimensional Transition Metal Dichalcogenides

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Abstract:

Semiconducting two-dimensional transition metal dichalcogenides (TMDs), in particular molybdenum disulfide (MoS_2) and tungsten diselenide (WSe_2), have been the focus of intense research in recent years for their potential use in next-generation, scaled down electronic and optoelectronic devices due to their unique chemical, optical, and mechanical properties. TMDs are an excellent material candidate to replace silicon in digital CMOS technology, yet there still exists a need for optimized device fabrication and a scalable growth process for controllable large area, single-crystalline films. This project focused on two main objectives: WSe_2 device fabrication for Hall mobility measurements and the construction of a new metal organic chemical vapor deposition (MOCVD) system for advanced material synthesis of MoS_2. Van der Pauw structures were fabricated by photolithography, inductively coupled reactive-ion plasma etching, and metal thin film deposition by e-beam evaporation. Devices were fabricated on several WSe_2 samples of varying morphology and were characterized by field emission scanning electron microscopy, profilometer, and Raman spectroscopy. A fully functional MOCVD system equipped with metal organic precursor "bubbler" chambers was designed and fabricated to be used for synthesis of MoS_2.

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Introduction:

Mono- and few-layered WSe_2 devices possess properties such as transparency, high flexibility, direct or indirect bandgap, high I_{ON}/I_{OFF} ratio, near-perfect subthreshold swing, and high field effect mobility [1]. This material, if proven scalable and robust to conventional nanofabrication techniques, could yield a more efficient, low cost and high quality semiconductor material for industrial fabrication. We used standard photolithography to make three types of devices to test this.

Mono- or few-layered TMDs have been predominantly obtained by mechanical exfoliation from bulk crystals or powder precursor CVD. Mechanical exfoliation is not a high-throughput, scalable method while powder precursor CVD has issues precisely controlling layer thickness, uniformity, island growth, grain size, and unwanted deposition of metallic or metal oxide particulates. Modifying the currently used powder precursor CVD to a MOCVD system would greatly reduce these issues and also be compatible with existing silicon microelectronics manufacturing.

Experimental Procedure:

An exposure mask for the lithography process was designed using L-Edit, a computer aided design software, and fabricated by a laser writer. The created mask contained the layout for three devices; dual gated radio frequency field effect transistors (FET), van der Pauw structures (vdP), and transmission line measurement devices (TLM). Three successive iterations

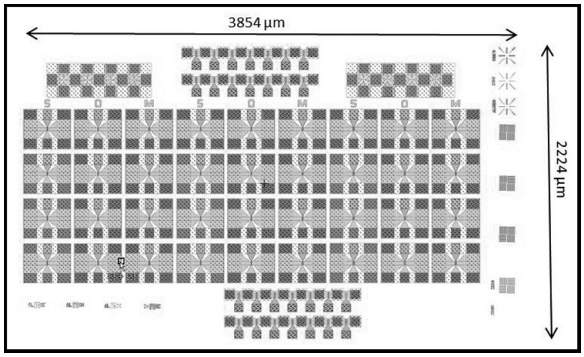

Figure 1: Exposure mask device design layout.

of photolithography were performed in order to fabricate the following layers: alignment mark layer, isolation (WSe_2 etch) layer for defining the active channel regions, and ohmic (source/drain) layer to define the contacts. A bilayer resist stack was used for lift-off of both alignment mark and contact layers. Ten nanometers of titanium (Ti) and 100 nm of gold (Au) were deposited using e-beam evaporation. A single resist layer was used for the isolation layer, and an oxygen based dry etch was successfully developed.

Constructing the MOCVD system consisted of common metal assembly tasks such as tightening bolts, joining brackets and drilling screws to assemble the frame and fasten the gas panel components. The gas lines were fully purged and evacuated

before orbital welding was performed to route the gas lines to the furnace and create a higher quality smoother weld bead. The switch box was wired by both soldering and terminal block connectors.

