Using Electron Microscopy to Analyze Two-Dimensional Materials and Their Junctions

[1] David Muller: [1] Yimo Han (Mentor), [2] **Mark Marsalis** (REU Intern)

[1] Applied Engineering and Physics Department, Cornell University
[2] Department of Physics, Texas Tech University

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Abstract

Electron microscopy techniques have helped us examine two-dimensional materials such as graphene and MoS2-WSe2 monolayers. With transmission electron microscopy (TEM), we were able to study graphene grains at a large scale, and implementing dark field (DF) TEM, we were able to analyze the graphene grain orientations and grain boundaries. With high-atomic resolution images collected through scanning transmission electron microscopy (STEM), we were able to distinguish different atoms (Mo, W, S, and Se) throughout the interface with a contrast proportional to the atomic number squared (Z^2). We applied STEM to study the monolayer MoS2-WSe2 lateral junctions, and we have observed defects, more specifically dislocations, found at the head of these newly formed MoS_2 nanowires. After statistically analyzing these nanowires, we found the width remained, on average, less than ~2 nm, independent of length. With these electron microscopy techniques, we can further investigate the grain structure or nanowire formation within two-dimensional materials.

DF-TEM of Graphene

To observe two-dimensional materials, especially graphene, we use transmission electron microscopy (TEM). In TEM, electron beams are deflected by magnetic lenses, resulting in parallel beams that are perpendicular to the sample shown in Fig. 1. While spanning a large region, some electrons are reflected, deflected, or travel through the material, depending on the sample density. Some electrons that travelled through graphene produced a diffracted (scattered) beam, and we processed a dark field (DF) image, and then obtained a diffraction pattern for that region. With DF-TEM, the objective aperture selects a portion of the outer-ring diffraction pattern, even though it is the same region, a dark field image will appear slightly different at different aperture placements shown in Fig. 2.

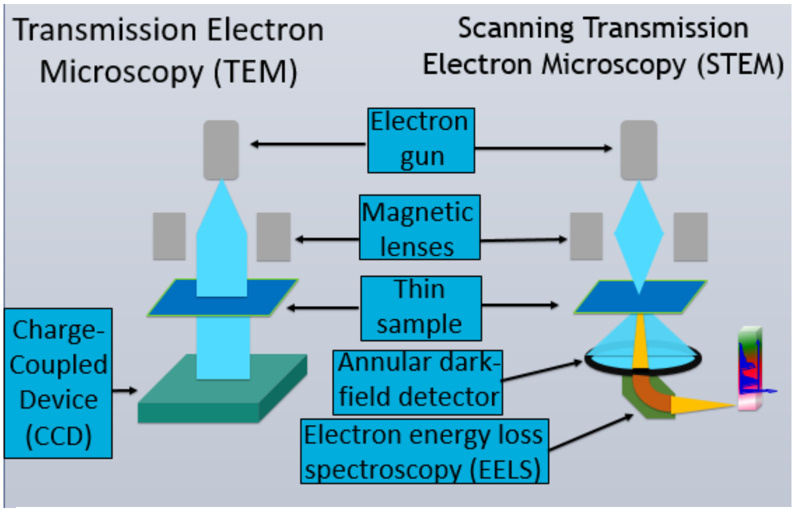

Figure 1:Schematic of TEM and STEM.

This contrast is given by Bragg’s Law, which states, an electron will interact with a crystal lattice and be deflected at an angle determined by the spacing and orientation of the atomic planes in the crystal, therefore, some electrons will be collected in one aperture as opposed to another, giving us slightly different images that reflect the different orientation of the local lattice.

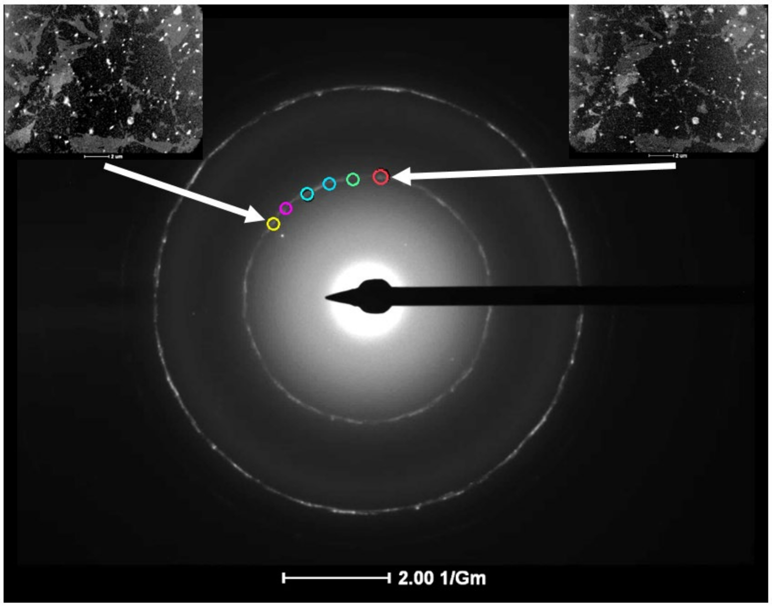

Figure 2DF-TEM diffraction pattern of graphene with DF images (inserts) correlating to specific aperture placements (circles).

Under DF-TEM, graphene grain boundaries and orientations can be examined. Grain boundaries are lines of defects or dislocations that separate different grain orientations, which refer to the grain size, shape, and lattice orientation. To see all the grain orientations and boundaries, we created false-color composite images of graphene in correlation to specific aperture placements on the diffraction pattern (figure not shown).

