Friday Morning, November 1, 2013

Scanning Probe Microscopy Focus Topic
Room: 202 C - Session SP+AS+EM+GR+MI+NS+SS-FrM

Probing Electronic and Transport Properties
Moderator: S. Allen, The University of Nottingham, UK

8:20am **SP+AS+EM+GR+MI+NS+SS-FrM1 STM Mapping of Thermoelectric Power on Graphene across Defects and Boundaries**, ***J. Park***, Oak Ridge National Laboratory, *G. He, R.M. Feenstra,* Carnegie Mellon University, *A.P. Li*, Oak Ridge National Laboratory

We present the spatially resolved thermoelectric power on epitaxial graphene on SiC by a scanning tunneling microscopy (STM) method. A thermovoltage is induced by a temperature difference between tip and sample and variations of thermovoltage are distinguished at defects and boundaries with atomic resolution. The epitaxial graphene shows a high thermoelectric power of 42 µV/K with a big change (9.6 µV/K) at the monolayer-bilayer boundary. Also, the thermopower is modified by Friedel oscillations of the charge density in graphene. Besides the change at the monolayer and bilayer graphene boundary, the thermopower also provides spectroscopy maps which reveal domain structures induced by collapsed graphene wrinkles that not obvious in STM images. The thermopower distribution measurement with STM thus allows probing the electronic, thermoelectric, and structural properties down to the individual defect level.

8:40am **SP+AS+EM+GR+MI+NS+SS-FrM2 New Milestones in Scanning Probe Microscopy: Graphene on Rh(111) Studied by DFT, STM and NC-AFM**, ***A. Thissen***, SPECS Surface Nano Analysis GmbH, Germany

Graphene and is its interface with metallic substrates is proposed to be used in many technological applications. It can act as a protection layer for the underlying substrate, as a spin-filtering material separating two layers of a ferromagnetic material, or, in case of its growth on a lattice mismatched surfaces [for example, Ir(111), Rh(111), or Ru(0001)], as a template for the preparation of ordered arrays of clusters.

For graphene on Rh(111) [Fig.1(a-c)] several regions of different arrangements of carbon atoms above a Rh(111) substrate can be found: ATOP [A; carbon atoms are above Rh(S-1) and Rh(S-2) atoms], HCP [H; carbon atoms are above Rh(S) and Rh(S-2) atoms], FCC [F; carbon atoms are above Rh(S) and Rh(S-1) atoms], and BRIDGE [B; Rh(S) atoms bridge the carbon atoms]. These places are marked in Fig.1(a) by circle, down-triangle, square, and stars, respectively. Among them, the BRIDGE positions are expected to be the most energetically favorable for the nucleation of deposited atoms on top of a graphene layer.

In this contribution we present the combined study of the graphene/Rh(111) system via application of the state-of-the-art DFT calculations, STM, and NC-AFM. The calculated imaging contrast for STM between all high-symmetry positions for graphene/Rh(111) is in very good agreement with experimental results and this contrast does not depend on the sign of the bias voltage applied between a tip and the sample. As opposed to the latter observation, the imaging contrast in atomically-resolved AFM measurements depends on the frequency shift of the oscillating tip that can be understood on the basis of measured force-spectroscopy curves.

For this the KolibriSensor™, a new quartz sensor that excels in its performance reliability is used either for RT to HT studies in an SPM Aarhus 150 or for LT studies in the new Tyto™ scan head mounted into a JT-SPM. It is controlled by the Nanonis Control System.

9:00am **SP+AS+EM+GR+MI+NS+SS-FrM3 Electric Field Tuning of 2-dimensional Electrons in Graphene and Topological Insulators**, *J.A. Stroscio,* ***J. Ha***, National Institute of Standards and Technology **INVITED**

The recent advances in classification of matter in terms of topological band theory have spurred a great deal of interest in synthesizing new materials demonstrating new topologically related properties. In a large class of these materials there are robust surface states on the spatial boundaries with vacuum. These surface states possess linear dispersive bands with chiral properties, similar to graphene. In this talk I will review our scanning tunneling spectroscopy measurements of graphene in applied electric field and magnetic fields [1-4] and compare them to some new results of applying electric fields in tunneling spectroscopy measurements of topological insulators [5,6].

