SYMPOSIUM M

Nanotube-Based Devices

April 22 – 25, 2003

Chairs

Patrick Bernier
Universite Montpellier II
CC26
Montpellier 05, F-34095 FRANCE
33-467-143538

Siegmar Roth
Max-Planck-Inst for Solid State Research
Stuttgart, 70569 GERMANY
49-711-6891401

David L. Carroll
Clemson Univ
118 Kinard Lab
Clemson, SC 29634-0978
864-656-5305

Gyu-Tae Kim
Dept of Electrical Engineering
Korea Univ
Seoul, 136-701 KOREA
82-2-329-03250

Symposium Support
CarboLex, Inc.
Ctr for Optical MS&E Technologies, Clemson University
IBM Corporation
ILJIN Nanotech Co.
Michelin Americas R&D Corporation
Nanoledge SA, France
†RHK Technology, Inc., USA
School of MS&E, Clemson University
†2003 Spring Exhibitor

Proceedings to be published in both book form and online
(see *ONLINE PUBLICATIONS* at www.mrs.org)
as Volume 772
of the Materials Research Society
Symposium Proceedings Series

* Invited paper

SESSION M1: SYNTHESIS AND ELABORATION
Chairs: Patrick Bernier and Alan B. Dalton
Tuesday Morning, April 22, 2003
Nob Hill A/B (Marriott)

8:30 AM *M1.1
CONTROLLED GROWTH OF PECVD PRODUCED MULTIWALL CARBON NANOTUBES/FIBRES. W.I. Milne, K.B.K Teo, M. Chhowalla, D.G. Hasko, H. Ahmen, G.A.J. Amaratunga and S.B. Lee, Univ of Cambridge; P. Legagneux, G. Pirio, E Balossier and D. Pribat, Thales Research and Technology, FRANCE; Vu Thien Binh and V. Semet, University Claude Berbard Lyon, FRANCE; O. Groening, University of Fribourg, SWITZERLAND; M. Castignolles and A. Loiseau, University of Montpellier and CNRS-ONERA, FRANCE.

Since the discovery by Ren et al (1) that vertically multiwall carbon nanotubes could be grown using Plasma Enhanced Chemical Vapour Deposition (PECVD), there has been considerable interest in the use of this technique for the production of nanotubes/nanofibers for applications such as electron emission sources in displays, microwaves amplifiers and parallel ebeam lithography. In the literature today, there are reports of the growth of aligned nanotubes from various plasma techniques such as hot filament PECVD (1), dc (glow discharge) PECVD (2,3) microwave PECVD (4) and inductively coupled plasma PECVD (5). This paper aims to provide a comprehensive parameteric study of the growth, structure and properties of carbon nanotubes/nanofibers grown by dc PECVD. The paper will include production of Ni capped tubes, open ended and branched tubes. The electron emission characteristics of individual nanotubes were also investigated. The field enhancement factor of individual nanotubes were measured from Fowler-Nordheim plots and compared with the geometrical enhancement from the aspect ratio (h/r = 250) of the structures. Maximum field emission currents of 20μA per nanotube emitter were obtained. (1) Z.F. Ren, P. Huang, J.W. Xu, J.H. Wang, P. Bush, M.P. Siegal and P.N. Provencio, Science 282, 1105 (1998). (2) V.I. Merkuov, D.H. Lowndes, Y.Y. Wei, G. Eres, and E. Voelkl, Appl. Phys. Lett 76, 3555 (2000). (3) M. Chhowalla, K.B.K. Teo, C. Ducati, N.L. Rupesinghe, G.A.J. Amaratunga, A.C. Ferrari, D. Roy, J. Robertson and W.I. Milne, J. Appl. Phys. 90, 5308 (2001). (4) C. Bower, W. Zhu, S. Jin and O. Zhou, Appl. Phys. Lett 77, 830 (2000). (5) L. Delzeit, I. McAninch, B.A. Cruden, D. Hash, B. Chen, J. Han and M. Meyyappan, J. Appl. Phys 91, 6027 (2002).

9:00 AM M1.2
DIRECTED GROWTH OF SINGLE-WALLED CARBON NANOTUBES FOR DEVICE DEVELOPMENT. Lance Delzeit, NASA Ames Research Center, Moffett Field, CA; Ramsey Stevens, ELORET Corp, Sunnyvale, CA.

SWNT electronic devices require the horizontal placement of SWNTs between two metal contacts. CVD has demonstrated both patterned (1,2) and horizontal growth between source and drain contacts to make nanotube transistors (3,4). The latter, however, occurred by chance when randomly growing nanotubes bridged across two contacts. In PECVD, nanotubes align in the direction of an electric field (5-7). Further, nanotubes dispersed between two electrodes show alignment with application of an electric field between the electrodes (8). Even in thermal CVD, application of an electric field perpendicular to the substrate (without striking a plasma) has been shown to help align MWNTs vertically (9). In this work, we report the directed growth of SWNTs along a surface using an electric field. This, when combined with lithographic techniques, will allow for the creation of devices for which the growth process will provide the device wiring. 1. A.M. Cassell, N.R. Franklin, T.W. Tombler, E.M. Chan, J. Han, and H. Dai, J. Am. Chem. Soc. 121, 7975 (1999). 2. L. Delzeit, B. Chen, A. Cassell, R. Stevens, C. Nguyen, and M.Meyyappan, Chem. Phys. Lett., 348, 368 (2001). 3. C. Zhou, J. Kong, and H. Dai, Appl. Phys. Lett. 76, 1597 (2000). 4. X. Liu, C. Lee, C. Zhou and J. Han, Appl. Phys. Lett. 79, 3329 (2001). 5. L. Delzeit, I. McAninch, B.A. Cruden, D. Hash, B. Chen, J. Han, and M. Meyyappan, J. Appl. Phys., 91, 6027 (2002). 6. K. Mathews, B.A. Cruden, B. Chen, M. Meyyappan, and L. Delzeit, J. Nanosci. Nanotech. 2, xxx (2002). 7. V.I. Merkulov, A.V. Melechko, M.A. Guillorn, D.H. Lowndes, and M.L. Simpson, Appl. Phys. Lett., 79, 2970 (2001). 8. X.Q. Chen, T. Saito, H. Yamada, and K. Matsushige, Appl. Phys. Lett., 78, 3714 (2001). 9. Y. Avigal and R. Kalish, Appl. Phys. Lett., 78, 2291 (2001).

9:15 AM M1.3
CONTROLLING THE MORPHOLOGY OF CARBON NANOTUBES PERIODICALLY INSERTED WITH METAL PARTICLES BY SEQUENTIAL CATALYTIC GROWTH. Vincent Jourdain, Henning Kanzow, and Patrick Bernier, Université Montpellier II, GDPC, Montpellier, FRANCE; Marie Castignolles and Annick Loiseau, ONERA, Chatillon, FRANCE.

In catalytic decomposition, the growth kinetics of carbon nanotubes is usually considered to be controlled by the step of diffusion through the bulk of the catalyst [1,2]. In these conditions, multiwall and bamboo carbon nanotubes are produced. Meanwhile, very few experimental data is available concerning the influence of the rate-determining step on the structure morphology, the way to control this step or simply the conditions to initiate the growth at the catalyst level. To study these points, we attempted to transfer the rate-determining step to the catalyst supply with carbon, by using very low activities of carbon in the gas phase. In these CVD conditions, we synthesized quasi-periodic nanofilaments with an elementary unit consisting of a carbon nanotube with a Ni/Fe particle encapsulated at one end [3] (the whole looking like a nanoscale match). The periodicity of these nanostructures relates them to the bamboo nanotubes although they differ from them by their periodic metal inclusions and the high aspect ratio of their elementary units. To explain these characteristics, we propose a mechanism based on a sequential growth based on the kinetic mismatch between the growth of the nanotube and its supply with carbon. Quantitative structural study of the elementary units along the nanofilaments by image analysis of HRTEM micrographs enables to determine different growth regimes controlled by the size of the catalyst particle and the carbon supply, and to estimate the critical carbon concentration in the catalyst particle to initiate the growth. The periodic insertion of these nanotubes with metallic particles and the possibility to cleave them into single units ("matches") make them potentially very interesting objects for new magnetic nanodevices. [1] Baker et al., J. Catalysis 30 (1973) 89 [2] Lee et al., J. Phys. Chem. B 106 (2002) 7614 [3] Jourdain et al., Chem. Phys. Lett. 364 (2002) 27.

9:30 AM M1.4
FERROMAGNETIC METAL NANOCLUSTERS ENCAPSULATED IN CARBON NANOTUBES. Ma Xicheng, School of Chemistry and Chemical Engineering, Shandong Univ., Jinan, PR CHINA; Cai Yuanhua, Lun Ning, Wen Shulin, School of Materials Science and Engineering, Shandong Univ. Jina, PR CHINA.

