Nanotubes: Science and Applications Topical Conference
Room: C-209 - Session NT-TuM

Nanotubes: Electronics and Field Emission
Moderator: B. Simard, National Research Council of Canada

8:20am **NT-TuM1 Room Temperature Coulomb Diamond Characteristics in Single Electron Transistor with Position Controlled Grown Carbon Nanotube Channel**, ***K. Matsumoto***, National Institute of Advanced Industrial Science & Technology, Japan, *T. Kamimura*, Tsukuba University, Japan, *M. Maeda, K. Sakamoto, K. Kurachi*, Meiji University, Japan

Even at room temperature, the clear Coulomb diamond structures were obtained in the single electron transistor which used the position controlled grown carbon nanotube as a channel, and Coulomb energy of the device is as high as 400meV. The position contr ol of the carbon nanotube for the channel of the device was successfully achieved using the patterned chemical catalyst process without any difficulty, i.e., using the conventional photo-lithography process, 3 nm thick iron (Fe) catalyst was patterned fo r the source and drain structure on the SiO_2/Si substrate. Using the thermal CVD process, one carbon nanotube started to grow and bridged the gap between the source and drain patterned Fe catalysts. Ohmic metal was then deposited on to the source an d drain regions and on the backside of the Si substrate for the gate. The electrical properties of the device were all measured at room temperature. The device showed the large Coulomb gap of 800mV at around zero gate bias and the Coulomb energy of the de v ice is as high as 400meV that correspond to Coulomb temperature of 5000K. The Coulomb oscillation characteristics was also obtained and its modulation ratio is as high as 96~99% at the drain bias of around 20mV ~100mV even at room temperature. Five Coul omb diamond structures were obtained between the gate bias of @+ -@2V with the different structures sizes. This may come from the multi-islands formation by the residual chemical catalysts and/or the defects in the carbon nanotube. The corresponding island size is only 1nm diameter sphere. Using the position controlled grown carbon nanotube as a channel, ultra-high Coulomb energy of the single electron transistor is easily realized.

8:40am **NT-TuM2 Current Measurement with Tapping Mode AFM to Determine the Electrical Properties of Carbon Nanotubes**, ***M. Stadermann***, *J.J. Boland, M.R. Falvo, R. Superfine, S. Washburn*, University of North Carolina at Chapel Hill

Measurement of contact resistance and electronic transport properties of carbon nanotubes are typically performed with static contacts. Movable contacts provide many advantages over static contacts but difficulties arise from an inability to position the probe precisely on a nanotube, and to control the exact position of the electrical measurement due to thermal drift and piezoelectric hysteresis. The technique presented here allows characterization of the conductivity of different parts of a surface by applying a small voltage to a conductive AFM-tip and then scanning the surface in tapping mode. The resistance of the surface is determined from the current pulses flowing between tip and sample whenever the tip intermittently makes contact with the surface. The advantage of this technique is that electrical and topographical data are taken simultaneously and are therefore in registry. A further advantage is the high number and density of data points taken at constant contact force during a single scan. This method is applied to map out the contact resistance of carbon nanotubes on graphite and examine the coupling between charge transfer modes along and across the tube. It is found that the contact resistance of the nanotube varies with the contact angle.

9:00am **NT-TuM3 Modeling of Gate Bias Modulation in Carbon Nanotube Field-Effect Transistors**, ***T. Yamada***, NASA Ames Research Center

The threshold voltages of a carbon nanotube (CNT) field-effect transistor (FET) are derived and compared with those of the metal-oxide-semiconductor (MOS) FETs. The CNT channel is so thin that there is no voltage drop in a CNT diameter direction perpendicular to the gate electrode plane, and this makes the CNTFET characteristics different from those in MOSFETs. The relation between the voltage and the electrochemical potentials, and the mass action law for electrons and holes are examined in the context of CNTs, and it is shown that the familiar relations are still valid because of the macroscopic number of states available in the CNTs. This situation is significantly different from that of quantum dots. Using these relations, we derive an inversion threshold voltage V_{Ti} and an accumulation threshold voltage V_{Ta} as a function of the Fermi level E_F in the CNT channel, where E_F is a measure of doping. V_{Ti} of the CNTFETs has a much stronger dependence on E_F than that of MOSFETs, while V_{Ta}s of both CNTFETs and MOSFETs depend quite weakly on E_F with the same functional form. This means that the transition from normally-off mode to normally-on mode is much sharper in CNTFETs as E_F is modulated through doping, and this property has to be taken into account in circuit design.