STEM of MoS2-WSe2 Junction

For MoS2-WSe2 monolayers, we gathered high-atomic resolution images through scanning transmission electron microscopy (STEM), and we're able to see individual atoms (Mo, W, S, and Se) within the lattice. STEM works similarly to TEM, but the electron beam is deflected onto a small atomic-scale region on our sample. After interacting with the sample, the electron beam behavior is similar to TEM, but, shown in Fig. 1, electrons are collected by an annular dark field (ADF) detector, producing ADF-STEM images. Simultaneously, we use electron energy-loss spectroscopy (EELS) to collect stray electrons that were not gathered by the ADF detector, and this identifies elements and other local information like atomic dimensions or electronic structures. Then, a high-atomic resolution image is produced with a contrast that is proportional to the atomic number squared (Z^2).

After observing the high-atomic ADF-STEM images of MoS2-WSe2 junctions, we found MoS2 nanowire formations within WSe2 shown in Fig. 3. In Fig. 3
we found dislocations at the head of these nanowires. From these images, we compiled a data set for the number of nanowires found at the interface, and gathered statistics regarding nanowire dimensions. The histogram in Fig. 4 shows a Poisson distribution, and we found the most reoccurring length was ~5 unit cells. In Fig. 4 (insert), we observed that ~93.3 ± 9.66% of the nanowires did not exceed an average width greater than ~6 unit cells, regardless of length, but we're unsure what caused some nanowires to grow beyond this width, and more data is required for an accurate percentage.

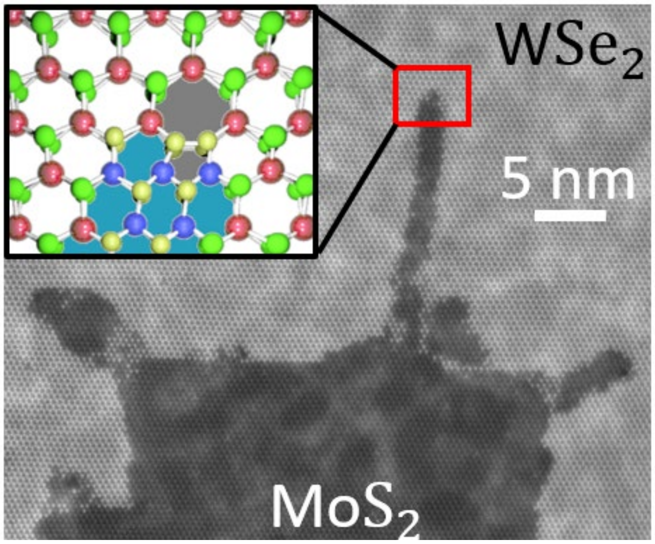

Figure 3Figure 3STEM image of MoS2-WSe2 junction with an insert showing a dislocation schematic.

Figure 4:

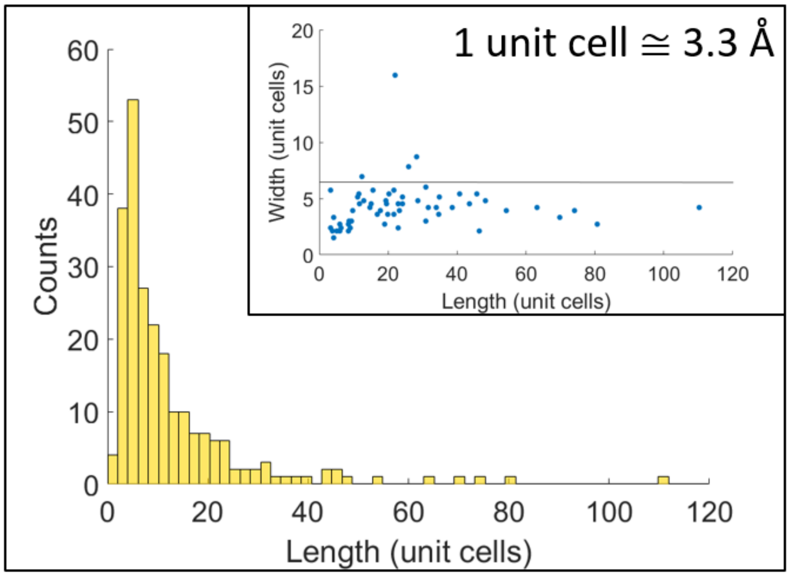

Figure 4Nanowire statistics show a histogram of the length and scatter plot of length versus width (insert).

Conclusion

For our research, TEM was shown to be more efficient for observing large scale areas of graphene while STEM was better suited for atomic scale observation of MoS_2-WSe_2 lateral junctions. DF-TEM was useful in the analysis of graphene grain boundaries and orientations. With atomic resolution ADF-STEM, we examined monolayer MoS_2-WSe_2 lateral junctions, and detected MoS_2 nanowires with dislocations present at the head. We gathered statistics for the nanowires and found the most frequent length was ~5 unit cells, and ~93.3 ± 9.66% of the nanowires exhibited a width less than ~6 unit cells regardless of length, but more data is needed for an accurate percentage. We hope to further understand how and why these nanowires formed at the MoS2-WSe2 junction in order to better predict their behavior. In the future, we can envision using similar microscopy techniques to study other two-dimensional materials.

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