Ferromagnetic nanoclusters are very useful for a magnetic recording. However, application of ferromagnetic nanoclusters is limited due to air-oxidation. One way to solve air-oxidation is to encapsulate ferromagnetic nanoclusters with inert materials such as carbon when they are produced. In this presentation, we demonstrated a very simple method for preparation of Co-filled CNTs. This method provides a new way for encapsulating ferromagnetic materials into the cavity of CNTs. In our experiments, very-high-quality carbon nanotubes encapsulated cobalt nanoclusters were successfully prepared by evaporation of a mixture of carbon and cobalt using high-frequency plasma. These nanotubes had a purity of over 90% and were uniform in structure with an inside diameter of 10-20 nm, an outside diameter of about 30-40 nm, and a length on the micrometer order. Their walls are highly graphitized. Almost all of these CNTs were filled with cobalt nanoclusters (nanoparticles, nanorodes or nanowires), the extent of the filling inside the CNTs is in excess of 50%. Under appropriate conditions, aligned Co-filled CNTs were also formed. Both high-resolution transmission electron microscopy (HRTEM) and energy dispersive X-ray spectroscopy (EDS) were used to characterize the morphology, microstructure and composition of the as-made products. Experimental results showed the encapsulated cobalt always as high temperature alpha-Co phase with fcc structure. Moreover, the encapsulated cobalt were found consists of abundance of twinned boundaries and stacking faults, which were presumed to be responsible for some novel properties of these encapsulates. Magnetic properties of these encapsulates were measured by using a SQUID magnetometer under different fields and temperatures, experimental results showed that these encapsulates possessed excellent magnetic properties, which makes it feasible to use them for a high-density magnetic recording. Further studies to optimize the preparation parameters and investigate the relationship between the microtwines and the magnetic properties are still in pursuing.

9:45 AM M1.5
NOVEL PROCESS METHODOLOGY FOR UNIFORMLY CUTTING NANOTUBES. Steve Lustig, Anand Jagota, Mark Harmer, Paula Hietpas, Greg Mitchell, Roger French, Ed Boyes, Kerry Sams, Tim Gierke, Central Research & Development, DuPont, Wilmington, DE.

We present a novel methodology for the controlled cutting of nanotubes and other nanostructures to well-controlled lengths and sizes. The continuing increase in complexity of electronic devices, coupled with decreasing size of individual elements, are placing more stringent demands on the resolution and accuracy of fabrication patterns. The ability to fabricate on a nanometer scale guarantees a continuation in miniaturization of functional devices. Particularly interesting is the application of nanotubes' chemical and electronic properties which vary with their dimensions and structure. One realization of this process includes the use of photolithography or electron beam lithography to place protective resist patterns over the nanostructures to be cut. Those sections which are not covered by the resist pattern are removed by reactive ion etching. This is a scaleable process which permits the simultaneous cutting of many nanostructures and ensembles of nanostructures. The lengths, shapes or length distributions can be predicted from theory and thus specified for a given application requirement. Nanostructures which can be cut in this process includes nanotubes, nanofibers and nanoplanes. Large scale production of nanostructures with uniform length or specific size-distribution can be used in electronic applications such as field-emission transistors, optoelectronic elements, single electron devices and sensors.

10:30 AM *M1.6
SINGLE-WALLED CARBON NANOTUBE / POLYMER COMPOSITES: PROCESSING AND PROPERTIES. Karen I. Winey, Univ of Pennsylvania, Dept of Materials Science and Engineering, Philadelphia, PA.

Individual single-wall carbon nanotubes (SWNT) possess superior mechanical, thermal and electrical properties and efforts in our laboratory focus on developing processing methods to produce SWNT/polymer composite that harness these extraordinary properties. We have developed and used a variety of solution-based preparation methods that are applicable to a wide range of amorphous thermoplastics, semi-crystalline thermoplastics, and theromosets. Melt fiber spinning of the composites having thermoplastic matrices has been used to align SWNT to a high extent. Dispersion was evaluated using primarily optical microscopy, while alignment was discerned using both polarized Raman spectroscopy and form factor scattering in small angle x-ray scattering. In addition to structural characterization, a variety of physical properties have been measured: elastic modulus, toughness, flame retardation, electrical conductivity, and thermal conductivity. Two types of composites will be highlighted. Composites using poly(methyl methacrylate) have been loaded with up to 10wt% SWNT, show good dispersion and highly aligned SWNT, and exhibit higher stiffness and a >120% increase in thermal conductivity with only 2wt% SWNT. After the SWNT has been functionalized with 18-carbon alkane chains, composites using nylon6 have been successfully loaded with up to 4wt% SWNT.

11:00 AM M1.7
CONTROLLED GROWTH OF SINGLE-WALLED CARBON NANOTUBES FROM ORDERED MESOPOROUS SILICA. Limin Huang, Stephen P. O'Brien, Columbia University, Department of Applied Physics & Applied Mathematics, New York, NY; Shalom J. Wind, IBM T.J. Watson Research Center, Yorktown Heights, NY.

Single-walled carbon nanotubes have shown promising electrical properties for future generations of integrated molecular electronic devices. The integration requires the ability to assemble individual carbon nanotubes (CNTs) into desired architectures with controlled diameter and orientation. We report the growth of CNTs with controlled orientation and diameter (1-4 nm) from thermally stable, highly ordered mesoporous SiO_2 thin films by methane chemical vapor deposition (CVD). Controlled incorporation of an Fe precursor into one-dimensional (1D) and three-dimensional (3D) pore channels of mesoporous SiO_2 results in a nanostructure catalytically active for CNT growth and stable to typical CVD temperatures. Growth of CNTs starts within the mesoporous SiO_2, whose pore direction and pore dimension play an important role in the orientation and diameter of the CNTs at the early stage of the growth. Mesoporous silica with different pore sizes (2-6 nm) has been used to study the effect of pore size on the dimensions of the nanotubes. Parallel CNT assemblies have been created by a simple procedure that allows the lateral growth of the CNTs with controlled tube dimension from line-patterned mesoporous SiO_2 thin films, which were fabricated by soft-lithography. The flexibility of constructing complex nanotube assemblies and nanotube junctions by this simple method suggests its high potential for fabricating future integrated molecular electronic nanodevices.

11:15 AM M1.8
FLAME SYNTHESIS OF CARBON NANOTUBES. Murray J. Height, Jack B. Howard, and Jefferson W. Tester, Dept of Chemical Engineering, Massachusetts Institute of Technology, Cambridge, MA.

Flames offer potential for synthesis of carbon nanotubes in large quantities at modest costs. This study aims to examine conditions for carbon nanotube formation in premixed flames and to characterize the morphology of solid carbon deposits and their primary formation mechanisms in the combustion environment. Single-walled nanotubes have been observed in the post-flame region of a premixed acetylene/oxygen/argon flame operated at 50 torr with iron pentacarbonyl vapor used as a source of metallic catalyst. A thermophoretic sampling method and transmission electron microscopy were used to characterize the solid material present at various heights above burner (HAB), giving resolution of formation dynamics within the flame system. Gas-phase composition and temperature profiles were also obtained to give a complementary view of conditions leading to nanotube formation. Temperature measurements were performed using thermocouples and gas phase composition profiles were obtained via sampling probe and gas chromatography. Catalyst particle formation and growth is observed in the immediate post-flame region, 10 to 50 mm HAB, with coagulation leading to typical particle sizes on the order of 5 to 10 nm. Nanotubes were observed to be present after 50 mm HAB (~50 milliseconds). Between 50 and 70 mm HAB (period of 30 ms), nanotubes are observed to form and coalesce into clusters. Based on the rapid appearance of nanotubes in this region, it appears that once initiated, nanotube growth occurs quite rapidly, on the order of 1 to 10 microns per second. High resolution TEM revealed the nanotubes to be primarily single-walled. A nanotube formation "window" is evident with formation limited to fuel equivalence ratios between a lower limit of 1.5 and an upper limit of 1.9. A continuum of morphologies ranging from relatively clean clusters of nanotubes to amorphous material is observed between the lower and upper limits. Rapid quenching of the post-flame gases using secondary injection of argon favors the formation of amorphous carbon rather than nanotubes. We suggest that the diversity of morphologies is due to competition between amorphous and structured carbon precipitation pathways.

11:30 AM M1.9
STRUCTURAL CHARACTERISTICS OF CARBON NANORODS AND NANOTUBES GROWN USING ELECTRON CYCLOTRON RESONANCE CHEMICAL VAPOR DEPOSITION. Yun-Sung Woo, Duk-Young Jeon, Korea Advanced Institute of Science and Technology, Dept of Materials Science and Engineering, Taejon, KOREA; In-Taek Han, Young-Jun Park, Ha-Jin Kim, Jae-Eun Jung, Jong-Min Kim, Samsung Advanced Institute of Technology, FED project, Suwon, KOREA; Nae-Sung Lee, Sejong University, Dept of Advanced Materials Engineering, Seoul, KOREA.

Electron cyclotron resonance chemical vapor deposition (ECR-CVD) is one of the promising routes for the low temperature synthesis of multi-walled carbon nanotubes (MWNTs), since the plasma zone in the ECR-CVD is remote from the substrate, giving rise to a benefit of maintaining the substrate in low temperatures during deposition. Moreover, radio-frequency (RF) or direct-current (DC) biasing can impart ion bombardment energies to the substrate without disturbing the ECR plasma. We recently succeeded in synthesizing the vertically aligned MWNTs at temperature as low as 400°C using ECR-CVD with RF biasing to the substrate. The morphology of MWNTs varied with the applied RF bias voltages, which results from the different degree of ordering in graphene layers in the MWNT wall. It was also observed that the distance between the two graphene layers of carbon nanorods formed at lower RF bias voltages is measured to be about 0.385 nm, which is much larger than that of MWNTs grown at high RF bias voltages, having typical value of about 0.344 nm for graphite. Raman analysis indicated that the shortening of the C-C bond length occurs with the structural change from carbon nanorod to well-graphitized MWNTs, which is considered to be related with lower concentration of sp^3 C-C bonds. This was proved by electron-energy-loss spectra, showing that the relative ratio of π to σ peak appears to be larger for carbon nanorod than MWNTs. The investigation using NMR and XPS also showed the differences of bonding characteristics between carbon nanorod and MWNTs.