Gate mapping tunneling spectroscopy has proved to be a powerful probe of the 2-dimensional electron system in graphene. In the presence of moderate disorder the charging of graphene quantum dots localized in the disorder potential has been observed with graphene on SiO_2 [1]. Intrinsic many body effects were observed in the renormalization of the dispersion velocity when substrate disorder was reduced using boron nitride spacer layers between graphene and SiO_2 [4]. In contrast, removing the substrate and creating suspended graphene membranes was seen to generate pseudomagnetic fields localizing the carriers in response to the strain generated from the forces between the probe and graphene membrane [3].

In the topological insulator Sb_2Te_3, we achieved gate tunable devices which are suitable for low temperature scanning tunneling microscopy (STM) studies by designing sample holders with back gating capability [5]. Thin films are epitaxially grown on pre-patterned $SrTiO_3$ substrates which are mounted on the specially designed sample holders. This allows *in-situ* gating on epitaxial films without any *ex-situ* processing of the sample [5]. In 3 QL thick Sb_2Te_3 films we observe a gap opening at the Dirac point due to the coupling of the top and bottom surface states [6]. More importantly, the gap is found to be tunable by the gate field, indicating the possibility of observing a topological phase transition in this system. A comparison of the data with an effective model of 3D topological insulators suggests that 3QL Sb_2Te_3 belongs to the quantum spin Hall insulator class.

[1] S. Jung *et al*., *Nature Physics***7**, 245 (2011).

[2] G. M. Rutter *et al*., *Nature Physics***7**, 649 (2011).

[3] N. N. Klimov *et al*., *Science***336**, 1557 (2012).

[4] J. Chae *et al*., Phys. Rev. Lett. **197**, 116802 (2012).

[5] T. Zhang *et al*., Phys. Rev. B **87**, 115410 (2013).

[6] T. Zhang *et al*., arXiv:1304.3661.

9:40am **SP+AS+EM+GR+MI+NS+SS-FrM5 SPM: Manipulating Spin to Operating Molecular Nanomachines**, ***S.-W. Hla***, Argonne National Laboratory **INVITED**

We combine scanning tunneling microscope (STM) imaging, manipulation and spectroscopy to investigate and manipulate magnetic, electronic, and mechanical properties of atoms and molecules on surfaces. This talk will highlight advances achieved by STM studies at atomic and molecular scale [1-3]. In spintronic area, we will present imaging and manipulation of atomic spin using a spin-polarized STM tip [1]. Here, individual cobalt atoms assembled as a chain on a Mn monolayer on W(110) surface appear different shapes due to their spin directions. In nanoscale superconductivity area, donor-acceptor type $(BETS)_2GaCl_4$ molecular clusters on a Ag(111) surface opens up the possibility to explore superconducting phenomena locally [2]. In this part, electronic structure evolutions at molecule-metal boundaries and manipulation of superconducting clusters will be presented. Quenching of surface state electrons due to the molecular superconducting state will also be discussed. Finally, operations of complex molecular motors using STM manipulation on a Au(111) surface will be shown. Interestingly a selective tunneling into specific rotor arms result in a controlled directional rotation of the motor. The inherent molecular design is critical to achieve such directional control. These innovative experiments are tailored to address several critical issues covering both for fundamental understanding, and for demonstration of novel molecule based nanodevices on materials surfaces.

[1] D. Serrate, P. Ferriani, Y. Yoshida, S.-W. Hla, M. Menzel, K. von Bergmann, S. Heinze, A. Kubetzka, and R. Wiesendanger. *Imaging and manipulating the spin direction of individual atoms.* ***Nature Nanotechnology*** **5**, 350-354 (2010).

[2] K. Clark, A. Hassanien, S. Khan, K.-F. Braun, H. Tanaka, and S.-W. Hla. *Superconductivity in just four pairs of* $(BETS)_2$*-*$GaCl_4$ *molecules.* ***Nature Nanotechnology*** **5**, 261-265 (2010).

[3] U.G.E. Perera . F. Ample, H. Kersell, Y. Zhang, G. Vives, J. Echeverria, M. Grisolia, G. Rapenne, C. Joachim, and S.-W. Hla. *Controlled clockwise and anticlockwise rotational switching of a molecular motor. Nature Nanotechnology***8**, 46-51 (2013).

