Nanotubes - Science and Applications
Room 309 - Session NM+NS-MoA

Carbon Nanotubes: Nanoelectronics and Field Emission

Moderator: S. Sinnott, University of Kentucky

2:20pm **NM+NS-MoA2 Analysis of Long-Channel Nanotube Field-Effect-Transistors (NT FETs)**, ***T. Yamada,*** NASA Ames Research Center

Recent experiment on carbon NT p-channel FETs with a long channel (3 µm)@footnote 1@ is analyzed theoretically. They observed saturation of drain current (I@sub d@) as a function of drain voltage (V@sub d@), which plays a crucial role in digital applications. Two possible mechanisms can make the carrier acceleration by V@sub d@ ineffective and bring about the I@sub d@ saturation: (1) Coulomb repulsion from other carriers forming a self-consistent spatial distribution, leading to channel pinch-off; (2) phonon scattering due to a large field created by V@sub d@, leading to carrier velocity saturation. Since the former causes the saturated current I@sub dsat@ to depend quadratically on gate voltage (V@sub g@) and the latter linearly, two mechanisms are distinguishable. Noticing the quadratic dependence in their measurement, we argue that the Coulomb-induced pinch-off formation was the mechanism in these long-channel NT FETs. The maximum field was about 10 kV/cm and the velocity saturation for holes still did not occur. This field is comparable to that of electrons in silicon. |I@sub d@|-V@sub g@ characteristics did not show a sharp rise at the onset of strong inversion, during the transition from accumulation to inversion, as V@sub g@ was increased. This is significantly different from the familiar behavior of metal-oxide-semiconductor FETs. In NT FETs, I@sub d@ was practically zero for a wide range V@sub g@ = 3 to 40 V beyond accumulation. We argue that a high Schottky barrier for electrons existed at the source/drain metal-semiconductor contact and the electron flow was blocked in the inverted case although the hole flow was not in the accumulated case. Making Ohmic contact to both p- and n-NTs is mandatory for complementary circuitry, and will have to be explored for future electronics. @FootnoteText@ @footnote 1@C. Zhou, J. Kong, and H. Dai, Appl. Phys. Lett. 76, 1597 (2000).

2:40pm **NM+NS-MoA3 Electrical Transport in Carbon Nanotubes**, ***Ph. Avouris,*** *P.G. Collins, R. Martel, H.R. Shea,* IBM T.J. Watson Research Center*; H. Stahl, J. Appenzeller,* Physikalisches Institut, Germany **INVITED**

We will discuss studies of the electronic structure and electrical transport properties of individual and ropes of single-wall (SW) and multi-wall (MW) carbon nanotubes (CNTs). Both metallic and semiconducting NTs have been investigated. In the case of metallic NTs we will present results on the observation and interpretation of negative magneto-resistance, weak localization, strong localization, anti-localization, and Coulomb blockade phenomena. In the case of semiconducting NTs, we have observed band-bending, field switching, carrier depletion and inversion phenomena. Some evidence for non-local transport at elevated temperatures in MWNTs will be discussed. In the case of SWNTs ropes we have been able to obtain results on the efficiency of inter-tube electrical transport. Finally, the operation and characteristics of model NT-based devices such as field-effect transistors, single-electron transistors and low-pass filters will be discussed.

3:20pm **NM+NS-MoA5 First Principles Study of Electronic Properties of Molecule Functionalized Carbon Nanotube**, ***J. Zhao,*** *A. Buldum, J.P. Lu,* University of North Carolina at Chapel Hill*; J. Han,* NASA Ames Research Center

We studied the functionalized carbon nanotubes by using first principles methods based on density functional theory (DFT). The adsorption energy and structures are studied for various molecules including: O@sub 2@, N@sub 2@, H@sub 2@O, NO@sub 2@, CO@sub 2@, NH@sub 3@, He. The electronic structures calculations show that SWNT can be either charge donor or acceptor depending on the molecule. Thus the conductive properties of SWNTs can be dramatically changed by exposing to gases.

3:40pm **NM+NS-MoA6 Effect of Commensurate Contact on the Resistance Across the CNT/HOPG Interface**, ***S. Paulson,*** *M.R. Falvo, A. Seeger, R.M. Taylor II, S. Washburn, R. Superfine,* The University of North Carolina

We report measurements of the effect of atomic interlocking on the mechanical behavior and electrical conduction between bodies. We have manipulated carbon nanotubes on an HOPG substrate with a conducting AFM tip as an electrical probe. Along with our lateral force evidence of commensurate contact, we present the first data measuring the change in contact resistance between two atomically smooth surfaces as they go between the commensurate and incommensurate states. The conducting AFM tip contacts the CNT from the top and current is collected in the HOPG substrate, therefor our measurement of resistance is across the CNT diameter as opposed to its length. We find very low resistance for this circumferential current as compared to longitudinal currents that have been reported. Our results will be interpreted in light of models of coupling between the tip and the various electrical modes in the CNT. This work was supported by the National Science Foundation (HPCC, ECS), the Office of Naval Research (MURI), and National Institutes of Health (NCRR).