11:45 AM M1.10
PATENT DATABASES AND ANALYTICAL TOOLS FOR NANOTECHNOLOGY RESEARCH, DESIGN AND DEVELOPMENT. William N. Hulsey III, Hughes & Luce, LLP & IC2 Institute, University of Texas, Austin, TX.

As the successful development of concepts and implementations of nanotechnologies depends increasingly on more rapid and pervasive commercialization and market development, intellectual property legal protections take on greater significance. These protections and the assets arising from them derive from carefully balanced economic principles that encourage the development of creative writing, inventions, art and knowledge. In the fields of nanotube-based device design research, development, and commercialization, patents present a valuable resource, which may not be fully utilized by researchers and engineers. Many researchers and engineers, unfortunately, fail to either adequately or appropriately avail themselves of the rich informational resource that issued patents and published patent applications represent. To address this concern and make the patent system more accessible, the paper and presentation provide a brief overview of the patents, the patent system, and how they relate to other intellectual property laws. Then, there will be a demonstration of the use of analytic tools and worldwide patent and business databases to explain how to generate intuitive views of technologies that suggest opportunities, reveal risks and provide decisive insight into the scope and value of patents in areas important to nanotechnologies and their implementations. Patent research results will focus on the fields of nano-devices, nano-electronics, and especially carbon nanotubes. In particular, the information will present examples of the most recently issued patent and published patent applications of relevance to nanotechnology research, development, and commercial applications. Also, the presentation touches on major areas of development of nanobusiness relating to intellectual property rights that affect investment and venture capital, emerging markets, advances in applications, and commercialization of nanotube-based technologies. Through the integration of patent-related content and strong analysis tools, the presenter gives a demonstration of ways to use new research and innovation sources. The result may lead to researchers identifying more readily otherwise unseen development and licensing opportunities, as well as to improving productivity by identifying license-in opportunities early in the research and development process. Moreover, a brief address of most recent patent-related lawsuits and disputes relevant to nanotechnology commercialization will occur.

SESSION M2: ELABORATION AND CHARACTERIZATION

Chairs: William I. Milne and Karen I. Winey
Tuesday Afternoon, April 22, 2003
Nob Hill A/B (Marriott)

1:30 PM M2.1
STRUCTURAL ORGANIZATION OF CARBON NANOTUBES BY PROTEINS. Alan B. Dalton, Joselito Razal, Edgar Munoz, Ray H. Baughman, Univeristy of Texas at Dallas, NanoTech Institute, Richardson, TX; Geoff M. Giordano, Inga H. Musselman, Gregg R. Dieckmann, University of Texas at Dallas, Dept of Chemistry, Richardson, TX; Paul A. Johnson and Rockford K. Draper, University of Texas at Dallas, Department of Molecular and Cell Biology, Richardson, TX; J. Chen, Zyvex Corporation, Richardson, TX.

Carbon nanotubes have novel electrical and mechanical properties that can be exploited to improve existing technologies and perhaps create new technologies barely yet conceived. However, a practical problem in many potential applications for nanotubes is their organization into useful geometries. We describe the use of proteins to organize nanotubes into macromolecular structures. Amphiphilic polypeptides have been synthesized that bind nanotubes by hydrophobic interactions. The peptides are also designed to self-assemble by peptide/peptide interactions which subsequently generate controlled orientations of nanotubes by non-covalent interactions with the nanotube surface. Electron microscopy and polarized Raman studies reveal that the peptide-coated nanotubes assemble into fibers with the nanotubes aligned along the fiber axis. Most importantly, the size and morphology of the fibers can be controlled.

1:45 PM M2.2
PEPTIDES WITH SELECTIVE AFFIINITY FOR CARBON NANOTUBES. Siqun Wang, Steve Lustig, Hong Wang, Nancy Rizzo, Shekhar Subramoney, Bibiana Onoa, Anand Jagota, Ellen S. Humphreys, Sung-Yoon Chung, Yet-Ming Chiang, The DuPont Co, Wilmington, DE.

Peptides for selective affinity for carbon nanotubes have been discovered via phage display against nanotubes grown via thermochemical processing of SiC. Consensus binding sequences show a motif rich in His and Trp, with specific locations. Analysis of the hydrophobicity of the peptide chain suggests they act as symmetric detergents, with a hydrophobic region in the middle and hydrophilic regions at the ends. Binding specificity has been confirmed by demonstrating direct attachment of nanotubes to phage and free peptides immobilized on microspheres. The importance of the specific motif is shown by point mutation experiments that result in large changes in binding strength. A statistical mechanical treatment of peptide conformations shows a folding pattern in the binding sequence consistent with the geometry and structure of carbon nanotubes. Our findings open the possibility that short peptides with specific binding for different types of nanotubes can be found.

2:00 PM M2.3
A NOVEL ROUTE FOR MAKING POLYSTYRENE-GRAFTED SINGLE-WALLED NANOTUBE COMPOSITES-TOWARDS A BETTER NANOTUBE-POLYMER INTERFACE. Gunaranjan Viswanathan, Dept of Chemical Engineering, Rensselaer Polytechnic Institute, Troy, NY; Nirupama Chakrapani, Dept of Materials Science and Engineering, Rensselaer Polytechnic Institute, Troy, NY; Chang Y. Ryu, Dept. of Chemistry, Rensselaer Polytechnic Institute, Troy, NY; Pulickel M. Ajayan, Dept of Materials Science and Engineering, Rensselaer Polytechnic Institute, Troy, NY.

Polymer-carbon nanotube composites combine the unique properties of nanotubes with the ease of processability of polymers. Especially for application as structural reinforcements, a good interface between the nanotubes and the host matrix should exist for efficient load-transfer. We have developed a novel route for grafting polystyrene chains onto single-walled nanotubes to obtain homogeneous, well-dispersed composites. This is accomplished using an anionic polymerization scheme. Differential Scanning Calorimetry and Thermal Gravimetric Analysis techniques are used to characterize the thermal properties of the composites and also to evaluate the efficacy of the grafting mechanism. The kinetics and mechanism of initiation are studied using in-situ UV/Vis, 1H NMR and Raman spectroscopy.

2:15 PM M2.4
TRANSPARENT POLYMER-NANOTUBE COMPOSITES PRODUCED VIA SOLAR RADIATION, IONIZING RADIATION (GAMMA) AND HEAT (OVEN). L. M. Clayton and J.P. Harmon, Dept. of Chemistry, University of South Florida, Tampa, FL; M. Meyyappan and M. Cinke, NASA Ames Research Center, Moffett Field, CA; A. Cassell, Eloret Corporation, Sunnyvale, CA; A. Kumar and A.K. Sikder, Center for Microelectronics Research, University of South Florida, Tampa, FL.

Polymer-nanotube composites were produced via Solar Radiation, Ionizing radiation (gamma) and Heat (oven). These techniques were chosen to produce poly (methyl-methacrylate)/single-walled nanotube (PMMA/SWNT) composites which resulted in thin films with varying degrees of transparency in the uv and uv-vis region of the electromagnetic spectrum. Differential Scanning Calorimetry (DSC) characterized glass transition temperatures. Ultraviolet-visible spectroscopy (UV-VIS) quantified the transparency of the composites. Dielectric Analysis (DEA) characterized the alpha and beta transitions and Dynamic Mechanical Analysis (DMA) characterized viscoelastic properties. Scanning Electron Microscopy (SEM) captured images of the PMMA/SWNT composite. Samples were also exposed to ionizing radiation in order to understand radiation effects on the transparent thin film immediately after irradiation and several months after irradiation.

2:30 PM M2.5
LARGE SCALE GROWTH OF HIGHLY ALIGNED C-N NANOTUBES PRODUCED BY LOW TEMPERATURE CVD. Jiwen Liu, Richard Czerw, Jung-Ho Park, Scott Webster, and David L. Carroll, School of Materials Science and Engineering, Clemson University, Clemson, SC.

Nitrogen doped multiwalled carbon nanotubes (MWNTs) were synthesized by the decomposition of a pyridine-ferrocene mixture at 700 C. These tubes are highly aligned and very straight with a bamboo structure typical of n-doped MWNTs. The tubes have been characterized by scanning tunneling microcopy (STM) and spectroscopy (STS) as well as scanning electron microscopy and transmission electron microscopy. The atomic structure of the tubes from STM clearly shows pyridine-like structures, and there is a donor state near the Fermi level evident in the STS which indicates that these tubes are n-type conductors.

2:45 PM M2.6
SYNTHESIS OF C AND CNX NANOTUBES, USING THE AEROSOL METHOD. M. Glerup, M. Castignolles, H. Kanzow, P. Bernier, GDPC, Universite Montpellier II, Montpellier, FRANCE; A. Loiseau, LEM, ONERA, Chatillon, FRANCE.

