Thursday Morning, November 1, 2012

Electron Transport at the Nanoscale Focus Topic
Room: 16 - Session ET+NS+EM-ThM

Electron Transport at the Nanoscale: Nanowires and Junctions

Moderator: K. Clark, Oak Ridge National Laboratory, A.-P. Li, Oak Ridge National Laboratory

8:00am **ET+NS+EM-ThM1 Functional Imaging of Semiconductor Nanowires and Devices**, ***L.J. Lauhon***, Northwestern University **INVITED**

Microscopy has played a central role in the advancement of nanoscience and nanotechnology by enabling the direct visualization of nanoscale structure, and by extension predictive models of novel physical behaviors. Correlated imaging of nanoscale structure *and* properties is an important frontier that can provide a rational basis for engineering new materials and devices. I will describe our approach to correlated functional imaging with a focus on semiconductor nanowires. Nanocrystal growth modes such as the vapor-liquid-solid process provide the ability to tailor nanoscale structure and composition in three dimensions, creating new opportunities in a range of applications including light harvesting and solid state lighting. In this context, we have explored a number of important processing-structure-property relationships using atom probe tomography, scanning transmission electron microscopy, Raman microspectroscopy, and scanning photocurrent microscopy. From these studies, we develop a more comprehensive understanding of the influence of geometry, size, defects, dopants, and interfaces on carrier generation, recombination, and transport in nanostructured materials. This quantitative approach to characterization of model systems aims to identify applications that can derive significant benefits from the adoption of unconventional nanostructured materials.

8:40am **ET+NS+EM-ThM3 Electronic Transport and Structure Relations in Self-Assembled $GdSi_2$ Quantum Wires**, ***S.Y. Qin***, *T. Kim*, Oak Ridge National Laboratory, *Y. Zhang*, *W. Ouyang*, University of California Irvine, *H. Weitering*, The University of Tennessee, *C. Shih*, The University of Texas at Austin, *A.P. Baddorf*, Oak Ridge National Laboratory, *R. Wu*, University of California Irvine, *A.-P. Li*, Oak Ridge National Laboratory

Quantum wires are extremely narrow one-dimensional (1D) materials where electron motion is allowed only along the wire direction, and is confined in the other two directions. Quantum wires, as a smallest electronic conductor, are expected to be a fundamental component in all quantum electronic architectures. The electronic conductance in quantum wires, however, is often dictated by structural instabilities and electron localization at the atomic scale. Adding interwire coupling can often lead to the formation of change density waves. In both cases, the metallic state is not stable and a metal to insulator transition (MIT) occurs at low temperature. [1] Here we show that robust metallic conductance can be stabilized by interwire coupling, while the isolated single nanowires exhibit a MIT due to quantum localization.

We grow the quantum wires of $GdSi_2$ on Si(100) and study the evolution of electronic transport as a function of temperature and interwire coupling as the quantum wires are self-assembled *wire-by-wire*. As shown in Fig. 1, individual nanowires have a width of 16.7 Å, a height of 4 Å, and lengths of micrometers. These nanowires can be grown either in the form of isolated nanowires or bundles with a number of constituent wires separated by an atomic interwire spacing. We perform the correlated study of electronic properties by utilizing both scanning tunneling microscopy and nanotransport measurements on the same nanowire. [2] The approach takes advantage of our developments in fabricating nanocontacts using a field-induced atom emission process to bridge the atomic wires and the mesoscopic transport electrodes. [3] A MIT is revealed in isolated nanowires, while a robust metallic state is obtained in wire bundles at low temperature. The results provide a rare glimpse of the intrinsic structure-transport relations and the influence of local environments at the atomic scale. 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.

1. Changgan Zeng, P.R.C. Kent, Tae-Hwan Kim, An-Ping Li, Hanno H. Weitering, *Nature Materials*, **7**, 539 (2008).

2. Shengyong Qin, Tae-Hwan Kim, Wenjie Ouyang, Yanning Zhang, Hanno H. Weitering, Chih-Kang Shih, Arthur P. Baddorf, Ruqian Wu, and An-Ping Li, *Nano letters*, **12** (2), 938 (2012).

3. Shengyong Qin, Sondra Hellstrom, Zhenan Bao, Boyan Boyanov, and An-Ping Li, *Appl. Phys. Lett*. **100** (11), 022211 (2012).