4:00pm **NM+NS-MoA7 Ultra-Low Bias Operation of Field Emitter using Single Wall Carbon Nanotube Directly Grown onto Silicon Tip by Thermal CVD**, ***K. Matsumoto,*** Electrotechnical Laboratory, Japan*; S. Kinoshita,* Meiji University, Japan*; Y. Gotoh,* Tsukuba University, Japan*; T. Uchiyama,* Advanced Technology Institute, Japan*; S. Manalis,* Massachusetts Institute of Technology*; C. Quate,* Stanford University

The new carbon nanotube field emitter with single wall carbon nanotubes of a diameter of 1~2nm which were grown directly by thermal CVD onto the Si tips and protruded from them@footnote 1@ was developed. Owing to the 10 to 20 times smaller diameter of nanotube than the conventional Si tip, the new carbon nanotube field emitter showed the ultra-low threshold bias of 10V for the field emission of electron which is more than 10~50 times smaller value than the conventional Si emitter. The n-type silicon was etched by SF@sub 6@gas to form the 10900 silicon tips . After the chemical catalyst was spin coated, the sample was set in the furnace with hydro-carbonate gas flow at high temperature. The single wall carbon nanotube then started to grow and followed up the wall of the silicon tip to the top and protruded from the silicon tip. Three kinds of spacers of 6µm, 10µm, 21µm were prepared to change the distance between the anode and the carbon nanotube emitter. When the spacer is 21µm, the electrons began to emit at the applied bias of ~25V. The narrower the spacer, the threshold bias becomes smaller. When the spacer is 6µm, the electron starts to emit at the applied bias of as small as 10V. In the Fowler-Nordheim plot, the current follows the linear lines in 4~5 orders of magnitudes even at the different spacer thickness, which means the electrons are really field emitted from the carbon nanotube through the Fowler-Nordheim tunneling. This single wall carbon nanotube field emitter could be applicable to any kind of low power consumption flat panel displays in future. @FootnoteText@ @footnote 1@ J. Kong, C. Zhou, A. Morpurgo, H. T. Soh, C. F. Quate, C. Marcus, H. Dai, Applied Physics A69, p. 305, (1999).

4:20pm **NM+NS-MoA8 Field Emission Properties of Vertically Aligned Carbon Nanotubes Dependent Upon Gas Exposures and Growth Conditions**, ***S.C Lim,*** *D.J. Bae, K.H. An, Y.C. Choi, H.J. Jeong, Y.H. Lee,* Jeonbuk National University, Korea

Vertically aligned carbon nanotubes have been grown with different growth conditions by microwave plasma chemical vapor deposition and thermal chemical vapor deposition. The field emission properties of such grown carbon nanotubes are studied. Carbon nanotubes under high bias voltage are exposed to hydrogen, nitrogen, and oxygen. After each exposure, changes on turn-on volatage and slpoe of Fowler-Nordheim plots are observed. The saturation region of emission current at high bias voltage has been shifted. Degradation of field emission current from hydrogen and oxygen exposures has been observed. The ratio of change of emission current shows that oxygen exposure degrades the emission current more severely.

4:40pm **NM+NS-MoA9 Study on Field Emission Mechanism of Carbon Nanotube using High-resolution Electron Microscopy**, ***T. Kuzumaki,*** *H. Ichinose, Y. Horiike,* The University of Tokyo, Japan

In investigation of the relation between the tip structures and the field electron emission characteristics of the nanotube, we have found that the nanotube tip is plastically deformed during cold emission. Our studies with a high-resolution transmission electron microscope reveal that the deformation occurred at the local domain containing an isolated pentagonal carbon ring in the polyhedral cap and a convexity is formed along the electric field direction. Semi-empirical molecular orbital calculations show that the pentagon and heptagon pair is introduced into the hexagonal network with a pentagonal carbon ring by heterogeneous nucleation mechanism, and the resulting convexity structure is formed at the tip. The electron emission characteristics of the closed nanotube show that the threshold voltage was high for the first run and the current increased quickly. After the second run the emission started at rather lower voltage and increased gradually. Fowler - Nordheim (F-N) plots show that the first run does not show a straight line. There is no marked change to gradient the second run. The decreasing of the threshold voltage after the second run is possibly due to the structural change of the nanotube tip. The opened nanotubes also show the notable structural change at the tip. The deformed structure can be explained by introducing sp@super 3@ - like line defects in the hexagonal carbon network. In the opened nanotube, the gradient of the F-N plots is decreasing corresponding to change of structure. The formation of the emission site contributes greatly to the stable and highly efficient electron emission from the nanotubes.

5:00pm **NM+NS-MoA10 A Carbon Nano-Tube Based Electron Gun for Electron Microscopy***, O. Zik,* El-Mul Technologies Ltd., Israel*; **J.G. Leopold,*** Dept. of Appl Phys., Rafael Labs, Israel*; D. Rosenblatt,* Rosenblatt Associates

A novel electron gun geometry is proposed with a carbon nano-tube (CNT) grown in a conducting microfabricated crater separated from a gate by an insulating layer. Electron microscopy preferably utilizes point sources. Field enhancement is responsible for the increased emitted current. The field decreases after a very short range to the free space field of the device and the beam diverges. Because the point source and the electron optics are in practice far from ideal, large angular emission density is required with apertures cropping the diverging beam. Thus, a very small portion of the emitted current is useful. Best performance for point sources is gained when the emitter is a rounded, long and very sharp whisker - a 'point on plane' geometry. Such geometry can be realized with CNT's which have exceptional electron emission properties with very low energy spread. However, due to beam divergence, bare CNT's 'on a plane' are inadequate for Scanning Electron Microscopy (SEM) and to miniature SEM's, termed 'microcolumns', in particular. The crater geometry decreases field enhancement on the tip by an order of magnitude so that increased voltage is needed. Due to the excellent field emission of CNT's this voltage is acceptably low so as to obtain about 500nA while not exceeding the breakdown limit of the insulating layer. Our computer simulations support these results. For such geometry the CNT is immersed in a gun which in itself comprises a lens aligning the beam. Almost all the emitted current can be used in a micro-column. In addition to the low energy spread inherent to CNT's, this electron gun has very high brightness which is an advantage for SEM and lithography applications.

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