We will in this work present some of the results we have obtained using the aerosol method for the production of C and CNX nanotubes. We are using the aerosol method, though slightly modified [1], making us able to use a broad range of catalyst precursors and organic liquids as the carbon source. Thus we are able to use catalyst and mixtures of catalyst which are normally not possible in low tempertaure synthesis methods. We will present the state-of-the-art using this synthesis method. Nitrogen doped carbon nanotubes have been produced using the same method. By simply using a liquid mixture of a nitrogen and a carbon containing solvents we have been able to produce N-doped carbon nanotubes. Furthermore by simply changing the N/C ratio in the liquid mixture it is shown to be possible to change the N/C ratio in the synthesized nanotubes. The N/C ratio is determined using Electron Energy Loss Spectroscopy (EELS) and X-ray Photoemission Spectroscopy (XPS). The samples produced with this method are all very homogenious and with a very high purity. All samples are characterized using scanning and transmission electron microscopy (SEM), (TEM), respectively and X-ray diffraction and Raman spectroscopy. [1] M. Glerup, H. Kanzow, R. Almairac, P. Bernier, Electronic Properties of Novel Materials - XVI International Winterschool, Ed. by Hans Kuzmany, Jörg Fink, Michael Mehring, Siegmar Roth, AIP Conference Proceedings No. 633, (Woodbury, New York, 2002), p.161-164.

3:30 PM M2.7
SINGLE WALL CARBON NANOTUBE BASED "PEAPOD" DEVICES ON Si_3N_4/Si : SYNTHESIS AND CHARACTERIZATION.

B.C. Satishkumar, S.A. Paulson, A.T. Johnson and D.E. Luzzi, Department of Materials Science and Engineering, Department of Physics and Astronomy and Laboratory for Research on Structure of Matter, University of Pennsylvania, Philadelphia, PA.

We have produced filled SWNT "peapod" devices across windowed Si_3N_4/Si substrates, on which structures within the SWNTs can be characterized. Isolated and crossed SWNTs were grown on lithographically patterned Si_3N_4/Si substrates using methane and/or ethylene with iron as the catalyst. As a function of synthesis conditions, the diameter of the nanotubes varies in the range of 1-5 nm with lengths up to 5 mm. The unique morphology of these samples allows us to systematically control processing parameters, conduct multiple experiments on the same individual SWNT, and deposit contacts for electrical experiments. The effect of air oxidation, suspension in acids including H_2O_2, HNO_3 and HCl, and vacuum annealing on sample purity and SWNT structure have been characterized. Both empty and filled "peapod" devices have been produced. The formation of junctions between crossed nanotubes by thermal processing and electron beam irradiation and the effect on device properties will be reported. This method is also used to explore defect recovery processes and kinetics in single SWNT devices.

3:45 PM M2.8
INCORPORATION OF MULTI WALL CARBON NANOTUBES INTO GLASS-SURFACES VIA LASER-TREATMENT. T. Seeger, W.K. Maser, A.M. Benito, M.T. Martinez, Instituto Carboquimica, CSIC, Zaragoza, SPAIN; G. de la Fuente, ICMA, CSIC Universidad de Zaragoza, Zaragoza, SPAIN; A. Righi and J.L. Sauvajol, Groupe de Dynamique des Phases Condensees, UMR CNRS 5581, Université, Montpellier II, FRANCE.

Carbon nanotubes (CNT) are interesting candidates for the reinforcement in robust composites and for conducting fillers in polymers due to their fascinating electronic and mechanical properties. For the first time, we report the incorporation of multiwalled carbon nanotubes (MWNTs) into silica-glass surfaces by means of partial surface-melting caused by a continuous wave Nd:YAG laser. MWNTs were detected being well incorporated in the silica-surface. The composites are characterized using scanning electron microscopy (SEM), Raman-spectroscopy, scanning transmission electron microscopy (STEM) and high resolution electron energy-loss spectroscopy (HREELS). A model for the composite-formation is proposed based on heat-absorption by MWNTs and a partial melting of the silica-surface.

4:00 PM M2.9
REINFORCEMENT OF CARBON NANOTUBE ROPES BY LOCAL IRRADIATION. András Kis, Edina Couteau, Andrzej Kulik, László Forró, Swiss Federal Institute of Technology, School of Basic Sciences, Lausanne, SWITZERLAND; Jean-Paul Salvetat, CRMD-CNRS, Orleans, FRANCE; Jürgen Brugger, Swiss Federal Institute of Technology, School of Engineering, Lausanne, SWITZERLAND.

Since the discovery of carbon nanotubes (CNTs), they have attracted the attention of many scientists and engineers worldwide - partly because of their exceptionally high Youngs modulus, similar to that of diamond. This fact prompted the idea of using them as reinforcing elements. However, single walled carbon nanotubes (SWNTs) are often produced as bundles of weakly interacting tubes that easily slide past one another. As a consequence, the bending modulus of SWNT ropes can be as low as 10 GPa, even though single, isolated CNTs have a Young's modulus on the order of 1 TPa. This weakness, together with the inability to produce larger-scale structures, has stalled their application as the ultimate reinforcement fibre. We demonstrate how stable links can be induced between neighbouring tubes with a small dose of electron irradiation. A series of measurements using an atomic force microscope (AFM) has demonstrated that a modest irradiation by electrons inside a transmission electron microscope can induce the formation of cross-links that connect neighbouring tubes inside a SWNT rope while minimally disturbing overall structural integrity. AFM measurements have shown that the bending modulus of ropes has increased 40-fold: from 20 GPa, to 800 GPa, very close to the ideal value of 1TPa for a single tube. This method also offers a new and exciting opportunity of building larger-scale structures composed of strongly connected carbon nanotubes.

4:15 PM *M2.10
NUCLEAR MAGNETIC RESONANCE INVESTIGATIONS OF CARBON NANOTUBES BASED MATERIALS.
Christophe Goze-Bac, CNRS GDPC Université, Montpellier, FRANCE.

In this talk, NMR on pristine, functionalized and intercalated carbon nanotubes is presented. In the light of lineshape analysis and spinlattice relaxation studies with temperature from 400K down to 4K, we investigated the structures, dynamics and electronic properties of all these compounds. In particular, we focus on the presence or not of a metallic state. In pristine materials, from ^{13}C NMR, the metallic/semiconducting NT signatures are well identified which allows us to estimate their ratio in bulk samples. In functionalized NT, possible chemical modifications were found. After functionalization, the metallic behavior of the one-third $original - conducting$ NT is supressed, suggesting localization of conduction electrons on the defects or chemical functions of the NT. Intercalated NT with Li, Rb and Cs were also measured using ^{13}C and alkali NMR. We will present and discuss the results in terms of localization of alkali and electronic charge transfer. All the compounds are metallic and an universal behavior is found: *increasing concentration of alkali the density of state at the Fermi level gets higher.*

4:45 PM M2.11
LOCAL STRUCTURE AND ELECTRONIC STATES OF ALKALI-DOPED FULLERENE-PEAPODS STUDIED BY SOLID STATE NMR. Hironori Ogata, Masato Mukaiyachi, Hosei Univ, Dept of Materials Chemistry, Tokyo, JAPAN; Kouji Ito, Yahachi Saito, Mie Univ, Dept of Electronics and Electronic Engineering, Mie, JAPAN.

C_{60} encapsulated Single-walled Carbon Nanotubes(C_{60}@SWNTs) have specific one-dimensional structure and electronic properties and expected to have interesting nano electronic properties by alkali metal doping. Local structure and electronic states of potassium doped C_{60}@SWNTs is reported using solid state NMR spectroscopy. Doping of potassium was performed for ^{1}3C-enriched C_{60} encapsulated SWNTs in the evacuated and sealed glass tube at 220°C for 10 hours. In Raman spectrum of the sample, we observed a peak at 1424 cm^{-1}, which is assigned to the pentagonal pinch mode of $C_{60}{}^{6}$-(saturately doping). The sharp peak observed at 110 ppm in ^{13}C-NMR spectrum in C_{60}@SWNTs, which is associated with encapsulated C_{60}, broadened and exhibited up-field shift by potassium doping. No evidence of sp^3-carbon was observed in ^{13}C-NMR spectrum to 10 K. Temperature dependence of $(T_1)^*T$ exhibited a temperature dependence, due to elecron correlation effect. Detailed analytical results based on Luttinger liquid theory will be presented.

SESSION M3: POSTER SESSION
MOSTLY ELABORATION
Tuesday Evening, April 22, 2003
8:00 PM
Salon 1-7 (Marriott)

M3.1
CHEMICAL MODIFICATION OF SINGLE WALLED CARBON NANOTUBES. Urszula Dettlaff-Weglikowska, Viera Skakalova, Siegmar Roth, Jean-Michel Benoit, Max-Planck-Institut fuer Festkoerperforschung, Stuttgart, GERMANY, and Univ Nantes, Lab de Physique Cristalline, Nantes, FRANCE; Ralf Graupner, Univ Erlangen, Institut fuer Technische Physik, Erlangen, GERMANY.

Chemical functionalization of purified single walled carbon nanotubes (SWNT) has been performed using acidic chloride an forming amide. XPS and Raman spectra at each step of the chemical treatment provide direct evidence that the electronic properties of the SWNT have been modified. Depending on the nature of the terminating functionality, different charge transfer can be observed. After reaction with SOCl2 the carbon C(1s) peak (at 284.38 eV in pure nanotubes) is downshifted by 0.4 eV, suggesting acceptor behavior of the attached groups. This reaction strongly affects the metallic shape of the Breit-Wigner-Fano profile in the tangential mode of the Raman spectrum. Subsequent reaction with amines causes that metallic profile to reappear, indicating opposite direction of charge transfer. The XPS spectra show a shift of the C(1s) peak to the higher binding energy after reaction with amines (as compared to graphite and pure SWNT). The influence of the chemical treatment on the optical absorption spectra will be discussed.

M3.2
Abstract Withdrawn.

M3.3
ELABORATION OF SILICON-BASED NANOWIRES AND NANOCABLES. Karine Saulig-Wenger, David Cornu, Philippe Miele, Fernand Chassagneux, Stephane Parola, Laboratoire des Multimateriaux et Interfaces, UMR 5615 CNRS, Université Claude Bernard-Lyon 1, Villeurbanne, FRANCE; Thierry Epicier, GEMPPM, INSA Lyon, FRANCE.