10:20am **SP+AS+EM+GR+MI+NS+SS-FrM7 New Experiments and Applications Made Possible by a Low Temperature 4-Tip STM with UHV-SEM Navigation**, ***A. Bettac***, *B. Guenther, J. Chrost, J. Hilton, J. Koeble, A. Feltz*, Omicron NanoScience, Germany

A major challenge in the development of novel devices in nano- and molecular electronics is their interconnection with larger scale electrical circuits required to control and characterize their functional properties. Local electrical probing by multiple probes with STM precision can significantly improve efficiency in analyzing individual nano-electronic devices without the need of a full electrical integration. Recently we developed a microscope stage that merges the requirements of a SEM navigated 4-probe STM and at the same time satisfy the needs for high performance SPM at low temperatures.

Besides SEM/STM probe fine navigation and imaging with atomic resolution at temperatures of T<5K, the pm-stability of the LT NANOPROBE expands applications to tunneling spectroscopy and even the creation or modification of nanostructures or single atoms by a sharp and precise SPM probe. A further milestone in the development of the instrument was the implementation of the Qplus- NC-AFM mode for imaging on insulating surfaces. The Qplus measurement becomes important if nanowires/nanostructures are deposited on an insulating substrate for a better electrical decoupling of the nanowire from the substrate. In this case the Qplus sensor can be employed to locate the nanostructures and, after finding the structure, to carry out conductance measurements.

In this contribution we will present first Qplus results obtained with the LT Nanoprobe at low temperatures. Furthermore we will focus on measurements that prove the performance level of the instrument as well as on tunneling spectroscopy and atom manipulation experiments on Ag(111) at temperatures of T < 5K.

10:40am **SP+AS+EM+GR+MI+NS+SS-FrM8 Electrical Characterization of GaAs Nanowires with a 4-tip STM**, ***B. Voigtlaender***, *S. Korte, V. Cherepanov,* Peter Grünberg Institut (PGI-3), Forschungszentrum Jülich, Germany, *M. Steidl, W. Zhao, P. Kleinschmidt, T. Hannappel,* TU Ilmenau, Germany, *W. Prost,* University of Duisburg-Essen, Germany

III-V semiconductor nanowires are promising building blocks for novel semiconductor devices in future electronic and opto-electronic applications such as solar cells. In this context the distribution of the dopant over the nanowires is of great importance. Resistance profiles of as-grown freestanding GaAs nanowires were measured with a multitip scanning tunneling microscope (STM) used as nanoprober. Four point probe resistance measurements were performed along the nanowire. The dopant induced carrier concentration along the wire was determined from the resistance measurements and geometrical data. It was found that in the high temperature growth region (450°C) the carrier concentration is about one order of magnitude lower than in the low temperature regime (400°C). The NWs exhibit high mechanical elasticity, they can be deformed by the STM tips and revert to their original shape when released. Even extreme bending of a NW did not show a significant influence on its conductivity. These measurements were performed using a multi-tip scanning tunneling microscope (STM) in which four independent STM units are integrated on a diameter of 50 mm, resulting in an unsurpassed mechanical stability, enabling atomic resolution imaging with each tip. The heart of this STM is a new type of piezoelectric coarse approach called KoalaDrive. The coarse positioning of the tips is done under the control of an SEM. This multi-tip instrument is suited to perform electrical measurements such as local potential measurements at the nanoscale.

11:00am **SP+AS+EM+GR+MI+NS+SS-FrM9 Atomic and Electronic Structure of an Alloyed Topological Insulator $Bi_{1.5}Sb_{0.5}Te_{1.7}Se_{1.3}$**, ***W. Ko***, *I. Jeon, H.W. Kim, H. Kwon,* Samsung Advanced Institute of Technology, Republic of Korea, *S.-J. Kahng,* Korea University, Republic of Korea, *J. Park, J.S. Kim,* Pohang University of Science and Technology, Republic of Korea, *S.W. Hwang, H. Suh*, Samsung Advanced Institute of Technology, Republic of Korea

The alloyed compound $Bi_{2-x}Sb_xTe_{3-y}Se_y$ has been argued to exhibit both topological surface states and insulating bulk states, but not yet been studied with local probes on the atomic scale. Here we report on the atomic and electronic structures of $Bi_{1.5}Sb_{0.5}Te_{1.7}Se_{1.3}$ studied using scanning tunnelling microscopy (STM) and spectroscopy (STS). Although there is significant surface disorder due to the alloying of constituent atoms, cleaved surfaces of the crystals present a well-ordered hexagonal lattice in STM topographs with 10 Å high quintuple layer steps. STS results reflect the band structure and indicate that the surface state and Fermi energy are both located inside the energy gap. In particular, the surface states do not show any electron back-scattering; due to their topological nature they are extremely robust. This finding demonstrates that alloying is a promising route to achieve full suppression of bulk conduction in topological insulators whilst keeping the topological surface state intact.

