Electron Transport in Low Dimensional Materials Focus Topic
Room: 209 - Session ET+EM+NS+GR-TuM

Electron Behaviors in Nanoelectronics, Interconnect, and Carbon-based Materials
Moderator: J. Wendelken, Oak Ridge National Laboratory, A. Swan, Boston University

8:00am **ET+EM+NS+GR-TuM1 Electron Transport Study of Graphene on SiC Using Scanning Tunneling Potentiometry**, ***K. Clark****, S. Qin,* Oak Ridge National Laboratory*, G. He,* Carnegie Mellon University*, G. Gu,* The University of Tennessee*, R.M. Feenstra,* Carnegie Mellon University*, A.-P. Li*, Oak Ridge National Laboratory

The unique electronic and transport properties of graphene have helped this material emerge as a perspective graphene based electronic system. Single layers of graphene formed on SiC look to be a promising system for the realization of graphene electronics. To utilize the full potential of graphene on SiC a complete understanding of the physical and electronic properties of this system is needed. This study uses Scanning Tunneling Microscope (STM) images along with scanning tunneling spectroscopy to characterize the sample surface. STM images clearly show the distinction between 1 monolayer (ML) and 2ML regions. The 1ML to 2ML transition is further confirmed by point spectroscopy measurements and spectroscopic mapping across the boundary. Defects, grain boundaries, step edges and other potential scattering centers are thought to play a major role in the electronic properties, especially in transport, along the graphene sheets. Using a low temperature four-probe scanning tunneling microscope, potentiometry measurements are performed on epitaxial graphene grown on 4H-SiC. Potentiometry maps spanning the transition from 1ML to 2ML graphene layers show a contrast change indicating a potential change at this interface. Preliminary results of the transport along this potentially revolutionary new electronic system will be presented. This research was conducted at the Center for Nanophase Materials Sciences, which is sponsored at Oak Ridge National Laboratory by the Office of Basic Energy Sciences, U.S. Department of Energy.

8:20am **ET+EM+NS+GR-TuM2 Engineering the Electronic States of CVD Grown Few Layer Graphene by Twisting and Lattice Distortion**, ***M.H. Pan***, Oak Ridge National Laboratory*, X.T. Jia, S. Bhaviripudi,* Massachusetts Institute of Technology*, V. Meunier,* Rensselaer Polytechnic Institute*, M.S. Dresselhaus, J. Kong*, Massachusetts Institute of Technology

Few layer graphene (FLG) can have advantages over single layer graphene because it has a larger current-carrying capacity and the electronic properties are sensitive to more engineerable system parameters. In particular, Hass et al. have demonstrated that orientational disorder is normally present in carbon-face SiC epitaxial FLG samples.[1] Recently both theoretical and experimental studies suggest that strain can be used to engineer graphene electronic states through the creation of a pseudo–magnetic field. [2] Here we present both scanning tunneling microscopic/spectroscopic (STM/S) studies of chemical vapor deposition grown few layer graphene samples. There indeed exists a twisting between the stacked graphene layers, confirmed by both high-resolution STM images and low temperature spectroscopic measurements. Our results show that, by stretching graphene along three symmetry directions, a strain-induced pseudo magnetic field can lead to the formation of different Charge Density Wave (CDW) states at the top layer of graphene.

[i] Hass, J., Varchon, F., *Phys. Rev. Lett.* **100,** 125504(2008)

[ii] Levy, N. et al., *Science* **329**, 544 (2010).

8:40am **ET+EM+NS+GR-TuM3 Unique One- and Two-Dimensional Phenomena Observed in Carbon Nanotubes and Graphene***, **S. Cronin***, University of Southern California **INVITED**

Our ability to fabricate nearly defect-free, suspended carbon nanotubes

(CNTs) has enabled us to observe several phenomena never seen before in CNTs, including breakdown of the Born-Oppenheimer approximation[1], mode selective electron-phonon coupling[2], leading to negative differential resistance (NDR) and non-equilibrium phonon populations, and a Mott insulator transition[3]. In this work, Raman spectroscopy is used to measure individual, suspended CNTs under applied gate and bias potentials. Raman spectroscopy of periodic ripple formation in suspended graphene will also be reported. As will be shown, preparing clean, defect-free devices is an essential prerequisite for studying the rich low-dimensional physics of CNTs and graphene.

1. Bushmaker, A.W., Deshpande, V.V., Hsieh, S., Bockrath, M.W., and Cronin, S.B., "Direct Observation of Born-Oppenheimer Approximation Breakdown in Carbon Nanotubes." Nano Letters, 9, 607 (2009).

2. Bushmaker, A.W., Deshpande, V.V., Bockrath, M.W., and Cronin, S.B., "Direct Observation of Mode Selective Electron-Phonon Coupling in Suspended Carbon Nanotubes." Nano Letters, 7, 3618 (2007).