The discovery of carbon nanotubes (CNTs) has been the starting point of numerous studies devoted to nanoscale materials. Several works were initiated in order to prepare nanoobjects of various chemical composition such as BN or WS2 nanotubes and Si, Ga or SiC nanowires (NWs) which could be more efficient than CNTs for diverse applications. Among this materials, cubic silicon carbide (c-SiC) in the form of nanomaterials is particularly interesting because of its unique intrinsic chemical and electronic properties. For example, c-SiC NWs offer exciting opportunities in nanoelectronic for high temperature, high power and high frequency applications. Moreover, coaxial multielement nanostructures (nanocables, NCs) could offer good opportunities particularly as reinforcement agents for mechanical applications. But only few methods have been developed to elaborate such nanocables and they usually involve heavy technical apparatus. Recently, we prepared cubic silicon carbide nanowires by direct reaction between silicon and carbon at 1200°C under nitrogen. This simple method has been extended to the preparation of h-BN/c-SiC nanocables composed of a cubic SiC core coated with several layers of hexagonal boron nitride. Those nanocables are several micrometers long with 50nm diameter. By changing the experimental conditions (atmosphere, temperature), this method have been extended to the elaboration of various nanowires (like amorphous SiO_2 NWs or hexagonal Si_3N_4 NWs) and nanocables (like amorphous SiO_2 NWs or hexagonal Si_3N_4 NWs) and nanocables (like SiO_2/SiC NCs or h-BN/SiO_2/Si_3N_4 NCs). The structure of these nanomaterials have been investigated by EDX, HRTEM and EELS.

M3.4
NMR INVESTIGATIONS ON ALKALI DOPED CARBON NANOTUBES. M. Schmid, C. Goze-Bac, P. Bernier, GDPC, Univ. Montpellier, FRANCE; S. Krämer, M. Mehring, 2.Phys. Inst., Univ. Stuttgart, GERMANY; S. Roth, MPI-Stuttgart, GERMANY.

Alkali doped carbon nanotubes have attracted considerable interest as devices for energy storage. We have performed alkali- and ^{13}C-NMR measurements on alkali doped single walled carbon nanotubes. NMR-lineshapes and relaxation effects were investigated for different alkali dopants. A first simple structure model for alkali ions in carbon nanotube bundles is developed and compared to results from theory.

M3.5
THE EFFECT OF CATALYST GRAIN SIZE ON THE DIAMETER OF MPCVD GROWN CARBON NANOTUBES. S.G. Wang, Q. Zhang, S.F. Yoon, J. Ahn, Q.F. Huang, Microelectronics Centre, School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore, SINGAPORE; G.F. Zhong, Center of Excellence of Waseda University, Waseda Shinjuku-ku, Tokyo, JAPAN.

The unique structure and property make carbon nanotubes (CNTs) an attractive material for wide potential applications ranging from field effect transistor to electron field emitters. It is becoming increasingly apparent that one of the challenges to a successful application of CNTs is that the growth of CNTs can be well controlled. In this paper, the effect of nickel catalyst on the diameter of CNTs has been studied. The CNTs are grown using microwave plasma enhanced chemical vapor deposition. The experimental results show that the diameter of the CNTs increases with increasing the nickel catalyst grain size. The diameter of CNTs can be controlled through controlling the nickel catalyst grain size.

M3.6
PREPARATION OF BUNDLES OF SINGLE WALL CARBON NANOTUBES WITH DIAMETERS OF 0.4 nm BY THE PROCESS OF FERROCENE CATALYZED CHEMICAL VAPOR DEPOSITION OF N-HEXANE. Qixiang Wang, Guoqing Ning, Fei Wei, Guohua Luo, Tsinghua Univ, Beijing, CHINA.

Many of the extraordinary properties of carbon nanotubes depend on their diameter. The smallest carbon nanotubes have been associated with the smallest fullerenes, with nanotube diameters of 4 Å corresponding to those of C_20 structure. Carbon nanotubes with such small diameters have been observed experimentally in the pyrolysis of tripropylamine molecules in the channels of porous zeolite $AlPO_4$ (AFI) single crystals [1,2]. In this paper, bundles of single wall carbon nanotubes with the diameter of 0.4 nm were prepared by ferrocene catalyzed chemical vapor deposition of n-hexane with additives of thiophene at 1373 K. The properties of the single wall carbon nanotubes were characterized by electron microscopy (SEM, TEM, HRTEM), Raman shift, TGA, etc. The by-products of cycloalkane including anthracene and pyrene were detected by the Gas Chromatogram-Mass Spectrum (GC-MS), which illustrate the growth mechanism of the smallest nanotubes. The diameters of the SWNTs are about 0.4-1.8 nm. By adjusting the process parameters, such as sulphur concentration, temperature and carrier gas flowrate, we can produce high quality 0.4 nm SWNTs bundles. This work was supported by the National Natural Science Foundation of China (20236020, 50071057). References [1] N. Wang, Z.K. Tang, G.D. Li and J.S. Chen. Single-walled 4 Å carbon nanotube arrays. Nature, 2000, 408: 50 - 51 [2] Z.K. Tang, L.Y. Zhang, N. Wang, X.X. Zhang, G.H. Wen, G.D. Li, J.N. Wang, C.T. Chan and P. Sheng. Superconductivity in 4 Angstrom Single-Walled Carbon Nanotubes. Science, 2001, 292: 2462-2465

M3.7
HIGH EFFICIENT PURIFICATION OF MULTIWALLED CARBON NANOTUBES. Wang Yao, Huang Wei, Luo Guohua, Wei Fei, Tsinghua Univ, Dept of Chemical Engineering, Bejing, P.R. CHINA.

The large scale production of carbon nanotubes (CNTs) by catalytic chemical vapor deposition (CCVD) has expedited the industrial application of this unique material. However, the presence of catalyst and carrier in the raw soot can influence the properties of the CNTs and the behavior of a device made of this material, and is detrimental to the introduction of these materials into practical application. In this work, we present a systematic study of the removal of the metal catalyst and the carrier in multiwalled CNTs. The raw CNTs was produced by a low temperature CCVD method in a nanoagglomerated fluidized-bed reactor and subsequently annealed at temperatures between 1500 and 2300° in a vacuum furnace. The raw and purified samples were separately investigated by thermo-gravimetric analysis (TGA), inductively coupled plasma (ICP), high resolution transmission electron microscopy (HRTEM) and energy dispersive spectroscopy (EDS). The experimental results indicated that residual Fe catalyst and Al2O3 carrier were both efficiently removed during the graphitization procedure without any damage to the nanotubes, and the purity was enhanced from 85.93% to 99.93%. The purification mechanism is analyzed. It is suggested that Al2O3 is changed to Al by reaction with CNTs, which allows Fe and Al to be gasified at a lower temperature as a result of a nanometer effect. In summary, graphitization presents a low-cost and commercially viable method for purifying multiwalled CNTs. Keywords: Carbon nanotubes; Catalyst; Anneal; Purification; Gasification.

M3.8
GROWTH OF MULTI-WALLED CNx NANOTUBES: THE ROLE OF NATURE AND SIZE OF THE CATALYST PARTICLES. Marie Castignolles, M. Glerup, P. Bernier, GDPC, Universite Montpellier II, Montpellier, FRANCE; A. Loiseau, LEM, ONERA, Chatillon, FRANCE.

Multi-walled CNx nanotubes were produced using two different synthesis methods. The growth mecanism of nitrogen-doped carbon nanotubes synthesized by the two different methods is studied. The results will be discussed and presented is primarely based on detailed high resolution transmission electron microscopy (HRTEM) data coupled with electron energy loss spectroscopy (EELS). Firstly, CNx-nanotubes have been produced using an aerosol method. A description of the method can be found in ref. [1]. In our case, a mixture of C and N containing liquids and suitable metal complexes as the catalyst precursors are sprayed in the reactor chamber. For the exact information about the production of these CNx tubes look ref. [2]. The product obtained consists of long and characteristic bamboo-shaped nanotubes with morphologies and structures very close to those obtained by Trasobares et al. [3]. The dependence of the nanotube growth on the particle size and catalysts, eg. Fe, Ni and Co will be presented. In a second step, the aerosol method has been used in a pyrolysis configuration. The same aerosol mixture, as mentioned above, was used, but this time the liquid is pyrolysed over a substrate impregnated with the catalyst. Again syntheses were carried out with the different catalysts, e.g. Fe, Co and Ni. This presentation will end-up by comparing and discussing the growth mechanisms of the tubes obtained by the two different synthesis methods. [1] M. Glerup, H. Kanzow, R. Almairac, P. Bernier, Electronic Properties of Novel Materials - XVI International Winterschool Ed. by Hans Kuzmany, Jörg Fink, Michael Mehring, Siegmar Roth, AIP Conference Proceedings No. 633, (Woodbury, New York, 2002), p.161-164 [2] M. Glerup, M. Castignolles, H. Kanzow, A. Loiseau, P. Bernier, "Synthesis of C and CNx nanotubes, using the aerosol method" in these proceedings. [3] S. Trasobares, O. Stephan, C. Colliex, W.K. Hsu, H.W. Kroto, J. Chem. Phys. 116 (20), 8966-8972, (2002).

M3.9
Abstract Withdrawn.

