Activity report for MERIT internship

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This is an activity report for MERIT internship in University of Washington, Department of Physics, Xiaodong Xu lab for three months starting from the end of Oct 2022. The purpose of this internship is to learn the advanced device fabrication and optical measurement system building-up skills for the research on two-dimensional magnets and heterostructures. My research theme during the internship is the optical properties of 2D magnets and heterostructure.

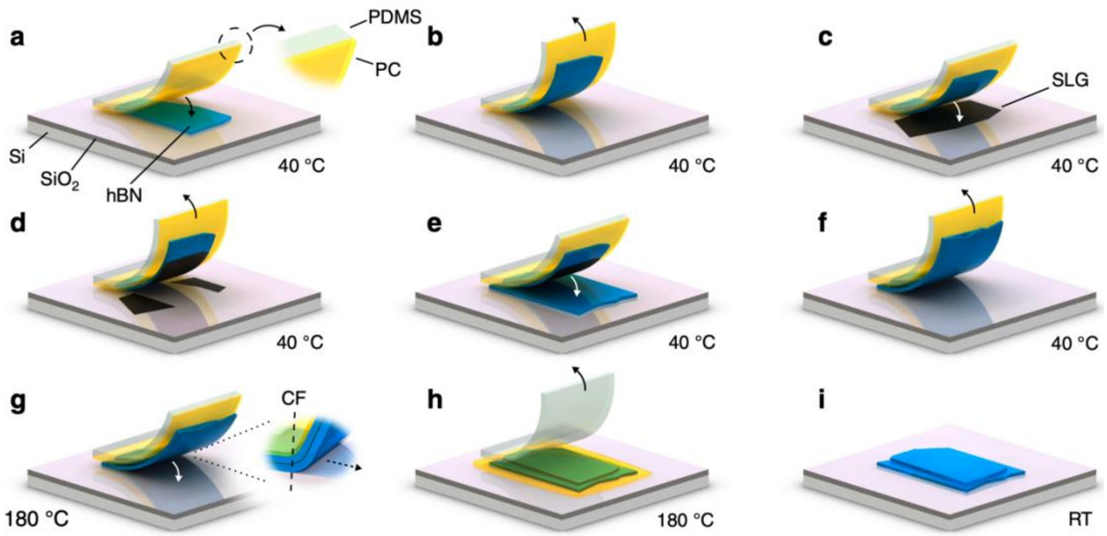

Figure 1. Schematics of pick-up technique. From **a** to **f**, the top hBN flake, single layer graphene (SLG) and the bottom hBN flake are picked up in sequence by the polycarbonate (PC) film on the polydimethylsiloxane (PDMS) stamp. From **g** to **h**, this hBN/SLG/hBN heterostructure is put back and dropped down to Si/SiO_2 substrate with PC film. Here, CF stands for contact front, which indicates the attaching condition of the heterostructure to the substrate. **i** is the final state of hBN/SLG/hBN heterostructure on Si/SiO_2 substrate. See details in D.G. Purdie, *et al.*, *Nat. Commun.* **9**, 5387 (2018).

The training of basic device fabrication skills and operation of equipment was intensively scheduled in the first month. I systematically learnt 2D magnets crystal exfoliation, flake transfer and pick-up techniques along with related equipment (N_2 and Ar glovebox, motorized transfer stage, electron beam lithography, evaporator, atomic force microscope (AFM)). To study 2D material heterostructures, a stable pick-up and

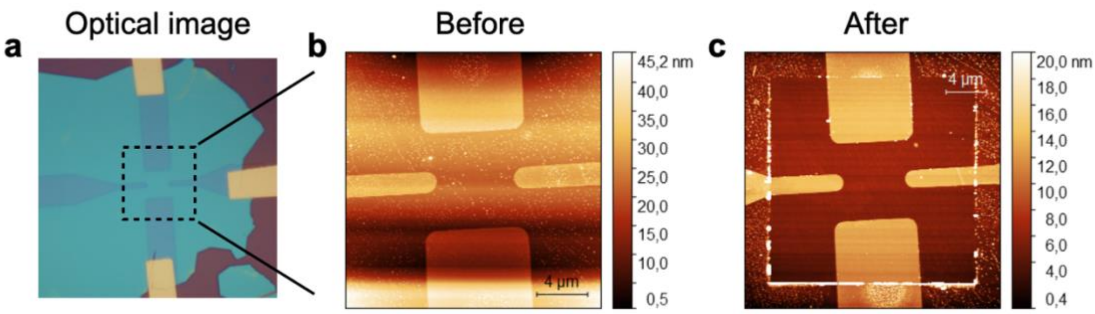

Figure 2. AFM scan results of bottom electrodes before and after AFM cleaning.

stack technique (see Figure 1) is indispensable, and my lab was suffering from our poor pick-up technique. Thus, the most important knowledge that I learnt in this period was how to make a reliable polycarbonate stamp for heterostructure fabrication.

