Nanometer-Scale Science and Technology
Room 210 - Session NS-ThM

Nanotube-based Devices

Moderator: S. Evoy, University of Alberta, Canada

8:20am **NS-ThM1 Quantum-dot Nanodevices with Carbon Nanotubes***, K. Ishibashi, S. Moriyama, T. Fuse, D. Tsuya, M. Suzuki,* RIKEN, Japan **INVITED**

Carbon nanotubes are attractive building blocks for extremely small nanodevices. In this paper, we present our effort to fabricate and demonstrate quantum-dot nanodevices, which includes following topics. 1) Single electron devices: A single electron transistor (SET), a single electron inverter that is consisting of two SETs in series, and a single electron XOR that has two input gates to SET, are fabricated in individual single-wall carbon nanotubes (SWCNTs) or multi-wall carbon nanotubes (MWCNTs), and their operation was demonstrated. 2) Quantum computing device (Qubit) and an artificial atom in the SWCNT: We focus on the spin qubit in association with observations of the artificial-atom like behavior. It is shown that the four or two electron shell structure was observed in single electron transport measurements at milli-Kelvin temperatures, and the shell filling of successive electrons and the Zeeman splitting of single particle states were confirmed in the magnetic field evolution of each Coulomb peak. The simple singlet and triplet states were directly observed in excitation spectroscopy measurements when two electrons were contained in a shell. These observations show that the SWCNT is very similar to natural atom with its unique shell structure and an energy scale of submillimeter to THz ranges. Despite the demonstrated wonderful properties as a building block of the nanodevices, we should admit that a breakthrough of device processes suitable for carbon nanotubes is really needed to realize more reliable and reproducible nanodevices.

9:00am **NS-ThM3 Stable Electron Emission from a Multi-Wall Carbon Nanotube in Low Vacuum***, H. Suga,* Nihon University, Japan*; H. Abe, M. Tanaka,* National Institute of Advanced Industrial Science and Technology (AIST), Japan*; T. Ohno,* Technex Lab Co., Japan*; Y. Nishioka,* Nihon University, Japan*; H. Tokumoto, T. Shimizu,* AIST, Japan

Carbon nanotubes have been studied intensively in order to realize functional devices utilizing their unique electrical and mechanical properties. Then we have tried to fabricate the electron emitter using a multi-wall carbon nanotube (MWNT). Electrons are usually emitted applying several kilo volts to tungsten tip apex in ultra high vacuum. Therefore it is necessary to prepare high voltage power supply and expensive vacuum pumps like ion pumps. Then the aim of our research is to realize the MWNT electron emitter, by which electrons can be extracted at voltages lower than 500V in low vacuum around 10@super -3@ to 10@super -5@Pa. MWNT electron emitters are fabricated as follows. Tungsten wire and tungsten loop were spot-welded, the wire was electrochemically etched. Then metal nano particles were smeared on the etched tip. Using a specially designed nano-manipulator combined with SEM (Tiny-SEM (W380mmxD350mmxH600mm) by Technex in Japan), a MWNT was attached on the tip apex, at first by the electron beam induced carbon deposition, and, to further assure the bonding between the MWNT and the tip, smeared metal nano particles were melted by heating tungsten loop. Typical length and diameter of the fabricated emitters are about 5µm and 20nm, respectively. Furthermore, in the SEM, the field emission can be carried out and the emitter-anode plane distance can be easily controlled on a micrometer scale, which is typically about 20µm. We measured turn-on field of 5 V/µm which is lower than conventional tungsten emitter in UHV. The emission current of 0.1 to 0.3µA can be attained at applied voltage of 70 to 160V on the same low vacuum condition. The stability of emission current about 1.5% at 0.3µA can be gained. The new way of high stability and the brightness and lifetime evaluation can be discussed in detail in the presentation. @FootnoteText@ hiroshi-suga@@aist.go.jp, tetsuo-shimizu@@aist.go.jp

9:20am **NS-ThM4 Carbon Nanotubes as Ballistic Phonon Waveguides and Electro-Mechanical Switches***, V. Deshpande, H.-Y. Chiu, H. Postma, M. Bockrath,* California Institute of Technology

PART I: Carbon nanotubes' exceptional thermal conductivity suggests that they may serve as efficient heat conduits to aid in the cooling of nanoscale circuits. Here, we report ballistic phonon transport, which provides the ultimate limit for heat dissipation. Upon heating freestanding nanotube devices with an electrical current, we find that the power required for the nanotube to reach a particular temperature is independent of nanotube length for devices shorter than ~500 nm, and follows a universal scaling law in the tube radius. This provides evidence for ballistic phonon propagation and suggests that, over such length scales, the heat carrying capacity of nanotubes has only fundamental limits imposed by their 1D nature. From our data, we obtain an estimate for the quantum of thermal conductance that is in good agreement with the Landauer picture of phonon transport. We then present a coherent picture of nanotube breakdown based on the thermal activation of bond-weakening electronic transitions. Finally, we find that the efficient propagation of heat to the electrical contacts enables the contacts to be annealed and improved in-situ. PART II: NEMS devices are competitive in switching speed with electronic devices, because of their low mass and small size. We are developing relay devices using multi-walled nanotubes (MWNTs) that exploit the ability of concentric nanotube shells to act as low-friction linear bearings. Analysis of our data yields a measurement of the retraction force on the inner nanotube shells from the outer shells, which agrees with theoretically expected value. We are able to electrostatically telescope shells of a MWNT to establish electrical contact and turn the device to a conducting "on" state. The device can be turned "off" again by applying a sufficiently large gate voltage to bend the nanotube segments until the connection is broken. Possible applications include memories, logic gates, and high-gain nanomechanical amplifiers.