9:20am **NT-TuM4 Charge Imaging and Manipulation Using Carbon Nanotube Probes**, *S.-D. Tzeng, C.-L. Wu, Y.-C. You, T.T. Chen,* ***S. Gwo***, National Tsing-Hua University, Taiwan, ROC, *H. Tokumoto*, AIST, Japan

Direct imaging and manipulation of electric and magnetic domain structures (spontaneously or artificially formed) on the nanoscale has become increasingly important because of the recent developments in high-areal-density storage devices using charge-trapping, ferroelectric, or ferromagnetic materials. Electrostatic force microscopy (EFM) and magnetic force microscopy (MFM), variations of scanning force microscopy (SFM) which utilize nano-sized conducting or magnetic probes to sense the distributions of long-range forces, are two of the most widely used techniques for this purpose. To date, the major difficulty related to the long-range force imaging is to decouple the short-range interactions without degrading the lateral resolution. This problem is especially severe with the conventional micromachined EFM and MFM probes, typically consisted of a cantilever and a tip of conical or pyramidal shape. Carbon nanotubes (CNTs) are novel nanostructures which have a great potential to be used as the probing tips for the scanning probe techniques. It has been shown that CNTs are electrically conducting, mechanically robust with unprecedented elastic properties, chemically stable, and having a perfect cylindrical geometry with very large aspect ratio for imaging long-range forces. Recently, several groups have reported experimental approaches to attach a single CNT to a conventional SFM-tip. Among them, scanning electron microscope (SEM) based technique is the preferred method for preparing CNT tips with controllable tube diameters, lengths, and desired orientations. In this work, we show that CNT is an ideal tip material for "true" local probing of long-range electrostatic forces with a lateral resolution better than 5 nm. Moreover, we demonstrate that CNT tip can be used to manipulate charges on the charge-trapping media (such as Si_3N_4 thin films and Si_3N_4/SiO_2 dielectric multi-layers) with an areal density greater than 60 $Gbit/in^2$.

9:40am **NT-TuM5 Band Gap Engineering in Carbon Nanotubes**, ***J. Lee***, Seoul National University, *H. Kim, J. Ihm,* Seoul National University, Korea, *S.-J. Kahng,* Soongsil University, Korea, *H. Shinohara,* Nagoya University, Japan, *Y. Kuk*, Seoul National University, Korea

Carbon nanotubes have been successfully used for nanometer-sized devices such as diodes, transistors and random access memory cells. Despite these achievements, efforts to integrate these unit devices into functional systems have not yet succeeded. We report a method for constructing self-assembled, multiple quantum dots in a semiconducting carbon nanotube and demonstrate a spatial modulation of the band gap using a low-temperature scanning tunneling microscope.[1] When we imaged topographies of the semiconducting SWNTs at bias voltages of -0.8V to +1.0V, parts of the nanotubes appeared brighter than other areas, suggesting that the diameter may be greater there than at other areas or that the local electronic structure is modified by the inserted fullerene. In the dI/dV spectra, strong VHS peaks corresponding to conduction and valence band edges are clearly observed. The original band gap of about 0.5 eV is narrowed down to about 0.2 eV where the fullerene is expected to be located. There are two possible senarios to explain the observation: 1) Elastic strain can change the band gap significantly. For example, a strain of 4% in the tube axis direction can induce a gap reduction of 60% for the (15,1) tube. 2) Charge transfer from the nanotube to the metallofullerenes or the Au(111) substrate may also induce a change in the electronic structure. We have demonstrated that we can synthesize this band gap-engineered system by self-assembly instead of epitaxial growth.

[1]J. Lee, H. Kim, S.-J. Kahng, G. Kim, Y.-W. Son, J. Ihm, H. Kato, Z.W. Wang, T. Okazaki, H. Shinohara, & Y. Kuk, Nature, 415, 1005 (2002).

10:00am **NT-TuM6 Modifying and Probing the Electrical Properties of Carbon Nanotube Devices using an Atomic Force Microscope**, ***J.-Y. Park***, *Y. Yaish, S. Rosenblatt, M. Brink, P.L. McEuen*, Cornell University

An atomic force microscope (AFM) is used to probe and modify electrical properties of nanotube devices. In one set of experiments, a metalized AFM tip in electrical contact with the nanotube is utilized as a local voltage probe. These measurements reveal the voltage distribution along a nanotube as well as the contact resistance between the nanotube and the metal electrodes. For semiconducting nanotube field effect transistors, these measurements give important information about the bending of the semiconducting bands along the length of the tube. In other experiments, electrical pulses applied to the AFM tip are used to permanently modify the electrical properties of nanotube devices. By controlling the height and duration of the pulses, electrical breaks ("cuts") or tunneling barriers ("nicks") can be created at any point along the tube. The application of these modification techniques in combination with mechanical manipulation for the creation of more advanced device geometries will also be discussed.

