Nanometer-scale Science and Technology
Room 213D - Session NS-MoM

Carbon Nanotubes-Electrical Properties

Moderator: M.C. Hersam, Northwestern University

8:40am **NS-MoM2 Quantitative Analysis of Electronic Properties of Carbon Nanotubes by Scanning Probe Microscopy: from Atomic to Mesoscopic Length Scales***, **V. Meunier**, S.V. Kalinin, J. Shin, A.P. Baddorf, R.J. Harrison,* Oak Ridge National Laboratory

Scanning Probe Microscopy techniques are the key to real space imaging of electronic transport properties, including the electrostatic potential distribution and local field effects, in low-dimensional systems. The interpretation of SPM data in terms of the local electronic properties of 1D systems such as carbon nanotubes requires quantitative analysis of the tip-nanotube interactions. Here, the electrostatic interactions between a point charge and a carbon nanotube are studied using a combination of first principles density functional calculations and continuum electrostatics modeling. The atomistic first principles investigation is extended to mesoscopic length scales by matching to a continuum electrostatic approach. Furthermore, realistic tip shape effects are included using an image charge model. An approach for the measurement of tip radius of curvature from the electrostatic SPM data is presented. Within this approach, we can quantitatively describe, for the first time, the capacitive tip-surface interactions and predict the magnitude of the tip gate effect in nanoscale systems, such as carbon nanotubes and semiconductor nanowires.

9:00am **NS-MoM3 Electronics and Optoelectronics with Single Carbon Nanotubes***, **P. Avouris**,* IBM T.J. Watson Research Center **INVITED**

Carbon nanotubes (CNTs) are 1D nanostructures with unique properties that recommend them for applications in future nanoelectronics and optoelectronics. I will discuss the electronic structure and electrical properties of semiconducting carbon nanotubes and the fabrication and performance of nanotube devices. Transport experiments and simulations will be used to determine the switching mechanism of nanotube transistors, the nanotube-metal interactions and the role of the ambient environment on the transistor properties. I will then discuss how these findings can be utilized to produce high performance p-, n- and ambipolar nanotube field-effect transistors (CNTFETs) and logic circuits. Semiconducting CNTs are direct gap materials. This, plus their 1D character have important implications for their optical properties. I will first discuss the nature of the excited states of CNTs. I will show that CNTs form strongly bound 1D-exciton states and discuss the scaling properties of these excitons. Spectra obtained by recording the photocurrent of single CNTs employed as channels of CNTFETs will be presented. I will then show that an ambipolar nanotube field-effect transistor can act as a single molecule, electrically-driven light source. The spectra, polarization and the dependence of the light intensity on applied bias will be used to prove that the light is generated through radiative e-h recombination in the CNT. Spatially-resolved studies of the emission as a function of applied bias will be used to map the boundaries of the electron and hole currents and to determine the recombination lengths. These results show that a CNTFET is a particularly versatile molecular device that can be used, depending on the bias conditions, as a high performance electrical switch, a light detector or a light source.

9:40am **NS-MoM5 Ballistic Transport of Hole in 4µm Carbon Nanotube Channel Transistor with Coulomb Blockade Effect***, **K. Matsumoto**,* Osaka University, Japan

We have succeeded in observing the coexistence of the ballistic transport and Coulomb blockade effects of hole in the carbon nanotube channel transistor. The carbon nanotube was grown by the thermal chemical vapor deposition. After the growth of carbon nanotube, the source, drain, gate electrodes were formed. The distance between the source and drain electrode is 4µmm, that means the effective channel length of carbon nanotube is 4µmm. The sample was measured at 8.6K. The dependence of the drain current on the gate bias shows the periodic Coulomb oscillation and Coulomb diamond characteristics with the periods of 150mV. The drain current decrease with the increase of the gate bias, which means the carrier is hole. From the size of the Coulomb gap, the total charging energy was estimated to be as small as 3.1meV. From this charging energy, the length of the island was estimated to be about 4µmm, which coincides with the carbon nanotube channel length. This fact means that the entire carbon nanotube works as one island for the Coulomb blockade effect for the hole. At the outside of the Coulomb blockade regions, the drain current shows the negative differential conductance with the periods of as small as 400µmV. This negative differential conductance is attributed to the resonant tunneling of the hole through the quantum confinement state formed inside the carbon nanotube. From the periods of the negative differential conductance, the length of the quantum well formed inside the nanotube was calculated to be as large as about 4µmm, which again coincides with the entire carbon nanotube channel length. This result means the quite important facts that the quantum confinement state is formed in the entire carbon nanotube and tunneling barrier is formed at the source and drain electrodes. Therefore, hole can transport ballistically through entire carbon nanotube channel of 4µmm by keeping the coherency of the hole wave.

