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Zürich, December 4, 2018

Report on the PhD thesis of Carlo Bernard: "Building Centimeter Sized Heterostacks of 2D Materials: Growth, Transfer and Characterisation"

Sehr geehrter Herr Studiendekan, dear Thierry,

Carlo Bernard started his PhD project in the surface physics group at the university of Zürich (UZH) in October 2012, where I was his main supervisor. His thesis is about experimental investigations in the emerging field of two-dimensional (2D) materials. Beyond the urge for the better understanding of 2D materials at the fundamental level, it is expected that they will enable the production of new apparati and devices with unprecedented properties.
In the course of his work Carlo mainly worked with hexagonal boron nitride (h-BN) and graphene (g). He also contributed significantly to collaborations of UZH within the European Future and Emerging Technology Flagship Graphene (see Chapter 5 Molybdenum Diselenide on hexagonal Boron Nitride).
After Bernard learnt the craft of surface science in our group (Chapter 2) he started to explore new directions, like it is the exfoliation of single layers of graphene or hexagonal boron nitride from the growth substrate. He performed exfoliation experiments within a wet transfer protocol (Figure 3.6), where he harvested centimetre sized sheets of hexagonal boron nitride and graphene that are grown with a chemical vapour deposition (CVD) method on single crystalline metals. The films may be transferred to arbitrary substrates, in particular to insulators. Carlo Bernard built centimetre-sized structures that he could analyze with a four-point probe for measuring the sheet resistance (Figure 4.1). After implementation of a magnet into the four-point probe setup (Figure 3.7) it was as well possible to measure the Hall charge carrier sign and concentration.
Figure 3.13 shows the charge carrier mobility vs. sheet resistance plot for 13 different heterostructures that were produced. The plot reflects the state of the art at UZH. In particular it can be seen that structures consisting in a graphene/hexagonal boron nitride structure have a low charge carrier density, though without a positive effect on the mobility that is as well an important figure of merit for 2D materials.

In a second approach Carlo Bernard investigated the possibility to grow heterostructures in situ, and to exfoliate and characterize the resulting h-BN/g structures. If transferred on the right substrate, as it is e.g. a 90 nm SiO_2 layer on a silicon wafer, atomically thick graphene grown on h-BN becomes directly visible in the optical contrast. Figure 4.1 shows a four-point probe device with this material, where the graphene did not form a continuous layer but where it is distributed in micrometer sized islands. Unsurprisingly there was no significant electric transport in this material. However, Bernard performed a very careful surface science analysis of this structure. He could demonstrate by help of low temperature scanning tunnelling microscopy measurements performed at the Swiss light source (SLS) (Figure 4.3) that lateral heterostructures were formed, where graphene grows into the same layer as the hexagonal boron nitride. By means of angle scanned photoelectron diffraction also performed at the SLS it was possible to corroborate details of the carbon structures that he grew at in the millibar pressure range (Figure 4.4).

In summary we have a dissertation in hand dealing with modern surface science in the sense that part of the experiments and applications are performed outside of the vacuum, with systems that essentially consist in surfaces only and that have no bulk. This is difficult, though Carlo Bernard took this challenge and carefully worked out conclusions on which further research will foot. I therefore recommend the Faculty of Science at UZH the acceptance of this thesis, without reservations.

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