Monday Evening, January 16, 2017

PCSI
Room Ballroom South - Session PCSI-MoE
Van der Waals Heterostructures II & New Techniques II

Moderators: Lincoln Lauhon, Northwestern University, Kyle Seyler, University of Washington

7:30pm **PCSI-MoE-1 Controlled Interfaces in 2D Materials**, ***Arend van der Zande,*** University of Illinois at Urbana Champaign **INVITED**

Interfaces are ubiquitous in material science and technologies. For example, grain boundaries often dominate the mechanical and electrical properties in crystalline materials, while interfaces between dissimilar materials form the fundamental building blocks to diverse technologies, such as building electrical contacts in transistors and PN diodes in solar cells. Interfaces become even more important in 2D materials such as graphene and transition metal dichalcogenides, where the lack of dangling bonds enables material stability down to a single monolayer. In this entirely surface-dominated limit, the usual rules governing 3D interface devices, such as depletion regions, break down.

In this talk, we will discuss our work on engineering in- and out-of-plane 2D materials interfaces, and taking advantage of the outstanding mechanical properties of atomic sheets to build novel devices. We will examine the structure of atomically-thin membranes and the impact of in-plane and out of plane interfaces such as grain boundaries and heterostructures on the mechanical, optical, and electronic properties, and discuss how to utilize interlayer interactions to tailor band alignment and build new optoelectronic devices such as tunable photodiodes. In addition, atomic membranes represent the ultimate limit of mechanical devices. We will discuss our progress on engineering devices utilizing 3D deformations of 2D sheets. Looking to the future, the rapidly expanding family of 2D materials with a diverse set of electronic properties provide a promising palette for discovering emergent phenomena and a motivation for developing overarching design principles for understanding, controlling and manipulating lower dimensional interfaces in 1D, 2D and 3D.

8:00pm **PCSI-MoE-7 Long-lived Spin/Valley Dynamics of Resident Electron and Holes in Gated Monolayer Wse$_2$**, ***Prasenjit Dey,*** *L Yang, S Crooker,* Los Alamos National Laboratory; *C Robert, G Wang, B Urbaszek, X Marie,* Institut National des Sciences Appliquées, LPCNO

Monolayer transition-metal dichalcogenides (TMDs) such as MoS_2, $MoSe_2$, WS_2 and WSe_2 represent an excellent platform to explore the spin and valley dynamics of electrons, holes, and excitons. Although excitons and charged excitons (trions) are known to exhibit rather short recombination lifetimes of the order of 10 picoseconds, it was recently demonstrated by optical Kerr-rotation spectroscopy that *resident* electrons in electron-doped MoS_2 and WS_2 monolayers exhibit surprisingly long nanosecond-timescale spin lifetimes and spin coherence [1,2].

These developments have opened up a new route to investigate the dynamics of resident carriers (both electrons and holes) in 2D semiconductors. Here we extend these measurements to single exfoliated flakes of monolayer WSe_2 that are electrostatically gated to tune the carrier density (see Figure). We employ both continuous-wave Kerr rotation (CWKR) spectroscopy and also time-resolved Kerr rotation (TRKR) spectroscopy to directly measure the dynamics of spin and valley polarization of resident carriers in both the electron and hole-doped regimes [3]. Both CW and TR- Kerr rotation data as a function of transverse magnetic field and temperature for different electron and hole doping will be discussed.

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[1] Luyi Yang *et al.*, *Nature Physics***11**, 830 (2015).

[2] Luyi Yang *et al.*, *Nano Letters***15**, 8250 (2015).

[3] P. Dey *et al.*, submitted (2016).