Results:

After each layer, devices were examined by optical microscope and field-emission scanning electron microscope (FESEM). Fortunately, WSe_2 films that are bonded to the substrate by van der Waals forces remained on the substrate even with exposure to various solvents and chemicals throughout processing, which is reassuring for future device fabrication. The majority of the devices had a visible, defined channel region shown in Figure 2. However, each device had a lack of continuous coverage in the WSe_2 channel region also shown in Figure 2, which obviates the need for more uniform, wafer-scale TMD growth.

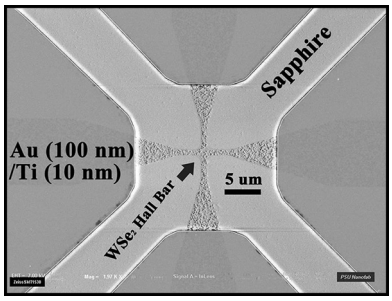

Figure 2: Finished vdP device.

A fully functional MOCVD system was designed and built, shown in Figures 3 and 4. Over 150 parts/components were ordered to create the three bubbler input system allowing multiple metal organic precursors to be used in TMD synthesis. Each bubbler has a mass flow controller and three pneumatic actuators controlled by the switchbox. Each bubbler temperature can be controlled individually by the temperature read-outs on the right side of the switchbox. The user is protected by the fully ventilated sheet metal and Plexiglass® sliding door enclosure.

Conclusions:

WSe_2 proved to be a robust and compatible material for scalable device nanofabrication. In addition, it was found that WSe_2 is easily etched by an oxygen plasma and remains on the substrate throughout the fabrication process.

Even though the measurements were not taken from the vdP devices, the fabrication steps to making the devices will help future WSe_2 research. Scientific investigators can continue to use the exposure mask and fabrication steps knowing they can achieve functioning devices if coalesced and continuous WSe_2 films are successfully grown.

The new MOCVD system will contribute to future molybdenum disulfide (MoS_2) research for many years to come. The system will allow the operator to precisely control various parameters of material synthesis to create uniform films. Readouts will give an exact flow rate for each bubbler and precursor allowing for easier repeatability and reliability. Ultimately, the new system will aid in the synthesis of uniform, large-area MoS_2, which will not only assist in device fabrication within the group, but also shed light on MoS_2 integration in manufacturing.

Acknowledgments:

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References:

[1] Z. Weijie, et al., "Evolution of Electronic Structure in Atomically Thin Sheets of WSe_2 and WSe_2"; arXiv. Org, Cornell University Library.

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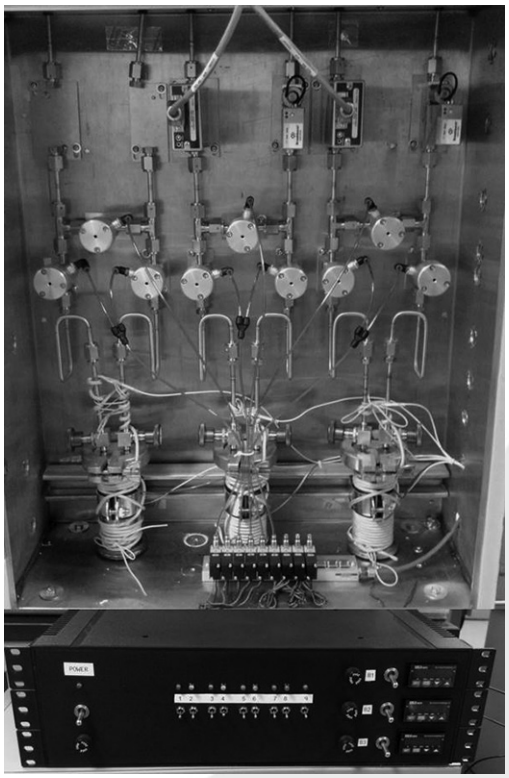

Figure 3, left: Finished MOCVD gas panel and switch box. Figure 4, right: Fully ventilated protective enclosure.