Besides, I realized the importance of AFM cleaning to make clean bottom electrodes for electrical measurements (Figure 2). Meanwhile, I finished the fabrication of several magnet heterostructure devices.

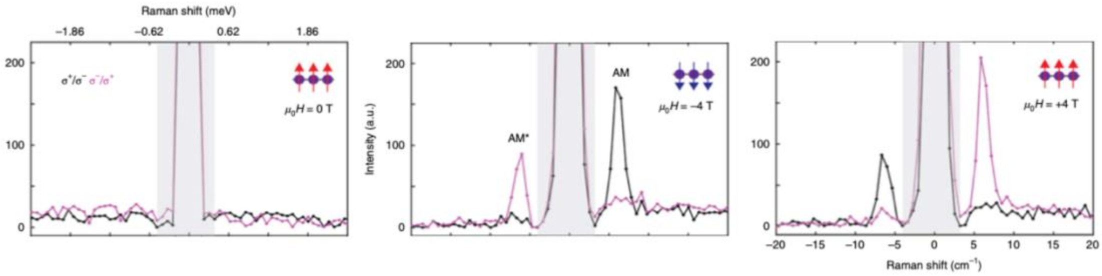

Figure 3. An ultra-low cut-off Raman spectrum of CrI_3. See more details in J. Cenker, *et al.*, *Nat. Phys.* **17**, 20-25 (2021)

The training for optical measurement system was gathered in the second month. I learnt how to use the optical set-up for Raman, photocurrent, and photoluminescence (PL) measurements on magnet/magnet interfaces. Raman spectroscopy is an important method to study the phonons or other excitations in 2D materials. Raman shift cut-off is one important parameter for a Raman measurement system. A low Raman shift cut-off can be very helpful, when studying low energy excitations in materials. In Xu lab, I learnt that the set-up using Bragg filter can greatly decrease the cut-off, comparing with traditional long-pass filter. A Raman system with extremely low cut-off can greatly benefit the study of 2D material heterostructure, especially twisted or Moiré systems.

Another important concept that I learnt in training for optical set-up was to construct the optical system block by block, which means separating different parts by their functions. Independent modules can make the adjustment of measurement set-up much easier. I carried out Raman and PL measurements on several magnet heterostructure samples during this month.

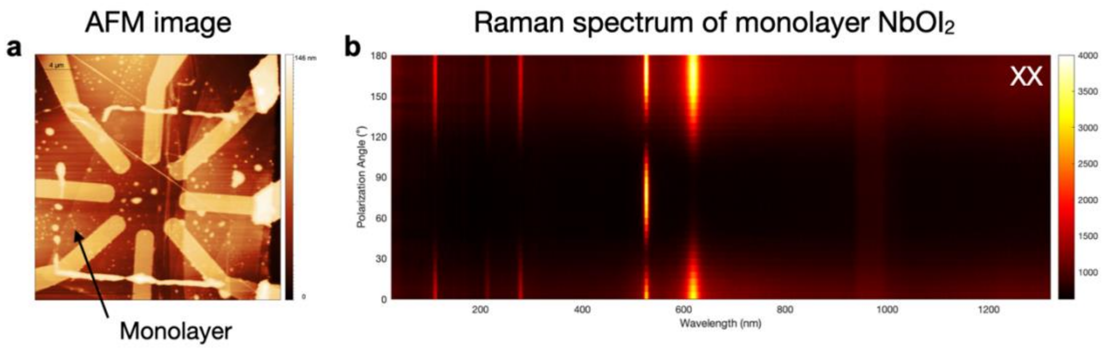

Figure 4. AFM image and polarization dependent Raman spectrum of $NbOI_2$

In the last month, I carried out experiments on 2D ferroelectric material $NbOI_2$. $NbOI_2$ is a novel 2D ferroelectric material with in-plane polarization. Basic characterization experiments (Raman spectrum and photocurrent) were carried out on thin $NbOI_2$ sample (down to monolayer). The polarization dependence of Raman spectrum at room temperature was consistent with previous published data. As to photocurrent measurement, there was no observable photocurrent signal, because of the insulating thin layer $NbOI_2$. During these three months, I was supported a lot by the students in Xu lab. They were very happy to share knowledge about all the techniques and tricks about experiments. We also had many casual discussions about my measurement results, which helped me a lot understand the physics behind the data. I am very grateful for all the supports during my stay.

To summarize the internship, I learnt advanced device fabrication and optical set-up construction skills. Meanwhile, projects on 2D magnet heterostructures and ferroelectric $NbOI_2$ were carried out. Now, the research on 2D magnet heterostructure is still in progress as a collaborated project between our lab and Xu lab.

In the end, I want to thank Professor Yoshihiro Iwasa (my supervisor) and Professor Xiaodong Xu in University of Washington for providing me such a great chance to experience the research life in United States. I also want to thank MERIT-WINGS program and JSPS DC1 for building such an excellent platform and the financial supports on my study and life. Besides, I want to show my gratitude to Department of Applied Physics, School of Engineering and University of Tokyo for the education I have received so far.