"Beyond graphene" is a field of science that has attracted tremendous attention in recent years. From phosphorene to transition metal dichalcogenides (TMDs), these novel materials possess fascinating electrical, mechanical and tribological properties. To study these materials in the monolayer form, scientists most commonly rely upon mechanical exfoliation for sample production, a low yield and repetitive method that slows the pace of experiments. There is a genuine need for reproducible growth methods for high quality monolayer materials that could enable comprehensive studies of their unexplored properties and potentially scalable fabrication of novel devices and circuits. In my presentation I will discuss our recent progress in the field “beyond graphene” and more specifically the growth by chemical vapor deposition (CVD) of monolayer TMDs in different atomic configurations (1H and 1T’ phase) and their application as biosensors.

We have developed a reproducible CVD growth method for monolayer single crystal MoS$_2$ and WS$_2$ flakes in the 1H phase. The flakes are n-type semiconductors with reasonable values of mobility, high on/off ratio and a tunable band gap dependent on the layer number. Using a patterned growth technique, we can predetermine the growth location of MoS$_2$ flakes (figure 1a) in desired structures, for example “NBIC @ UPENN” consisting solely of monolayer MoS$_2$ flakes (figure 1b). Patterned growth of MoS$_2$ provides a feasible pathway towards growth of arrays of MoS$_2$ flakes at precise locations suitable for fabrication of scalable arrays of compact MoS$_2$ FETs (figure 1c).

We extended this growth process for high quality monolayer MoS$_2$ to high-yield production of MoS$_2$-based nano-biosensor devices. We have incorporated monolayer MoS$_2$ into scalable arrays of highly sensitive sensors for enkephalin (figure 2ab). Natural enkephalins are endogenous opioid pentapeptides involved in pain perception, cognitive functions, affective behaviors and locomotion. We have also studied the remarkably large responses of MoS$_2$ based sensors to various vapor analytes. Using the Transmission Line Measurement (TLM) approach, we quantified the intrinsic MoS$_2$ contribution to the sensor response and that due to the contact resistance. These sensors are currently being incorporated into wearable/flexible formats on plastic substrates (figure 2c).

Chemical functionalization procedures for graphene and TMDs (e.g., MoS$_2$) reported to date differ dramatically due to their divergent surface chemistries. A universal chemical functionalization scheme for any given 2D material is highly desirable but fundamentally challenging. We have resolved this issue by developing a universal functionalization scheme based upon a heterostructure of two-dimensional materials. This heterostructure performs admirably as a biosensor, with high yield, excellent reproducibility, and low concentration detection limits.

Monolayer MX$_2$ materials manifest in 3 different atomic configurations referred to as 1H, 1T and 1T’ (figure 3a). The 1H phase is highly symmetric, typically air stable, and the most commonly studied phase to this point. The 1T phase differs from the 1H phase by a rotation of the top layer of chalcogenide atoms with respect to the bottom layer so that as viewed along the c-axis, the chalcogenide atoms form a hexagon around the metal atom. The 1T’ phase is created by a distortion of the 1T phase and has attracted high interest due...
to theoretical predictions that it supports non-trivial topological electronic states. It has been proposed that monolayer 1T'-MX$_2$ compounds are large-gap quantum spin Hall insulators, making them promising for applications in novel switching devices, spintronics, and quantum computation. Experimentally the 1T' phase is extremely challenging to achieve and difficult to isolate by exfoliation in the monolayer form due to its high instability in air. We recently reported successful growth and study of CVD grown monolayer 1T'-MoTe$_2$. Aberration-corrected scanning TEM (ACSTEM) images confirm the atomic distortion that differentiates the 1T from the 1T' phase (figure 3b), and initial electrical data suggest a weak antilocalization effect in the material. We applied a related growth process to produce monolayer 1T'-WTe$_2$ which enabled experiments probing its degradation process in air. We also developed novel encapsulation methods to stabilize the 1T' materials and enable multiple characterization measurements of this phase.

Through reproducible growth methods we are able to grow a variety of monolayer MX$_2$ materials by CVD. We incorporated the 1H-MX$_2$ materials into scalable bio and vapor sensors and onto flexible substrates. We were able to grow materials in the 1T' phase and perform initial studies on monolayer 1T'-MX$_2$ materials with compelling ACSTEM images revealing the distorted phase.

**References**

[3] Carl H. Naylor et al., In prep.

**Figures**

**Figure 1:** MoS$_2$ pattern growth. a) Schematic of the growth process for MoS$_2$ using patterned molybdenum source. b) Optical micrograph of MoS$_2$ flakes grown at locations that form NBIC @ UPENN. Scale bar, 100 μm. c) Schematic of scalable MoS$_2$ FETs by pattern growth technique.

**Figure 2:** MoS$_2$ biosensor. a) Photograph of the electrode array chip. Optical micrograph showing interdigitated electrodes corresponding to a set of 10 sensors, scale bar 500μm and 10μm respectively. b) MoS$_2$ structure and functionalization schematic. c) Photograph of scalable flexible MoS$_2$ biosensor.

**Figure 3:** 1T'-MoTe$_2$. a) Ball and stick model displaying all three phases of TMDs. b) ACSTEM image of as grown 1T'-MoTe$_2$ and the simulation are in good agreement, scale bar is 1nm.