9:40am **NS-ThM5 Carbon Nanotube Transistors and How They Are Different***, J. Appenzeller,* IBM Research Division, US **INVITED**

Over the last few years carbon nanotubes (CNs) have attracted an increasing interest as building blocks for electronics applications. While metallic nanotubes are considered as interconnects in integrated circuits, semiconducting tubes are evaluated as field-effect transistor (FET) components. Since the first CNFET operation has been demonstrated in 1998,@footnote 1,2@ device performance has been significantly improved.@footnote 3,4,5@ Among other things it has been shown that CNFETs operate in the ballistic regime even at room-temperature, provided that not too large drain and gate voltages are applied and that their channel length does not exceed a couple of hundred nanometers.@footnote 6,7,8@ One of the more unexpected findings in the context of CNFETs was that they cannot be described within a conventional MOSFET model. The most critical observation has been that carbon nanotube transistors in fact behave as Schottky barrier devices.@footnote 9,10@ It was found that switching in nanometer size semiconductors, such as carbon nanotubes, contacted with source/drain metal electrodes is determined entirely by the metal/semiconductor interfaces and their field-dependence, provided that transport in the semiconductor is ballistic. Making use of this particular type of nanotube property, we have been able to gain important insights into the topic of multi-mode transport in CNFETs@footnote 11@ and, most importantly, have recently successfully fabricated the first band-to-band tunneling CNFET with a much more abrupt switching behavior than can be obtained with any conventional transistor approach.@footnote 12@ @FootnoteText@ @footnote 1@ S.J. Tans A. Verschueren, and C. Dekker, Nature 393, 49 (1998). @footnote 2@ R. Martel T. Schmidt, H.R. Shea, T. Hertel, and Ph. Avouris, Appl. Phys. Lett. 73, 2447 (1998).@footnote 3@ A. Bachtold, P. Hadley, T. Nakanishi, and C. Dekker, Science 294, 1317 (2001).@footnote 4@ A. Javey, H. Kim, M. Brink, Q. Wang, A. Ural, J. Guo, P. McIntyre, P. McEuen, M. Lundstrom, and H. Dai, Nature Materials 1, 241 (2002).@footnote 5@ S. Wind, J. Appenzeller, R. Martel, V. Derycke, and Ph. Avouris, Appl. Phys. Lett. 80, 3817 (2002).@footnote 6@ M. Fuhrer, H. Park, and P.L. McEuen, IEEE Trans. on Nanotech. 1, 78 (2002).@footnote 7@ A. Javey, J. Guo, Q. Wang, M. Lundstrom, and H. Dai, Nature 424, 654 (2003).@footnote 8@ S. Wind, J. Appenzeller, Ph. Avouris, Phys. Rev. Lett. 91, 058301 (2003).@footnote 9@ S. Heinze, J. Tersoff, R. Martel, V. Derycke, J. Appenzeller, and Ph. Avouris, Phys. Rev. Lett. 89, 106801 (2002).@footnote 10@ J. Appenzeller, J. Knoch, V. Derycke, R. Martel, S. Wind, and Ph. Avouris, Phys. Rev. Lett. 89, 126801 (2002).@footnote 11@ J. Appenzeller, J. Knoch, M. Radosavljevic, and Ph. Avouris, Phys. Rev. Lett. 92, 226802 (2004).@footnote 12@ J. Appenzeller, Y.-M. Lin, J. Knoch, and Ph. Avouris, Phys. Rev. Lett. 93, 196805 (2004).

10:20am **NS-ThM7 Carbon Nanotube Schottky Diodes for High Frequency Applications***, E.W. Wong, H.M. Manohara, E. Schlecht, B.D. Hunt, P.H. Siegel,* Jet Propulsion Laboratory, California Institute of Technology

We have demonstrated Schottky diodes using semiconducting single-walled nanotubes (s-SWNTs) with titanium Schottky and platinum Ohmic contacts for high frequency applications. The devices demonstrate rectifying behavior with large reverse bias breakdown voltages of greater than -15 V. In order to decrease the series resistance, multiple SWNTs are grown in parallel in a single device, and the metallic tubes are burnt-out selectively. At low biases these diodes showed ideality factors in the range of 1.5 to 1.9. Results from devices containing multiple nanotubes suggest that these diodes can act as direct detectors at room temperature at 2.5 terahertz (THz) frequency with noise equivalent powers (NEP) potentially comparable to that of the state-of-the-art gallium arsenide sold-state Schottky diodes, in the range of 10@super -13@W/Hz@super 1/2@. In essence, the SWNT Schottky diodes with multiple parallel tubes per device with individually reduced resistances to the order of a few k@OMEGA@ promise superior performance compared to that of the state-of-the art solid-state Schottky diodes for applications at high frequencies.