10:00am **NS-MoM6 Carbon Nanotube Photo-detectors***, **M.S. Marcus**, O.M. Castellini, J.M. Simmons, M.A. Eriksson,* University of Wisconsin-Madison

We demonstrate two different nanotube device structures for use as photo-detectors: Bundle devices on quartz using photo-generated currents in the bundle, and transistor devices on Si/SiO@sub 2@ substrates that use photo-generated voltages in the substrate to provide a gating effect. The transistor devices are fabricated on SiO@sub 2@/p-Si substrates, where the p-Si is used as a gate for the nanotube channel. Light is absorbed by not only the carbon nanotube producing photocurrents, but also in the silicon gate that produces a photo-voltage at the interface between the Si/SiO@sub 2@. We observe that photo-voltages of ~15mV change the channel current by up to 1nA in the transistor. The small addition of the photo-voltage when the nanotube is illuminated by a modulated light source acts to probe the derivative of the channel current with respect to the gate voltage. When the laser illuminates at large distances from the nanotube we find that there are smaller but still measurable changes in the channel current, indicating that the carriers responsible for photo-gating are mobile. In order to isolate the nanotube-light interaction from the silicon gate, we have fabricated nanotube bundle devices on transparent quartz substrates. We measure a variety of response times, some of which are surprisingly slow sometimes taking ~8ms to transition from a light off to on state. We propose that inter-tube coupling plays a role in the long response times, and present a model of why it can take photo-generated carriers a long time to be extracted as photocurrent.

10:20am **NS-MoM7 Field Electron Emission from Aligned Carbon Nanotube Bundles at an Ultra-Low Threshold of 1 V/µm***, **K.-Y. Lee**, M. Katayama, N. Hayashi, Y. Terao, T. Miyake, K. Himuro, S. Honda, J.-G. Lee,* Osaka University, Japan*; T. Hirao,* Kochi University of Technology, Japan*; H. Mori, K. Oura,* Osaka University, Japan

To realize a practically applicable field electron emitter made of carbon nanotubes (CNTs), it is desirable to enhance the electric field concentration determined by the aspect ratio and number density of the individual CNT. As predicted theoretically, the field emission from an aligned CNT array becomes maximum when the ratio of intertube distance to the height of each individual CNT is about 2. We have succeeded in fabricating an architecture that satisfies such an optimal condition by using pillars of aligned CNT bundles. This provides a promising method of obtaining the optimal ratio of interpillar distance (R) to pillar height (H). Patterns of 50 µm diameter and 250 µm pitch of the Fe(5 nm)/Al(10 nm) multilayer catalyst were fabricated on a Si substrate by photolithography and sputtering. The pillars of aligned CNT bundles were grown on the patterns at 700°C by thermal chemical vapor deposition with C@sub 2@H@sub 2@ under a pressure of 600 Pa. Each pillar was composed of CNTs with a number density of about 10@super 10@ cm@super -2@. To obtain the optimal R/H of 2, the pillar height of about 125 µm was adopted. The pillar array exhibited a striking field emission characteristic. The threshold field needed to produce a current density of 10 mA/cm@super 2@, E@sub th@, was 1.0 V/µm. The obtained E@sub th@ is extremely low compared with those for other materials that have been reported so far. Monitoring the electron field emission by means of a fluorescent screen demonstrated the emission uniformity. More details of the results on field emission characteristics, and SEM, TEM observations of the carbon nonotube bundles will be presented.@footnote 1@ This work was partly supported by the Handai Frontier Research Center, and a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science, and Technology. @FootnoteText@ @footnote 1@M. Katayama, K.-Y. Lee, S. Honda, T. Hirao, and K. Oura, Jpn. J. Appl. Phys. (in press).

10:40am **NS-MoM8 Modeling of Gas-modulated Carbon Nanotube Schottky Barrier**, ***T. Yamada,*** NASA Ames Research Center

It is reported that the Schottky barrier between a semiconducting carbon nanotube (NT) and a metallic electrode is sometimes modified in the gaseous environment. There are three different cases: (1) there is no charge transfer between the gas and the NT/electrode (gas not charged) and the gas does not have a dipole moment (not polarized), (2) the gas is not charged, but is polarized, and (3) there is a charge transfer between the gas and the NT/electrode and the gas is charged. Case 1 will cause no Schottky barrier modulation. Case 2 will result in the Schottky barrier modulation through the modified work function in either the NT or the electrode due to the dipole moment in the gas. This is understood within the usual Schottky theory. Case 3 will also result in the Schottky barrier modulation, but depending on whether the NT and electrode are connected (closed) or not (open), the modulation is significantly different. The charged gas will attract the opposite charges in the NT and electrode. In the open circuit condition, the gas-NT and the gas-electrode interactions determine how much opposite charges are induced in the NT and electrode, respectively. However, in the closed-circuit condition, which is the usual condition in electronics applications, the induced opposite charges will move around the system and keep the Fermi level constant everywhere. This means that the induced opposite charges are redistributed in the NT and electrode. We have solved this redistribution problem and shown that the Schottky barrier modulation is large when the NT is in the depletion mode, while the modulation is negligible when the NT is consistently in the accumulation mode.