9:00am **ET+NS+EM-ThM4 Multi-Segment Nanowire Heterojunctions of AuGe and Ge: Fabrication and Electrical Transport**, *X.D. Li*, *G.W. Meng*, Chinese Academy of Sciences, China, *S.Y. Qin*, ***A.-P. Li***, Oak Ridge National Laboratory

One-dimensional (1D) multiple segment nanostructures that contain heterojunctions between various metals and semiconductors are of great interest due to their fascinating chemistry and size-, shape-, and material-dependent properties. Here we report on the synthesis and electronic characterization of multi - segment nanowire (NW) junctions of Au1-xGex and Ge. The 1D heterostructures are grown with a low - temperature chemical vapor deposition process, assisted by electrodeposited Au NWs inside nanochannels of anodic aluminum oxide template.[1,2] The Au-catalyzed vapor-liquid-solid growth process occurs simultaneously in multiple locations along the nanochannel, which leads to multi-segment Au1-xGex/Ge heterojunctions. The structures of the as-grown hybrid NWs, analyzed by using transmission electron microscopy and energy dispersive X-ray s pectroscopy elemental mapping, show clear compositional modulation with variable modulation period and controllable junction numbers. Remarkably, both GeNW and Au1-xGexNW segments are single crystalline with abrupt interfaces and good crystallographic coherences. The electronic and transport properties of individual NW junctions are measured by using a multi-probe scanning tunneling microscope (STM). The semiconducting nature of Ge segments and the metallic behavior of Au1-xGex segments are examined by scanning tunneling spectroscopy (STS). The transport current-voltage curves across the heterojunctions show a characteristic rectifying behavior, which is discussed in association with the potential barriers at the junction. The high yield of multiple segment NW junctions and the ability to control predictably the properties of a metal-semiconductor can facilitate the applications in nanoelectronics and optoelectronics that harness multiple functionalities of hetero-interfaces.

[1] Li, X. D.; Meng, G. W.; Xu, Q. L.; Kong, M. G.; Zhu, X. G.; Chu, Z. Q.; Li, A. P. Controlled Synthesis of Germanium Nanowires and Nanotubes with Variable Morphologies and Sizes. *Nano Lett.* **2011**, *11*, 1704–1709.

[2] Li, X. D.; Meng, G. W.; Qin, S. Y.; Xu, Q. L.; Chu, Z. Q.; Zhu, X. G.; Kong, M. G.; Li, A. P. Nanochannel-Directed Growth of Multi-Segment Nanowire Heterojunctions of Metallic Au1-xGex and Semiconducting Ge. *ACS Nano* **2012**, *6*, 831–836.

9:20am **ET+NS+EM-ThM5 Single Charge Nano Memory using Nano Carbon Material**, ***K. Matsumoto***, *T. Kamimura*, Osaka University, Japan

Single charges nano memory which can shift the threshold voltage by the stored single charge and operated at room temperature was realized using the carbon nanotube as an ultra short channel of 10nm.

The double gate stack insulator layers of Al2O3(3nm) and SiNx (27nm) are deposited using the atomic layer deposition to the suspended carbon nanotube with source and drain electrodes of 70nm separation. The carbon nanotube channel was then surrounded by this double gate stack insulator layers and the gap between the source drain electrodes with the insulator layrers reduced down to as small as10nm. The gate metal was then deposited through this gap to form the gate electrode of 10nm.

The dependence of the drain current on the top gate bias shows weak oscillation along the gate bias with the period of 220mV. The oscillation is attributed to the single charge injection from CNT channel to the Al2O3/ SiNx interface trap, which make the threshold voltage shift of 220mV. The injection of charge is regulated by the Coulomb blockade that stops the next charge to be injected to the trap. The around trip of the gate bias produces the hysteresis. The width of the hysteresis was also regulated by the single charge injection and shows the stepwise increase.

Thus, we have succeeded in fabricating the single charge memory operated at room temperature.