10:40am **NS-ThM8 Study of High-Field Electron Transport in Multi-Wall Carbon Nanotubes by MCBJ Technique***, **M. Tsutsui,** Y. Taninouchi, S. Kurokawa, A. Sakai,* Kyoto University, Japan

Multi-wall carbon nanotubes are foreseen to be a promising candidate for interconnects within atomic and molecular transistors owing to their high current carrying capacity. However, there still remain some controversies on high-field electron transport in MWNTs, in particular the conductance versus bias voltage (G-V) characteristics. In the present study, we have investigated high-field electron transport in MWNTs utilizing mechanically controllable break junction (MCBJ) technique. One of the advantages in this technique is that electrode gap distance can be manipulated with pico-meter resolutions after MWNTs being suspended between the electrodes. Bridging of MWNTs over Au electrodes is accomplished by repeatedly breaking Au contacts in a nanotube-dispersed solution. Measured G-V characteristics show that the conductance of MWNTs linearly increases with the bias up to 3 V. An important role of the nanotube/electrode contact resistance on the electron transport through MWNTs is suggested from G-V characteristics acquired at various electrode separations. Bias-polarity asymmetry is observed in Joule heating effects on nanotube/electrode contacts at high biases, and its implications will be discussed in the presentation.

11:00am **NS-ThM9 Enhancement on Field Emission Performance of MWNTs Impregnated with RuO@sub 2@ and Rooted into Metal Substrate***, **H. Liu,*** The Graduate University for Advanced Studies, Japan*; T. Noguchi, K. Tatenuma,* KAKEN Inc., Japan*; S. Kato,* The Graduate University for Advanced Studies, Japan

We have shown that field emission characteristics of MWNTs are drastically enhanced by RuO@sub 2@ impregnation and MWNT rooting into a metal substrate. These new key technologies improve both increase of field enhancement factor due to a proper surface density of subnano and nano sized RuO@sub 2@ particles on MWNT surfaces and increase of electrical conductivity, thermal conductivity, high-temperature resistance and tensile strength due to their high adhesivity between MWNTs and the metal substrate. In this paper, we demonstrate that the electron emission current from bulky MWNTs could reach 1.2A/cm@super 2@ at 6.0V/µm and reach the maximum of 1.9A/cm@super 2@ at 7.5V/µm even in the continuous DC mode in optimization processes for the impregnation and the rooting. According to analysis of microscope images of the substrate, the results above can be corrected by a factor of 2.5 times considering that an area of 40% on the substrate was only covered with MWNTs because surface density of MWNTs on the substrate has not yet fully controlled in the process of the rooting. In the presentation, the detail of these results and discussions will be given with results of endurance running tests at the high current density.

11:20am **NS-ThM10 Topologically Induced Localized States in Single Wall Carbon Nanotubes***, **S.-J. Kahng**,* Korea University, Korea*; S. Lee, H. Kim, J. Lee, Y. Kuk,* Seoul National University, Korea

The local electronic structures of semiconducting single wall carbon nanotubes was studied with scanning tunneling microscopy. We performed scanning tunneling spectroscopy measurement at selected locations on the center axis of carbon nanotubes, acquiring a map of the electronic density of states. Spatial oscillation was observed in the electronic density of states with the period of atomic lattice. Defect induced interface states were found at the junctions of the two semiconducting nanotubes, which are well-understood in analogy with the interface states of bulk semiconductor heterostructures. The electronic leak of the van Hove singularity peaks was observed across the junction, due to inefficient charge screening in a one-dimensional structure. Several paired, localized gap states were observed in semiconducting single-wall carbon nanotubes. A pair of gap states is found far from the band edges, forming deep levels. Another pair is located near the band edges, forming shallow levels. The deep levels are explained by a vacancy-adatom complex while the shallow levels are explained by a pentagon-heptagon structure. Our experimental observation indicates that the presence of the gap states provides a means to perform local band-gap engineering as well as doping without impurity substitution.

11:40am **NS-ThM11 Optimization of Impregnation of Subnano RuO@sub 2@ Clusters on MWCNT for Field Emission Displays***, **T. Noguchi**, K. Tatenuma,* KAKEN Inc., Japan*; S. Kato,* High Energy Accelerator Research Organization (KEK), Japan

For applications of MWNTs to FEDs and the other electron sources, we reported the achievement of a remarkably high DC current density close to 300mA/cm@super 2@ with a threshold electric field of 2V/µm using a new technology of impregnation of subnano RuO@sub 2@ clusters on MWCNT surfaces and of MWNT rooting into a metal substrate. Here we focus on optimization of the impregnation for better electron emission property of MWNTs on ITO glass substrates. Preliminary investigation showed that two orders of magnitude less quantity of the impregnation was sufficient for MWNTs of high purity than MWNTs of low purity to obtain the same emission property. The quite different quantity of the impregnation for proper emission would be explainable based on possible absorption of RuO@sub 2@ particles into the impurities of MWNTs.

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