SESSION M4: TRANSISTORS AND DEVICES

Chairs: Siegmar Roth and Yoshikazu Nakayama
Wednesday Morning, April 23, 2003
Nob Hill A/B (Marriott)

8:30 AM *M4.1
CARBON NANOTUBE ELECTRONICS AND PHOTONICS. Phaedon Avouris, IBM Research Division, T.J. Watson Research Center, Yorktown Heights, NY.

I will discuss the electrical properties of semiconducting carbon nanotubes on the basis of our proximal probe and electrical transport experiments and theoretical calculations. Questions that will be addressed include the nanotube - metal electrode interaction, the resulting charge transfer and the role of the ambient environment. I will then discuss how these findings can be utilized to produce high performance p-type, n-type and ambipolar nanotube field-effect transistors and circuits. The effects of photon and electrical excitation of nanotubes will also be presented and discussed.

9:00 AM *M4.2
INTERACTION OF NANOTUBE DEVICES WITH ANALYTES: EXPLORING DEVICE ISSUES. Keith Bradley, Alexander Star, Jean-Christophe P. Gabriel, George Grüner, Nanomix Inc. Emeryville, CA.

We have fabricated various Field Effect Transistor device architectures with single wall carbon nanotubes as the channel element (NTFETs) and have used the interaction of these devices with various gases and coating layers to explore the importance of nanotube-metal contact and channel doping on the device characteristics. We find that nanotubes are the essential nonlinear elements of the devices with Schottky-barrier effects of secondary importance. We also find that charge transfer interactions between certain analytes and the nanotubes lead to changes of the device characteristics, these changes can be accounted for by standard models of nanotube-molecule interactions and of NTFET devices. Device architectures that allow sensing of a wide range of analytes will also be discussed.

9:30 AM M4.3
SCHOTTKY ELECTRONIC DEVICE FABRICATED FROM POLYANILINE/SINGLE WALLED CARBON NANOTUBE COMPOSITE. Praveen C. Ramamurthy, MSE, Clemson University, Clemson, SC; William R. Harrell, ECE, Clemson University, Clemson, SC; Richard V. Gregory, MSE, Clemson University, Clemson, SC; Ashutosh M. Malshe, ECE, Clemson University, Clemson, SC; Kris McGuire, Apparao M. Rao, Physics & Astronomy, Clemson University, Clemson, SC.

Composites of high molecular weight polyaniline and single walled carbon nanotubes are investigated for applications to electronic devices. Schottky-type contacts were fabricated using this composite, along with pure polyaniline for comparison. The measured electrical characteristics show current levels in the polyaniline/single walled carbon nanotube composite devices that are nearly an order magnitude higher than those measured in the neat polyaniline devices. In this paper, the electronic properties of both the composite and pure films are studied and compared. Composite materials and devices with various weight percentages of single walled carbon nanotubes were also fabricated. Current voltage (I-V) characteristics of these devices indicate a significant increase in current with an increase in carbon nanotube concentration in the composite. Analysis of the forward I-V characteristics of these composite devices show two power law regions, with a slope of 1 in the lower voltage range and a slope between 1.1 and 1.5 in the higher voltage range. These characteristics are consistent with ohmic conduction at low voltages and space-charge-limited conduction at higher voltages.

9:45 AM M4.4
INTERCONNECTING CARBON NANOTUBES WITH AN INORGANIC METAL COMPLEX. Fiona Frehill and Johannes Vos, School of Chemical Sciences, Dublin City University, IRELAND; Sakina Benrezzak, Physics Department, Trinity College Dublin, IRELAND; Antal Koos, Research Institute for Technical Physics and Materials Science, Budapest, HUNGARY; Zoltan Konya, Laboratoire de RMN, FUNDP, Namur, BELGIUM; Manuel Ruether and Werner Blau, Physics Department, Trinity College Dublin, IRELAND; Antonio Fonseca and Janos Nagy, Laboratoire de RMN, FUNDP, Namur, BELGIUM; Andrew Minett, Marc in het Panhuis, Physics Department, Trinity College Dublin, IRELAND.

Intermolecular carbon nanotube junctions were formed through amide linkages of amino functionalized multiwall carbon nanotubes and [Ru(dcbpy)(bpy)2](PF6)2, an inorganic metal complex [1]. Nanotube interconnects were visualized using atomic force microscopy. Absorption and emission spectroscopy showed significant changes between starting products and the resulting ruthenium nanotube complex, indicative of successful chemical modification. Ruthenium complexes could be essential in sensing applications through (electrochemical) monitoring of the change in redox potential or in transistor applications through (photophysical and electrochemical) switching of the contact between mult wall carbon nanotubes. [1] M. in het Panhuis et al, J. Am. Chem. Soc. vol 124 (2002).

10:30 AM *M4.5
INTEGRATION OF CARBON NANOTUBE DEVICES INTO MICROELECTRONICS. Wolfgang Hoenlein, Georg S. Duesberg, Andrew Graham, Franz Kreupl, Maik Liebau, Robert Seidel, Eugen Unger; Infineon Technologies, Corporate Research, Munich, GERMANY.

Many publications have addressed the unprecedented characteristics of carbon nanotubes (CNT) for various new applications. For microelectronics CNTs may be exploited for on-chip interconnects with highly improved electromigration behavior and resistances nearly independent of length. CNT field effect devices have shown tremendous improvements in performance over the last several years and may turn out to be strong competition for silicon MOSFETs. Most of the reports on functional devices rely, however, on deposition techniques which are not compatible with the requirements of the mature, and high-yield, silicon technology. In this talk the deposition methods used in CNT-technology are reviewed and compared with the requirements of microelectronics. Catalyst mediated chemical vapor deposition (CCVD) will be assessed in detail. A first step towards the integration of carbon nanotubes into microelectronics will be the CNT via, which is an interconnect between two metal layers in a chip. By using nanotubes instead of metal plugs, electromigration will be reduced due to the much higher allowed current densities in CNTs and their mechanical stability. Vias filled with individual multi-walled nanotubes will be the optimum choice for nano-vias with minimum lateral dimensions and maximum aspect ratios. The selective growth of single nanotubes in lithographically defined holes also paves the way for the realization of vertical CNT field effect transistors (VCNTFETs) with surrounding gates for optimum gate control. The control of catalyst morphology and process conditions may allow high yield production with sufficient homogeneity and reproducibility. We will discuss the performance data of the VCNTFET and compare them with the requirements for future devices. Finally, we will present a concept for a 3-dimensional all CNT-technology with the potential to succeed mainstream silicon.

11:00 AM *M4.6
PARALLEL FABRICATION OF NANOTUBE DEVICES BY MOLECULAR COMBING. Thierry Ondarçuhu, Christian Joachim, The Nanosciences Group, C.E.M.E.S.-C.N.R.S., Toulouse, FRANCE.

The positioning of a molecule in the gap between two electrodes obtained by nanolithography on a surface is the major problem to be solved for the fabrication of hybrid molecular devices. A challenge is to find a parallel deposition process that allows to fabricate, in one step, a large number of carbon nanotube (CNT) devices. We show that this can be achieved using wetting phenomena such as *molecular combing*. We used the capillary force exerted by a receding wetting line to align the nanotubes on the electrodes (1). A fine tuning of the CNT-surface interaction by surface modification, combined with molecular combing leads to CNT connected to both electrodes across the junction in 45% of the nanojunctions. This very good yield allows the systematic measurement of electrical characteristics of CNT down to 20 nm nanojunctions and is an important step for the miniaturization of these devices. We also obtained, with the same yield, fully coplanar hybrid CNT transistors with lateral dimensions of 100 nm (2). In order to take advantage of the large number of devices that can be fabricated on one surface we built a microcontactor set-up (3) under an AFM that allows simultaneous AFM characterization and electrical characterization of the devices. (1)Gerdes S., Ondarçuhu T., Cholet S., Joachim C., Europhys. Lett., 48 (1999) 292. (2)Ondarçuhu T., Joachim C., Gerdes S., Europhys. Lett., 52 (2000) 178. (3)Ondarçuhu T., Nicu L., Cholet S., Bergaud C., Gerdes S., Joachim C., Rev. Sci. Instr. 71 (2000) 2087.

11:30 AM M4.7
HIGH PERFORMANCE SELF-ASSEMBLED SINGLE WALL CARBON NANOTUBE FIELD EFFECT TRANSISTORS. A. Ribayrol, E. Valentin, S. Auvray, M. Gofmann, A. Filoramo, J.N. Patillon, J-P. Bourgoin, Laboratoire d'Electronique Moleculaire, joint between: Centre de Recherche MOTOROLA Paris, MOTOROLA Labs, Espace Technologique Saint-Aubin, Gif-sur-Yvette Cedex, FRANCE and CEA Saclay, DSM/DRECAM/SCM, Gif-sur-Yvette, FRANCE.

Even in an early stage of development, carbon nanotube based field effect transistors (CNTFETs) have been recently shown to potentially outperform future Si devices [1][2] of comparable scale. However, before CNTFETs become a successful technology, a controlled fabrication of devices on a large scale needs to be addressed. We have demonstrated a high-density selective placement of individual or small bundles of SWNT via modification of the substrate properties (self-assembly) [3]. Here, we demonstrate that this technique is suitable to direct a SWNT to a specific location on SiO2 (typically on 100 nm wide patterns line or crosses) where electrodes can be conveniently positioned. We will show that i) numerous CNTFETs can be produced at once and ii) our devices characteristics compare very well with state-of-the-art CNTFETs. Thus we validate the self-assembly approach to reliably realize efficient carbon nanotube based devices. We will finally consider how to improve the performance of these self-assembled CNTFETs in terms of material (using high K gate insulator) and/or gate geometry. [1] S.J. Wind, J.