9:40am **ET+NS+EM-ThM6 Combining Atomic Structure, Local Band Alignment, and Electron Transport through Individual Semiconductor Nanowires using Scanning Tunneling Microscopy**, ***R. Timm***, *O. Persson*, *M. Hjort*, *M.T. Borgström*, *L. Samuelson*, *A. Mikkelsen*, Lund University, Sweden

III-V semiconductor nanowires offer tremendous possibilities for device application in energy and information technology [1]. Due to their unique properties and extreme surface-to-volume ratio, it is both essential and challenging to investigate their atomic structure and to combine this information with electrical measurements on individual nanowires. Recently, we have managed to clean InAs nanowires from their native oxide and obtained first atomically resolved images of their side surfaces by

using scanning tunneling microscopy (STM) [2]. Here, we present a systematic STM study covering various nanowire surface structures emerging from different III-V material systems and different crystal structures. By combining STM imaging with scanning tunneling spectroscopy (STS) measurements we simultaneously study the surface structure and local electronic properties across the interfaces of nanowire heterostructures like polytypic nanowires, *p*-*n*-junctions, and material heterostructures.

In order to go further in combining local structural and electronic characterization as well as transport measurements of nanowire devices, we have developed a new method to perform STM/S on individual nanowires *in-situ* under device operation: For this, specific heterostructure nanowires, distributed on a SiO_x/Si substrate, are contacted with metal electrodes defined by electron beam lithography. Using a combined Atomic Force Microscopy (AFM) / STM setup, we can first locate an individual nanowire in AFM mode and then acquire STM images and STS spectra on the contacted nanowire. Thus, we obtain the LDOS spatially resolved along the nanowire, even while the nanowire is externally biased via the metal contacts, allowing simultaneous transport studies. We will show and discuss initial results for different heterostructure nanowire devices, demonstrating the large potential of this new method.

Finally, we can also use the STM to measure electron transport through individual upright standing nanowires still on their growth substrate: After imaging the nanowires from top by STM [3], a point contact between the STM tip and the Au particle on top of the nanowire can be established in ultrahigh vacuum, thereby overcoming the problems in contacting single nanowires known from conventional setups. A high accuracy and reproducibility of this method has been demonstrated for InP and InAs nanowires with different doping levels [4] as well as for Schottky barrier measurements on Au/GaAs nanowires.

[1] Y. Li *et al*., Mater. Today **9** (10), 18 (2006).

[2] E. Hilner *et al*., NanoLetters**8**, 3978 (2008).

[3] A. Fian *et al.*, Nano Letters **10**, 3893 (2010).

[4] R. Timm *et al., submitted* (2012).

10:40am **ET+NS+EM-ThM9 Point-Contact Spectroscopy Study of Topological Insulators and Superconductors**, ***Z. Jiang***, Georgia Institute of Technology

Recently, much attention has been given to an intriguing class of materials, the so-called topological insulators. This type of material exhibits a band gap in the bulk, but gapless states on the edge or surface, which are protected by topological order and cannot be analogized to previous conventional semiconductors or insulators. When topological insulators are in contact with a superconductor (e.g., Nb, a conventional *s*-wave superconductor), novel proximity effect occurs. Theory predicts that the proximity induced superconducting state is spinless and *p*-wave like, and Majorana bound states may appear at the edges. On the other hand, in a related research avenue topological superconductors are predicted to possess unconventional pairing symmetries and gapless surface Andreev bound states. Theoretically massless Majorana fermions could be realized in such materials and used as a building block for topological quantum computation.

Here we present our point-contact spectroscopy studies of topological insulators and superconductors. Specifically, we use a superconducting Nb tip to approach the surface of topological insulators and measure the interface conductance as a function of bias voltage, temperature and magnetic field. Indeed, we find that a superconducting state can be induced at the interface when the Nb tip is in good contact with the topological insulator, as evidenced by observation of a zero-bias conductance peak in the point-contact spectra at a temperature below the superconducting transition temperature of Nb. Such an induced superconducting state is robust even in a magnetic field up to 1T. In the study of topological superconductors, we use a normal-metal Au tip to approach the surface, and a zero-bias conductance peak is also observed. Owing to accurate control of the point-contact barrier strength (tip/sample) in our experiments, the obtained spectra are free of artificial background, and therefore can be quantitatively compared with existing theories; good agreement is achieved.