10:20am **NT-TuM7 Electrostatically Focused Microfabricated Field Emission Electron Sources with Single Vertically Aligned Carbon Nanofiber Cathodes**, ***M.A. Guillorn***, Oak Ridge National Lab, *A.V. Melechko, M.D. Hale,* Univ. of Tennessee, Knoxville, *R.J. Kasica, V.I. Merkulov*, Oak Ridge National Lab, *E.D. Ellis,* Univ. of Tennessee, Knoxville, *D.K. Hensley, M.L. Simpson, L.R. Baylor, J.H. Whealton, D.H. Lowndes*, Oak Ridge National Lab

Electron beam lithography using a single beam cannot achieve acceptable throughput levels to become a viable manufacturing technology. The digital electrostatic e-beam array lithography (DEAL) concept under development at the Oak Ridge National Laboratory proposes circumventing this problem by writing simultaneously with millions of e-beams from a massively parallel and digitally programmable array of microfabricated electron sources. Such a system will require a robust field emission (FE) source of electrons capable of operation in moderate vacuum. In previous work we have shown that microfabricated FE sources using a single vertically aligned carbon nanofiber (VACNF) cathode are well suited for this application.[1] The ability to synthesize individual VACNF deterministically and incorporate them into conventional device fabrication processes distinguishes this material from other nanostructured graphitic carbon-based FE cathodes. By extending the fabrication process presented in our earlier work we have realized multi-electrode FE devices using this technology. Here we present the design, fabrication and characterization of prototype electrostatically focused FE electron sources intended for use in the DEAL system. The dc operating characteristics of these devices were investigated and fit well to the Fowler-Nordheim model of FE. The divergence of the emitted electron beam from unfocussed devices was evaluated using a microchannel plate system and found to be between 10 and 15 degrees. The effect of the focusing electrodes was analyzed using this system and shown to dramatically improve the focus of the beam. A discussion of these results along with modeling of the device behavior will be presented.

[1]M.A. Guillorn, A.V. Melechko, L.R. Baylor, E.D. Ellis, et al, Appl. Phys. Lett. 79, 3506 (2001).

10:40am **NT-TuM8 Fabrication and Electrical Characterization of Multiwalled Carbon Nanotube Field Emission Devices with Integrated Focusing Electrodes**, ***M.D. Hale***, University of Tennessee, *M.A. Guillorn, M.L. Simpson,* Oak Ridge National Laboratory and University of Tennessee, *C.L. Britton, G. Eres*, Oak Ridge National Laboratory

We report on the fabrication of field emission devices with integrated focusing electrodes that use dense films of multiwalled carbon nanotubes for the emitter material. The fabrication process used to realize these devices is completely compatible with large-scale integrated device production techniques. The current vs. voltage characteristics of these devices were examined and displayed a low turn-on voltage for initiation of electron emission. The effects of the focusing electrode on the field emission characteristics were explored along with the gain, frequency response, and output impedance of these devices. Details on the fabrication process and aspects of device performance will be discussed.

11:00am **NT-TuM9 Field Emission Properties of Nanostructures Based on Molybdenum Ternary Compounds**, ***V. Nemanic***, *M. Zumer, B. Zajec*, Institute of Surface Engineering and Optoelectronics, Slovenia, *M. Remskar, A. Mrzel, D. Mihailovic*, Jozef Stefan Institute, Slovenia

We have investigated the field emission (FE) properties of quasi one-dimensional molybdenum ternary compounds synthesized by a catalytic transport reaction. The self-assembly of tip-shaped nanofibres leads to the growth of a thin foil composed of mutually oriented bundles, below 500 nm in diameter and up to 20 micrometers in length. All FE measurements were performed in a dynamically pumped UHV system at 10^{-9} mbar base pressure. The samples were mounted on the top of metal pins positioned some mm from the aluminized luminescent screen biased as the anode. Current - voltage (I-V) measurements were performed under continuous bias conditions up to 4.5 kV where the resulting macroscopic field reached approx. 0.9 V μm^{-1}. The I-V behavior follows predominately the Fowler-Nordheim equation over the measured range. The emission current from a few sites reached a value of some ten micro amps and the emission spots of various shapes were observed. The current initially dropped, but became relatively stable even on the time scale of few hundred hours.

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