8:15pm **PCSI-MoE-10 Building Complex Semiconductor Nanowires via *in situ* Growth Experiments**, ***Frances Ross,*** IBM T. J. Watson Research Center **INVITED**

Semiconductor nanostructures can be grown while under observation in a transmission electron microscope by flowing chemical vapor deposition precursor gases over a heated substrate. Video-rate observations, where tens or hundreds of images are obtained per second, provide a unique view of the physics of the self-assembly process that generates the individual nanostructures. Morphology, crystal structure and growth kinetics can be measured, including the response of the growth process to changes in parameters such as pressures and temperature [1]. We have used this technique to examine the epitaxy and self-assembly of Si, Ge, GaAs and GaN nanowires. These nanowires are grown from nanoscale metallic catalytic droplets that act to accelerate growth at the catalyst/nanowire interface (the *vapor-liquid-solid* growth mode), thereby forming an elongated crystal.

We find that the VLS growth mode allows quite complex nanowire-based structures to be grown controllably if we obtain a detailed understanding of the mechanisms at work. We first describe the formation of “nanocrystal-in-nanowire” structures, achieved by supplying metals such as Ni or Mn sequentially to the catalyst during Si nanowire growth [2]. We discuss the range of structures that can be achieved in other materials such as Ge and GaAs. We next consider the opportunities for crystal engineering in III-V nanowires. GaAs, for example, can grow in nanowire form in both the zinc blende crystal structure, which is the equilibrium phase, and the non-equilibrium wurtzite structure, allowing crystal phase heterostructures to be formed. *In situ* microscopy allows the mechanism of this phase selection to be clarified [3]. Finally, we describe nanowires grown into bridges between macroscopically large contacts. Electrical transport through such nanowires can be correlated with their structure and the morphology of the junctions at either end, also measured and controlled *in situ* [4], and electric fields can be used to control nanowire growth directions [5]. This is potentially useful for device integration. We conclude with a perspective on multi-modal experimental probes that may provide the promise of correlating nanowire surface chemistry with structure and properties measured *in situ*.

8:45pm **PCSI-MoE-16 GaN Nanowires as Probes for Scanning Tunneling Microscopy**, ***Sofie Yngman,*** Lund University, Sweden; *O Scholder,* Lund Univesrity, Sweden; *F Lenrick, M Khalilian, R Timm, L Samuelson, J Ohlsson, A Mikkelsen,* Lund University, Sweden

The high spatial resolution makes scanning tunneling microscopy/spectroscopy (STM/S) an excellent tool for advanced surface characterization, such as local density of states mapping on atomic scales. The most common probes today are metallic (W, Pt/Ir), however, over the years effort has been aimed towards developing probes with particular electronic, optical and mechanical properties[1]. Semiconducting materials, such as doped diamond and InAs nanowires (NWs)[2] have for example been proposed as alternatives.

The electronic, optical and mechanical properties of GaN NWs could make them interesting for both STM/S and Scanning Nearfield Optical Microscopies (SNOM). For the electrical measurements an important potential advantage is if tunneling can be made to occur from a narrow band of states close to the band-edge of the semiconductor. The X-ray optical density of GaN is much lower than W/Pt which significantly simplifies simultaneous STM and synchrotron radiation experiments. Such experiments are difficult with W probes due to the shadowing effect of the probe. Additionally, the large band gap GaN NWs can potentially function as light guides for SNOM applications. Finally, for the mechanical properties, GaN has a hardness which is on par with W and thus constitute a viable candidate in terms of stability and robustness.

We have successfully used GaN NWs based on LED technology[3] as probes in STM/S. We demonstrate atomic resolution imaging on GaAs (110) surfaces (Fig. 1(c)-(d) and STS (not shown). The morphology of the NWs has been tailored for STM by growing them with a sharp tip for measurements (Fig. 1(b)) and high thickness for robustness (Fig. 1(a)). The NWs are *n*-doped and grown by catalyst-free metal organic vapor phase epitaxy using a two-step process. The first growth forms the GaN NW core and the second growth adds a layer of high quality GaN which also builds up the ultra-sharp tip. Several different options for viable probe fabrication based arrays of grown NWs have been evaluated.