3. Bushmaker, A.W., Deshpande, V.V., Hsieh, S., Bockrath, M.W., and Cronin, S.B., "Large Modulations in the Intensity of Raman-Scattered Light from Pristine Carbon Nanotubes." Physical Review Letters, 103, 067401 (2009).

9:20am **ET+EM+NS+GR-TuM5 Probing Surface Band Conduction through Back-Gated Conductance Measurements on Si Nanomembranes**, ***W.N. Peng*****, J. Endres, S. Scott, Z. Aksamija, D.E. Savage, I. Knezevic, M.G. Lagally, M. Eriksson*, University of Wisconsin Madison

Silicon-on-insulator substrates provide large-area Si nanomembranes (SiNMs) mechanically supported by bulk handle wafers. Because of the intervening oxides, SiNMs are also electrically isolated from the substrates. The typical membrane thickness is less than a few hundred nanometers. Because they are so thin, SiNMs display interesting transport phenomena influenced by surface effects. Here, we demonstrate a novel method to probe surface transport via conductance measurements on SiNMs. When contacts are placed on the front surface, a current flows between the source and the drain via the membrane body as well as its surface. By utilizing an underlying back gate (the Si handle substrate), the conductance through the membrane can be continuously tuned and made smaller than the surface contribution, enabling experimental determination of the surface conductance. We measure the membrane conductance as a function of both the membrane thickness and the backgate voltage in ultra-high vacuum. In contrast to H-terminated Si surfaces, clean reconstructed Si(001)(2×1) surfaces show a constant-conductance regime when the backgate voltage is varied, and the conductance in this regime does not depend on membranes thickness. We demonstrate that the constant conductance (on the order of 10^{-9} Siemens) stems from an additional conduction channel through the dimer-reconstructed surface π^* band. By comparing the experimental results to numerical simulations, the surface band mobility is determined to be in the range 10-50 cm^2/Vs.

Research supported by NSF [UW MRSEC, award DMR-0520527, as well as awards 0937060 (subaward CIF-146) and ECCS-0547415] and DOE

9:40am **ET+EM+NS+GR-TuM6 Ferroelectric Field-Effect Transistor Behavior in CdS Nanotetrapods***, **S. Qin***, Oak Ridge National Laboratory*, W. Fu, L. Liu,* Chinese Academy of Sciences*, T.H. Kim,* Oak Ridge National Laboratory*, S.L. Hellstrom,* Stanford University*, W. Wang, W. Liang, X. Bai, E. Wang,* Chinese Academy of Sciences*, A.-P. Li*, Oak Ridge National Laboratory

Complex nanostructures such as branched semiconductor nanotetrapods are promising building blocks for next-generation nanoelectronics. Here we report on the electrical transport properties of individual CdS tetrapods in a field-effect transistor (FET) configuration with a ferroelectric $Ba_{0.7}Sr_{0.3}TiO_3$ film as high-κ, switchable gate dielectric. A cryogenic four-probe scanning tunneling microscopy is used to probe the electrical transport through individual nanotetrapods at different temperatures. A *p*-type field effect is observed at room temperature, owing to the enhanced gate capacitance coupling. And the reversible remnant polarization of the ferroelectric gate dielectric leads to a well-defined nonvolatile memory effect. The field effect is shown to originate from the channel tuning in the arm/core/arm junctions of nanotetrapods. At low temperature (8.5 K), the nanotetrapod devices exhibit a ferroelectric-modulated single-electron transistor behavior. The results illustrate how the characteristics of a ferroelectric such as switchable polarization and high dielectric constant can be exploited to control the functionality of individual 3-dimensional nano-architectures. *Acknowledgement:* The research at the Center for Nanophase Materials Sciences is sponsored at Oak Ridge National Laboratory by the Office of Basic Energy Sciences, U.S. Department of Energy. The research in Beijing is supported by MOST and CAS of China.

***** NSTD Student Award Finalist

10:40am **ET+EM+NS+GR-TuM9 Probing Electron-Electron Correlations in Quantum Dots Using Transport: Quantum Monte Carlo Studies**, ***H.U. Baranger***, Duke University **INVITED**

Strong electron-electron correlations occur in nanoscale systems in a variety of contexts – when electrons form a crystal at low density, for example, or in correlations between quantum dots. Nanoscale systems introduce in addition an unprecedented level of control over the physical parameters determining such correlations. As electron transport is one of the primary probes of nanosystems, the effect of e-e correlations on transport is a key issue. I shall discuss an example in which we used quantum Monte Carlo (QMC) techniques to calculate the conductance:

Consider a system of four quantum dots designed to study the competition between three types of interactions: Heisenberg, Kondo, and Ising. We find that the competition produces a rich phase diagram containing two sharp features: a quantum phase transition (QPT) between charge-ordered and charge-liquid phases, and a dramatic resonance in the charge liquid visible in the conductance. The conductance is calculated using a world-line QMC method: extrapolation of the imaginary time QMC data to zero frequency yields the linear conductance, which is then compared to numerical renormalization group results in order to assess its accuracy. The QPT is of the Kosterlitz-Thouless type with a discontinuous jump in the conductance at the transition. We connect the sharp resonance phenomenon with the degeneracy of three levels in the isolated quadruple dot and argue that this leads to an emergent symmetry. I shall end by discussing the sensitivity to parameter variation and possible experimental realizations in laterally gated quantum dots as well as carbon nanotubes.