11:00am **ET+NS+EM-ThM10 Identifying and Measuring the State Variables in TaOx Memristors**, ***P.R. Mickel***, *M. Marinella, C.D. James*, Sandia National Laboratories

We present evidence of the identification and characterization of a new state variable in TaOx memristors. Thus far, the state variable controlling the resistive switching has been believed to be the oxygen concentration in the conducting Ta filament. However, using voltage pulse measurements sensitive to small changes in resistance, we shown that the changing area of the conducting filament is in fact the dominant switching mechanism. The oxygen concentration in the Ta filament is shown to control the memristor resistance for low resistances, after which we observe a clear crossover to the area state variable dominated resistance range. Voltage and temperature dependence are investigated for the switching time-scales, τ, and magnitudes of filament area change, providing insight into their driving mechanisms and the resolution limits of their modulation.

11:20am **ET+NS+EM-ThM11 Terahertz Spectroscopy and Carrier Dynamics of Al Doped ZnO Nanowires**, *S. Balci, W. Baughman, D.S. Wilbert, G. Shen, N. Dawahre, P. Kung*, ***S.M. Kim***, The University of Alabama

Terahertz time domain spectroscopy (THz-TDS) has been widely investigated for many applications in sensing and imaging technologies over the past two decades. Terahertz wave, with a frequency between 300GHz to 10THz, is especially attractive for various applications including security monitoring, biomedical imaging, high speed electronics and communications, and chemical and biological sensing. There is also an increasing interest for nondestructive testing using the THz waves because they have unique properties of propagation through certain media and cover a number of important frequencies. For such applications, THz-TDS has become a powerful tool and measurement technique that can probe carrier dynamics at high frequencies, and thus may yield a better understanding of the characteristics of high frequency optoelectronics and many other fundamental properties of materials. Using THz-TDS, one can determine the frequency dependence of basic properties of materials, including their complex dielectric constant, refractive index and electrical conductivity. Unlike conventional Fourier-Transform spectroscopy, THz-TDS is sensitive to both the amplitude and the phase of the wave, thereby allowing for a direct approach to determining complex values of material parameters with the advantage of high signal to noise ratio and coherent detection. In addition, it is possible to carry out THz-TDS experiments without any electrical contact to the sample being probed, which significantly facilitates electrical measurements on nanostructures and nanomaterials.

In this work, we investigated the physical properties of ZnO:Al nanowires (NWs) in using THz-TDS both at room temperature and elevated temperatures for the first time. ZnO NWs were grown by thermal chemical vapor deposition and in-situ doped with Al, which increased their electrical conductivity by one order of magnitude compared to undoped nanowires. THz-TDS measurements yielded the relative change in the transmitted THz electric field magnitude and phase caused by the samples being probed, which was used to extract the nanowire material refractive indices through mathematical iterative calculations. These subsequently allowed a determination of the complex conductivity, refractive index, and absorption coefficient. To obtain the carrier dynamics parameters, we showed that the Drude-Smith model had to be applied to the frequency dependent complex conductivity in order to determine the plasma frequency and relaxation time. To gain a better understanding of the dependence on doping, the measurements were performed for both undoped ZnO NWs and Al-doped ZnO NWs, as well as a function of temperature in each case.

11:40am **ET+NS+EM-ThM12 Probing Surface-Independent Minority Carrier Transport in Semiconductor Nanowires using Kelvin Probe Microscopy**, ***A. Soudi***, *C. Hsu, Y. Gu*, Washington State University

In advancing semiconductor nanowire-based device technologies, a quantitative knowledge of carrier transport properties is required for a rational design of devices with controlled performance. The one-dimensional confinement of charge carriers and phonons can lead to novel transport properties, and thus represents an advantage of semiconductor nanowires in electronic and opto-electronic applications. However, due to the high surface-to-volume ratio, surface effects are prevalent in nanowires, and the measured carrier transport properties are usually dominated by surface-related processes, such as carrier trapping and recombination processes facilitated by surface states. To evaluate the intrinsic transport properties, especially those related to the confinement effects, the capability to probe surface-independent carrier transport properties is desired. Here we present studies of bulk limited minority carrier transport properties in semiconductor nanowires using the scanning Kelvin probe microscopy technique. Specifically, by measuring and modeling the spatial variations of the nanowire surface potential close to a nanowire-metal Schottky junction, both under an above-bandgap illumination and in the dark, the surface-independent minority carrier diffusion length was obtained.

Authors Index

Bold page numbers indicate the presenter