Figure 1 *– (a) SEM image of a GaN NW. (b) TEM image of a GaN NW tip apex. (c)-(d) STM image and line scan of a GaAs(110) surface acquired using a GaN NW probe.*

8:50pm **PCSI-MoE-17 TERS: New Method for Nanoscale Characterization of 2D Materials - from Graphene to TMDCs.**, ***Andrey Krayev,*** *S Bashkirov, V Gavrilyuk, D Evplov, V Zhizhimontov, A Robinson,* AIST-NT Inc.; *M Chaigneau,* Horiba Scientific

Recent advances in tip-enhanced Raman scattering (TERS) instrumentation, availability of commercial highly enhancing probes and development of dedicated TERS imaging modes have brought TERS characterization to the level of an everyday analytical method that can provide important information on structural and electronic properties of different materials at the scale of a few nanometers.

We report the results of TERS characterization of 2 classes of 2D materials: graphene and its derivative and two members of transition metal dichalcolgenides (TMDCs) class- MoS_2 and WS_2. We discovered that the gap mode TERS signal of these 2D materials becomes dramatically enhanced over wrinkles and creases, as well as over nanopatterns imprinted into flakes using a sharp diamond probe.

Resonant Raman spectra of TMDCs contain additional peaks normally forbidden by selection rules. TERS maps of few-layer-flakes of MoS_2 show that the spatial distribution of Raman intensity across the flake varies for different peaks, specifically, the lower energy component of the complex resonant 465cm^{-1} peak is significantly decreased at the edges of the flakes. TERS and tip-enhanced photoluminescence (TEPL) characterization of WS_2 grown on Si/SiO2 show that, similar to the case of MoS_2 flakes, the properties are not uniform across the flake: there exists a narrow, 150-200 nm wide, area along the edges of the flakes with decreased and blue shifted photoluminescence and in the same time enhanced TERS response, both of which indicate decreased charge carrier density in the vicinity of the flake outer edges.

Based on these results, we argue that TERS and TEPL can be an extremely useful tool for nanoscale characterization of the 2D materials.

8:55pm **PCSI-MoE-18 Robust High-Resolution Imaging and Quantitative Force Spectroscopy in Vacuum with Tuned-Oscillator Atomic Force Microscopy**, ***Omur Dagdeviren**, J Goetzen,* Yale University*; H Hoelscher,* KIT*; E Altman, U Schwarz,* Yale University

Since the first demonstration of atomic resolution in ultrahigh vacuum more than twenty years ago, frequency modulation-based noncontact atomic force microscopy (FM-NC-AFM) has significantly matured and is now routinely applied to study problems that benefit from high-resolution surface imaging. In FM-NC-AFM, control of the tip's vertical position is accomplished by detecting a shift in the cantilever's resonance frequency upon approach to the sample. Consistently ensuring reliable distance control during extended data acquisition periods has nevertheless remained challenging, as most FM-mode-based control schemes employ three feedback loops that may interfere. As a consequence, sample throughput in FM-NC-AFM is often low compared to ambient condition AFM, where the easy-to-implement amplitude-modulation (AM) control scheme is predominantly used. Transfer of the AM methodology to high-resolution measurements in vacuum is, however, difficult as with AM-AFM, instabilities during approach are common. In addition, the lack of viscous air damping and the related significant increase of the cantilever's quality factor generate prolonged settling times, which cause the system's bandwidth to become impractical for many applications. Here we introduce a greatly simplified approach to NC-AFM imaging and quantitative tip-sample interaction force measurement that prevents instabilities while simultaneously enabling data acquisition with customary scan speeds by externally tuning the oscillator's response characteristics [1]. After discussing background and basic measurement principle, examples for its application to a variety of sample systems are provided (see Fig. 1). A major advantage of this operational scheme is that it delivers robust position control in both the attractive and repulsive regimes with only one feedback loop, thereby carrying the potential to boost the method's usability.

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