11:20am **SP+AS+EM+GR+MI+NS+SS-FrM10 Schottky Barrier Height Measurements of Cu/Si(001), Ag/Si(001), and Au/Si(001) Interfaces Utilizing Ballistic Electron Emission Microscopy and Ballistic Hole Emission Microscopy**, ***R. Balsano***, *V.P. LaBella,* College of Nanoscale Science and Engineering

The Schottky barrier heights of both n and p doped Cu/Si(001), Ag/Si(001), and Au/Si(001) diodes were measured using ballistic electron emission microscopy (BEEM) and ballistic hole emission microscopy (BHEM), respectively. Measurements using both forward and reverse BEEM and BHEM injection conditions were performed. The Schottky barrier heights were found by fitting to a linearized Bell-Kaiser and Prietsch-Ludeke model. The sum of the n-type and p-type barrier heights are in good agreement with the band gap of silicon and independent of the metal utilized. These findings may help to improve models for Schottky barrier heights of non-epitaxial diodes.

11:40am **SP+AS+EM+GR+MI+NS+SS-FrM11 A STM Study of a Self Assembled Cu-Si Nanoisland on Si(110)**, ***P.K. Ng***, University of Illinois at Chicago, *B. Fisher, N.P. Guisinger,* Argonne National Laboratory, *C.M. Lilley,* University of Illinois at Chicago

The surface of a self-assembled copper-silicide (Cu-Si) nanoisland on a silicon (Si) substrate with (110) orientation was studied using surface tunneling microscopy (STM). Self-assembled Cu-Si nanostructures on Si are of technological interested because of their potential use in nanoscale devices. Self-assembled Cu-Si nanoislands were fabricated by electron beam evaporation of Cu onto a 600°C annealing Si substrate in ultrahigh vacuum (UHV) environment. In prior work, we used transmission electron microscopy (TEM) to analyze material composition of Cu-Si nanostructures via x-ray energy dispersive spectroscopy (XEDS) [1]. The XEDS data of a Cu-Si nanowire show a Cu_3Si phase [2]. The size of these nanostructures was on the scale of hundreds of nanometers and high resolution analysis was focused on the cross-sectional (or bulk) material. However, the surface of these self-assembled Cu-Si nanoislands has not yet been studied. Figure 1(a) in the attached supplemental document (and all the referring figures therein) shows a scanning tunneling microscopy (STM) micrograph of a self assembled Cu-Si nanoisland on Si(110). The facets on the nanoisland indicates a single crystal. As seen in Figs. 1(b)-(c), a higher resolution scan and analysis on the same nanoisland indicates a surface periodicity between scan points A to B of ~6.8 Å. These results corroborate that the faceted nanoisland is a single crystal. The surface of the nanoisland appears to have unknown absorbates, possibly from water or hydrogen contaminations, see Fig. 1(b). Interestingly, some of these absorbates do not randomly form on the surface but also in a periodical manner. As such, the surface may have a periodical affinity for certain absorbates. A full discussion of this study will be presented in the AVS proceeding.

[1] P. K. Ng, B. Fisher, K. B. Low, A. Joshi-Imre, M. Bode, and C. M. Lilley, "Comparison between bulk and nanoscale copper-silicide: Experimental studies on the crystallography, chemical, and oxidation of copper-silicide nanowires on Si(001)," Journal of Applied Physics, vol. 111, pp. 104301-7, 2012.

[2] P. K. Ng, B. Fisher, K. B. Low, R. E. Cook, and C. M. Lilley, "Crystallographic studies of self assembled Cu-Si nanowires on Si(001), Si(110), and Si(111)," in preparation, 2013.

Authors Index

Bold page numbers indicate the presenter