Appenzeller, R. Martel, V. Derycke, Ph. Avouris, Appl. Phys. Lett. 80 (2002) 3817 [2] S. Rosenblatt, Y. Yaish, J. Park, J. Gore, V. Sazonova, P.L. McEuen, Nanolett, 2 (2002) 869 [3] E. Valentin, S. Auvray, J. Goethals, J. Lewenstein, L. Capes, A. Filoramo, A. Ribayrol, R. Tsui, J-P. Bourgoin, J-N Patillon, Microelec. Eng. 61 (2002) 491.

11:45 AM M4.8
SOLDERING OF CARBON NANOTUBE BRIDGES USING ELECTRON BEAM DEPOSITED GOLD. Kristian Molhave, Dorte N. Madsen, Ramona Mateiu, Peter Boggild, MIC, Technical University of Denmark; Anne Marie Rasmussen, Michael Brorson, Claus J.H. Jacobsen, Haldor Topsoe A/S, DENMARK.

We have formed suspended bridges of carbon nanotubes between microcantilevers using electron beam dissociation of metal-organic vapors. By electron beam exposure of a surface in the presence of gold-carbon molecules emitted inside an environmental scanning electron microscope, we are able to form tips and other freestanding nanostructures of high metallic content. Suspended bridges made entirely of this material exhibit resistances less than 50 times that of pure gold, and consist of dense metallic cores surrounded by a crust of nanoparticles. We used standard microfabrication techniques to produce silicon chips with multiple microcantilevers extending over the edge. Individual multiwalled carbon nanotube grown catalytically by chemical vapor deposition, were positioned across two such 800 nm wide cantilevers using in-situ nanomanipulation tools. Drawing a cross-shaped gold-carbon bond on each end of the carbon nanotube, consistently resulted in electrical contact with resistances in the range 10-30 kΩ and linear current-voltage characteristics. Additional "cutting bonds" ensured that the nanotube would break off at the edge of the cantilever, to avoid mechanical stress at the soldering bond. We found that soldering bonds having a linewidth down to 10-15 nm form connections lasts for days in ambient conditions. The soldering material was also used to grow conducting supertips at the ends of microfabricated tweezers, narrowing the gaps down to 25 nm. The tweezers are capable of grabbing and releasing nanowires without applying a voltage directly between the grabbing electrodes. These results may be the first step towards an assembly system for integration of nanotubes and nanowires with MEMS structures.

SESSION M5/K6: JOINT SESSION NANOTUBES AND NANOWIRES THEORY

Chairs: George Gruner and Tchavdar Todorov
Wednesday Afternoon, April 23, 2003
Nob Hill A/B/C/D (Marriott)

1:30 PM *M5.1/K6.1
QUANTUM TRANSPORT THEORY IN CARBON NANOSTRUCTURES. Vincent Meunier, William Shelton, Thomas Zacharia, Oak Ridge National Laboratory, Oak Ridge, TN; Jean-Christophe Charlier, Université Catholique de Louvain, Louvain-La-Neuve, BELGIUM; Christopher Roland, North Carolina State University, Raleigh, NC; Jerry Bernholc, Marco Buongiorno Nardelli, Oak Ridge National Laboratory, Oak Ridge, TN, and North Carolina State University, Raleigh, NC.

It has been shown both experimentally and theoretically that carbon nanotubes and nanotube based structures show a great potential for use in future nanoscale devices. However, since carbon nanostructures are found in various morphologies and dimensionalities, it is particularly important to acquire a precise understanding of the process governing the electronic transport in all these novel systems. In this framework, we have investigated the electronic and quantum transport properties of a number of carbon nanotube based structures, including tapered (telescopic) and highly defective (Haeckelites) nanotubes, coalesced nanopeapods, as well as complex intramolecular networks comprised of up to four carbon nanotubes. In addition, we will discuss the critical role played by the metallic contacts in driving the characteristics of the electronic transport in these nanoscale materials.

2:00 PM *M5.2/K6.2
MANY-ELECTRON EFFECTS AND OPTICAL RESPONSE OF CARBON NANOTUBES. Steven G. Louie, Dept of Physics, University of California at Berkeley, and Lawrence Berkeley National Laboratory, Berkeley, CA.

Electron-electron interaction in general plays a more important role in reduced dimensional systems. In this talk, we examine the influence of many-electron effects, such as quasiparticle self-energy and electron-hole interaction (or excitonic) effects, on the optical response of carbon nanotubes. Recent advances in theory and computational methodology have allowed the first-principles calculation of these effects in the optical spectra of many systems including solids, surfaces, and nanostructures. These calculations, which solve the Bethe-Salpeter equation of the interacting two-particle Greens function, yield both exciton states and optical absorption spectra. Our results show that, indeed, many-electron effects can change qualitatively the absorption spectrum of carbon nanotubes. Exciton states with large binding energies are predicted to exist in semiconducting nanotubes and even in some metallic tubes. These exciton states dominate the optical response of the system.

2:30 PM *M5.3/K6.3
EFFECTS OF CURVATURE ON THE BANDGAPS OF QUASIMETALLIC CARBON NANOTUBES. C.T. White, Naval Research Laboratory, Washington, DC; J.W. Mintmire, I. Cabria, Department of Physics, Oklahoma State University, Stillwater, OK.

Extended single-walled carbon nanotubes can be grouped based on the graphene sheet model as either semiconducting or metallic. However, within the subset of "metallic" tubes only the armchair ones should be truly metallic due to symmetry with the remaining quasimetallic tubes having small band gaps that depend on the chiral angle and vary as the inverse square of the nanotube radius. Also, within this set of metallic and quasimetallic tubes theory predicts that the zigzag and armchair tubes yield the upper and lower limits for the band gap for a given tube radius. Recently, experimental results have confirmed that only the armchair tubes are truly metallic while the zigzag tubes do have gaps that vary as the inverse square of the nanotube radius. We present an approximate analytic expression for the band gaps of the quasimetallic zigzag tubes derived from an all valence tight-binding model. While comparing well to our earlier numerical results and experiment, this expression shows that the band gap in these tubes should depend sensitively on both on nearest neighbor carbon-carbon pi and sigma interactions. The possible consequences of these results for the use of quasimetallic tubes as electromechanical gauges will be discussed.

3:30 PM *M5.4/K6.4
UNUSUAL ELECTRONIC EFFECTS IN CARBON NANOSTRUCTURES: GEOMETRICAL PHASES IN GRAPHITIC CONES AND NEW BORON-BASED METALS AND SEMICONDUCTORS ON ONE DIMENSION. Vincent H. Crespi, Paul E. Lammert and Peihong Zhang, Departments of Physics and Materials Science and Engineering, The Pennsylvania State University, University Park, PA.

Carbon nanostructures provide both fascinating opportunities for fundamental physics in one and two dimensions and also opportunities for electronic applications. Whereas semiconducting carbon nanotubes have a translational phase defect, carbon nanocones have a rotational phase defect; this defect creates a novel geometrical phase and profoundly modifies the global electronic properties. One impediment to practical application of carbon nanotubes has been the lack of a facile means to separate metallic tubes from semiconducting ones. I will also propose two new boron-based tubular structures, one of which is always semiconducting and the other always metallic.

SESSION M6: THEORY

Chair: George Gruner
Wednesday Afternoon, April 23, 2003
Nob Hill A/B (Marriott)

4:00 PM *M6.1
SPECTROSCOPIC PROPERTIES OF C AND BN NANOTUBES: A FIRST PRINCIPLE APPROACH. Angel Rubio, Department of Material Physics, University of the Basque Country, Donostia International Physics Center (DIPC), Donostia-San Sebastian, SPAIN.

We present firts-principle calculations of the raman, infrared and optical spectra of both BN and C nanotubes withing the time-dependent density-functional framework. The results are compared with previous experimental data and new experiments on BN tubes. The optical spectra of small C-tubes can be used to discern tube chirality and provides strong evidence of depolarization effects for light polarised perpendicular to the tube. In the case of BN nanotubes, the wide bandgap of BN results in a non-resonant Raman spectrum with few peaks with weak signature of the radial-breathing mode. However the polar nature of BN leads to a much richer IR spectra. The IR spectra show signs of symmetry lowering due to the finite tube-length.
* Work done in collaboration with: L. Wirtz, R. Arenal de la Concha, A. Loiseau, S. Lefrand, T. Marinopoulus, N. Vast and L. Reining.

4:30 PM M6.2
CHARGING CARBON NANOTUBES. P. Keblinski and P.M. Ajayan, Materials Science and Engineering Department, Rensselaer Polytechnic Institute, Troy, NY; S. Nayak, Physics Department, Rensselaer Polytechnic Institute; and P. Zapol, Science Division, Argonne National Laboratory, Argonne, IL.

Density-functional calculations of charge distribution on negatively and positively charged nanotubes result in charge density profiles characterized by significant increase of charge density at the tube ends. These results are in quantitative agreement with classical electrostatic analysis, which assumes constant electrostatic potential on the conductive tube surface. At high charging levels, the tube ends are observed to be unstable due to Coulomb repulsion. By combining ab-initio calculations with classical electrostatics we determine, as a function of tube length and geometry of the tube end, the critical voltage beyond which nanotubes are unstable.
The work of PK, PMA and SN was supported by the Phillip Morris USA and the NSF funded Nanoscale Science and Engineering Center (NSEC) at RPI. SN also acknowledges support of National Computer Science Alliance DMR990003N. P.Z. acknowledges support by the U.S. Department of Energy, BES-Materials Sciences, under Contract W-31-109-ENG-38.