11:00am **NS-MoM9 Environmental Effects on Double Wall Carbon Nanotube Field Effect Transistors**, ***D. Kang***, *W. Park,* Samsung Advanced Institute of Technology, Korea; *J.R. Kim,* Chonbuk National University, Korea; *C.J. Lee,* Hanyang University, Korea; *J.J. Kim,* Chonbuk National University, Korea

With the rise of nanotechnology, there are many new interesting properties induced by their dimensions and geometries. One of the these is large surface area due to their unique geometric shapes such as nanotube and nanowires. For device applications harnessing these materials, large surface area effects on electrical properties should be investigated for a better understanding of nano devices. Double Wall Carbon Nanotube(DWCNT)s could be the best material to investigate the effects because their small band gap should enhance the response to their environments. In this letter, we fabricate DW-CNTFETs in a back-gated structure and investigate environment effects on the electrical properties of DW-CNTFETs in comparison to SW-CNTFETs. Purified double wall CNTs (DWCNT) were suspended in a solvent and spin coated on SiO2 grown on a heavily doped Si substrate. Scanning Probe Microscopy (SPM) located the position of the wires on the substrate. After the pattern for metals contacts were generated by electron beam lithography, metal electrodes were defined by lift-off process after 100nm Pd metal evaporation. We find that DW-CNTFET shows conversion from unipolar to bipolar in vacuum. However, the SW-CNTFET does not show the conversion in the measurement conditions we used in this study. In ambient air, both CNTFETs shows large hysteresis by electron trapping at slow states. We believe that water adsorption on the tube plays an important role for ambipolar conversion.

11:20am **NS-MoM10 Electrical Characterization of Carbon Welds between Multiwalled Carbon Nanotubes**, ***P. Rice***, *S.E. Russek, P. Kabos, R.H. Geiss,* NIST

Nanometer scale electronics based on carbon nanotubes have the potential to revolutionize the electronics industry by reducing circuit sizes dramatically and by increasing operational speed due to inherent properties of the nanotubes. Currently there are very few methods of connecting carbon nanotubes to electronics. The most prevalent so far is using the scanning electron microscope (SEM) focused at a junction between the nanotube and the circuit and growing a carbon contamination buildup we call a weld. This buildup, typical in most SEMs, is caused when the electron beam cracks carbon compounds commonly found on the surface of the sample and in the SEM atmosphere. The subsequent free and chemically active carbon quickly attaches itself to nearby surfaces and builds into mounds securely bonding the nanotube to the surface. Using microlithographic test structures we have measured the electrical characteristics of the nanotube and the welds from dc to MHz frequencies. These measurements have shown a semiconductor behavior of the nanotube and weld combination. To separate the weld electrical properties from the nanotube electrical properties we have built test structures that measure contact resistance between unwelded nanotubes and the same nanotubes after welding. Also, the molecular characteristics of the welds are very dependent on SEM parameters such as electron beam energy, alignment of the electron beam, vacuum pressure inside the SEM chamber, and molecular species near the beam impingement on the sample. We will correlate the structure of these welds to electrical properties as influenced by the SEM deposition parameters using transmission electron microscopy.

11:40am **NS-MoM11 Stiffness and Nonlinear Mechanical Properties of Single-Walled Carbon Nanotube Bundles**, ***P. Jaroenapibal***, *D.E. Luzzi, S. Evoy,* University of Pennsylvania

Nanoscale cantilevered resonators offer great potential as sensing devices due to their high sensitivity to added masses or external forces. Highly-sensitive resonators can be accomplished by using long, thin, stiff, low density, and high quality cantilevers. Hybrid carbon nanotubes represent a powerful platform for the development of tunable nanoresonator-based devices that would provide both high quality resonance and sensing specificity. We have studied the mechanical properties of single-walled carbon nanotube (SWNT) bundles through in-situ transmission electron microscope (TEM) observation of mechanical resonance. The observed resonant frequencies of SWNT bundles ranged from 0.2 - 9 MHz, with resonance qualities Q ranging from 77 to 800. An effective Young's modulus of E* = 76 ± 4 GPa is extracted from the resonance data. This relatively low value indicates that the individual SWNTs are weakly interacting within the bundle, where slippage can occur due to the low sliding resistance between the atomically smooth surfaces of neighboring tubes. Departure from Lorentzian responses, an onset of non-linear behavior was observed under large actuation amplitudes. Specifically, bi-stable responses were observed in 4 µm long and 30 nm wide bundles when their end-point displacement approached a critical amplitude of x@sub c@ = 800 nm. Such non-linear behavior reveals the onset of inter-tube interactions within the bundle when sufficiently large bending is applied. We will discuss this non-linear data with respect to an effective Poisson ratio that results from inter-tube interactions, and describe the impact of beam irradiation on such interactions. Mechanical properties of hybrid carbon nanotubes in which fullerenes or other molecules are encapsulated will also be discussed.

Author Index

Bold page numbers indicate presenter