This work was done in collaboration with Dong E. Liu and Shailesh Chandrasekharan (Duke University).

11:20am **ET+EM+NS+GR-TuM11 Resistivity Increase due to Electron Scattering at Surfaces and Grain Boundaries in Metal Thin Films and Nanowires**, *J.S. Chawla,* ***D. Gall***, Rensselaer Poltechnic Institute

The effect of surface and grain boundary scattering on the resistivity of Cu thin films and nanowires is quantified using (i) *in situ* transport measurements on single-crystal, atomically smooth Cu(001) layers, (ii) textured Cu(111) layers and patterned Cu wires with independently varying grain size, thickness and line width, and (iii) *in situ* grown interfaces including Cu-Ta, Cu-MgO, Cu-SiO2 and Cu-oxygen. In addition, the electron surface scattering is also measured *in situ* for single-crystal Ag(001) and TiN(001) layers. These findings are important for the development of future generation narrow low-resistivity Cu interconnects and TiN metal gates.

Cu(001), Ag(001), and TiN(001) layers with a minimum continuous thickness of 4, 5 and 1.8 nm, respectively, are grown by ultra-high vacuum magnetron sputter deposition on MgO(001) substrates and are found to be atomically smooth single crystals by a combination of x-ray diffraction θ-2θ scans, ω-rocking curves, pole figures, reciprocal space mapping, Rutherford backscattering, x-ray reflectometry, transmission electron microscopy, and *in-situ* scanning tunneling microscopy. Polycrystalline Cu layers with a 111-texture are deposited on thermally grown SiO2, with and without Ta barrier layer. Subsequent *in-situ* annealing at 350oC followed by sputter etching in Ar plasma yields Cu layers with independently variable thickness and grain size. Cu nanowires, 50 to 150 mm long, 70 to 350 nm wide, and 45 nm thick, are patterned using electron beam lithography and sputter etching.

In-situ electron transport measurements at room temperature in vacuum and at 77 K in liquid nitrogen for single-crystal Cu and Ag layers is consistent with the Fuchs-Sondheimer (FS) model and indicates specular scattering at the metal-vacuum boundary with an average specularity parameter p = 0.6 and 0.4, respectively. In contrast, layers measured *ex-situ* show completely diffuse surface scattering due to sub-monolayer oxidation. Electron transport measurements for polycrystalline Cu/Ta layers and wires show a ~10% and ~11% decrease in resistivity, respectively, when increasing the average lateral grain size by factor 2. *In-situ* deposition of 0.3 to 8 nm thick Ta barrier layers on Cu(001) leads to a resistance increase that indicates a transition from p = 0.8 to p = 0, independent of the Ta thickness. *In-situ* exposure of Cu(001) layers to O2between 10-3 and 105 Pa-s results in a sequential increase, decrease and increase of electrical resistance which is attributed to specular surface scattering for clean Cu(001) and for surfaces with a complete adsorbed monolayer, but diffuse scattering at partial coverage and after chemical oxidation.

11:40am **ET+EM+NS+GR-TuM12 Control of Contact Formation via Electrodeposition on GaAs Nanowires**, ***C. Liu****, O. Einabad, S. Watkins, K.L. Kavanagh*, Simon Fraser University, Canada

Copper (Cu) electrical contacts to as-grown gallium arsenide (GaAs) nanowires have been fabricated via electrodeposition. The nanowires are zincblende (111) oriented grown epitaxially on n-type Si-doped GaAs(111)B

substrates by gold-catalyzed Vapor Liquid Solid (VLS) growth in a metal organic vapour phase epitaxy (MOVPE) reactor. The epitaxial electrodeposition process, based on previous work with bulk GaAs substrates, consists of a substrate oxide pre-etch in dilute ammonium hydroxide carried out prior to galvanostatic electrodeposition in a pure Cu or Fe sulphate aqueous electrolyte at 20C. The conductivity of wires was controlled via the addition of carbon tetrabromide (CBr4) during growth. For nominally undoped GaAs nanowires, we find that Cu or Fe has a preference for growth on the gold catalyst avoiding the sidewalls. After etching the gold, both metals still preferred to grow only on the tops of the nanowire, consistent with the location of the largest electric field. Core-shell GaAs nanowires with highly conductive carbon-doped shells were fabricated via changing the Ga precursors form triethylgallium to trimethylgallium for radial growth. Increasing the conductivity of the nanowires in this way, not surprisingly; meant that Cu nucleation and growth began to occur on the sidewalls as well as on the gold catalyst. Finite element simulations will be compared to our electrodeposition results towards the calibration of nanowire conductivity.

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