4:45 PM M6.3
THEORETICAL AND COMPUTATIONAL INVESTIGATION OF DEVELOPMENT OF A CROSSBAR SWNT ASSEMBLY. Si-ping Han, Tahir Çağın, William A. Goddard, III, California Institute of Technology, Materials and Process Simulation Center, Pasadena, CA.

Single walled carbon nanotubes (SWNT) hold great potential for use both as interconnects and as switches for crossbar arrays of molecular electronic devices. Hence, the assembly of SWNT into crossbar arrays is important to the realization of molecular scale computing. Current methods for creating a crossbar assembly of SWNT may follow the following basic three steps process. 1. Create a grid-like chemical template on a substrate. 2. Deposit or grow SWNT onto this chemical template. 3. Control the alignment of SWNT. The successful development of self-assembled 2-D DNA tiles offers a cheap and reliable bottom up method of creating chemical templates with grid sizes ranging from 13 nm to 33 nm opens up possibilities. One could engineer these tiles so that single stranded DNA segments attached to the horizontal edges of the tiles stick out of the plane of the crystal, then one could attach molecules tagged with complementary DNA strands onto the DNA crystal in a grid fashion with densities equal to the periodicity of the crystals. Non-covalent functionalization of SWNT using 1-pyrenebutanoic acid, succinimidyl ester through pi-stacking interaction between the pyrene base and the sidewall of the SWNT as demonstrated by Stanford researchers may facilitate the deposition and alignment of SWNT on the 2-D DNA tiles. In this contribution, we will elucidate the crossbar array development and discuss the feasibility using the results obtained from quantum chemical and molecular dynamics calculations. 1. E. Winfree, F. Liu, L. Wenzler, N. Seeman, Nature 394,539 (1998). 2. R. Chen, Y. Zhang, D. Wang, H. Dai, J. Am. Chem. Soc. 123, 3838 (2001).

SESSION M7: ELECTRONIC EMISSION AND PROPERTIES

Chairs: Gyu-Tae Kim and Wolfgang Hoenlein
Thursday Morning, April 24, 2003
Nob Hill A/B (Marriott)

8:30 AM *M7.1
CARBON NANO TUBES ON LARGE AREA FED APPLICATIONS. C.G. Lee, S.J. Lee, S.Y. Whang, E.J. Chi, T.I. Yun, J.S. Lee, J.W. Kim[a], J.E. Jang[a], S.H. Cho, B.G. Lee, S.J. Lee, H.S. Han, S.H. Ahn, K.S. Ryu, K.W. Jung, J.H. Kang, S.H. Jin, S.K. Jo, J.E. Jung[a], J.S. Choi, T.S. Oh, S.K. Kang and J.M. Kim, Corporate R&D Center, Samsung SDI, Yongin-City, KOREA; [a]FED project team, Samsung Advanced Institute of Technology, Suwon, KOREA.

For large-size display applications, 32"-diagonal gated carbon nanotube (CNT) cathodes have been fabricated and characterized. The photo imageable paste by printing method was used for controlling emission uniformity. The cathode of unique triode structure was integrated for full color images. The cathode has been assembled with a phosphor screen plate and a driving circuit. The average brightness of 150 Cd/m^2 was obtained in the full-color moving image. The FEDs demonstrates the first full color TV images with carbon nanotubes.

9:00 AM *M7.2
CARBON NANOTUBES/NANOFIBRES BASED CATHODES FOR PARALLEL E-BEAM LITHOGRAPHY AND MICROWAVE VACUUM DEVICES. P. Legagneux, L. Gangloff, G. Pirio, E. Balossier, J.P. Schnell, P. Vincent and D. Pribat, Thales Research and Technology, FRANCE, K.B.K Teo, M. Chhowalla, D.G. Hasko, H. Ahmed, G.A.J. Amaratunga and S.B. Lee, Univ of Cambridge, UNITED KINGDOM; Vu Thien Binh and V. Semet, Univ Claude Bernard Lyon, FRANCE; O. Groening, Univ of Fribourg, SWITZERLAND; D. Friedrich, W. Bruenger, J.Eichholz and H. Hanssen, Fraunhofer ISiT, GERMANY; M. Castignolles and A. Loiseau, CNRS-ONERA and University of Montpelier, FRANCE.

Since the discovery by Ren et al (1) that the localised growth of vertically aligned carbon nanotubes/nanofibers could be obtained using Plasma Enhanced Chemical Vapour Deposition (PECVD), there has been considerable interest in the use of nanotubes/nanofibers as electron emission sources (2) for applications such as microwave amplifiers and parallel e-beam lithography. Future 10-50 W microwave vacuum amplifiers could be based on arrays of nanotubes delivering 1A/cm^2 and modulated at 30/60 GHz. Such performance could be obtained with an array of 5 microns height nanotubes with a spacing of 10 microns. The maximum emission current from individual nanotube was found to be 20 μA before degradation (3). In order to assess the suitability of nanotubes for this application, field emission properties from arrays of nanotubes will be presented. For parallel e-beam lithography, we have recently proposed a revisited concept based on an array of electron microguns independently driven by an active CMOS pixel array (4). The microgun consists of an electron emitter (i.e. one nanotube/nanofiber), an extracting and a focusing lens. First results on nanocathodes based on individual CNTs will be shown. This work was funded by the European commission through the IST-FET projects Nanolith and Canvad. (1) Z.F. Ren, P. Huang, J.W. Xu, J.H. Wang, P. Bush, M.P. Siegal and P.N. Provencio, Science 282, 1105 (1998). (2) W.I. Milne et al., invited paper during this conference. (3) V. Semet, V.T. Binh, P. Vincent, D. Guillot, K.B.K. Teo, M. Chhowalla, G.A.J. Amaratunga, W.I. Milne, P. Legagneux, and D. Pribat, Appl. Phys. Lett. 81, 343 (2002). (4) P. Legagneux, G.Pirio, E. Balossier, J-P Schnell, D. Pribat, K.B.K. Teo, M. Chhowalla, D.G. Hasko, G.A.J. Amaratunga, W.I. Milne, V. Semet, Vu Thien Binh, W.H. Bruenger, H. Hanssen and D. Friedrich, Phantoms Newsletter 5, 8 (2002).

9:30 AM M7.3
FIELD EMISSION BEHAVIOR OF CARBON NANOTUBES FILLED WITH 1-D MOLECULAR CHAINS. R.M. Russo, B.W. Smith, D.E. Luzzi, University of Pennsylvania, Dept of Materials Science and Engineering, Philadelphia, PA.

The future application of single-wall carbon nanotubes (SWNTs) depends on the ability to modify their intrinsic properties by manipulating their microstructure. A unique advantage of nanotubular structures is the ability to modify their function through the filling of their lumens. It has recently been proven that filling SWNTs with C_{60} modifies their intrinsic electronic structure. One area where this result could be very useful is field emission. Because of their long aspect ratio, SWNTs have been found to have superior, spacially resolved, field emission properties. The long term viability of SWNTs as superior cathode materials will be secured by the ability to tailor their properties to achieve higher current densities at lower turn on voltages. Using the benchmark systems, C_{60}@SWNT and Sc_3N@C_{80}@SWNT, we show that it is possible to modify field emission properties via filling. We observe several unique effects during I-V measurements and during long term constant voltage or constant emission current anneals. One is the existence of hystersis in the IV characteristics during a voltage cycle, which may be due to internal motion of the encapsulated molecules within the SWNTs. The second effect is the ability of the filled sample to recover its I-V characteristics very quickly after long periods of annealing at constant voltage. Possible reasons for these and other observed field emission properties will be discussed.

9:45 AM M7.4
FABRICATION OF CARBON NANOTUBE TRIODE USING HELICON PLASMA CVD WITH ELECTROPLATING Ni CATALYST. Masakazu Muroyama, Kazuto Kimura, Takao Yagi, Ichiro Saito, SONY Corporation, Atugi, Kanagawa, JAPAN.

Carbon nanotubes are considered to be a promising material for field emission displays. Preparation of highly purified carbon nanotubes in large quantity, well-aligned nanotubes, and low temperature synthesis on triode structure are prerequisites for this application. Control of carbon nanotube density was also required to maintain the field enhancement on nanotubes. In this work, carbon nanotube triode using Helicon Plasma-enhanced CVD with electroplating Ni catalyst has been successfully fabricated. The triode structure with 3μm gate hole and 3μm SiO insulator was used for analysis of field-emission properties. Isolated Ni metal catalyst was deposited selectively on the bottom of the cathode holes by electroplating methods to control the density of carbon nanotubes and also reduce the activation energy of its growth. Helicon Plasma-enhanced CVD (HPECVD) has been used to deposit nanotubes at temperatures from 400°C to 500°C. RF bias was also applied to the substrate holder to control the ion bombardment. A mixture of methane and hydrogen gas was used as the carbon source. Vertically aligned carbon nanotubes were also obtained selectively on the electroplating Ni catalyst. Field emission measurements were performed with a triode structure. At a cathode - anode gap of 1.1mm, the turn - on voltage for the gate was 170V.

10:30 AM M7.5
CHARGE TRANSPORT CHARACTERISTICS OF POLY (9, 9-DIOCTYLFLUORENE) AND POLY(N-OCTYLTHIOPHENE) SINGLE WALL NANOTUBE COMPOSITES. Richard Czerw, Scott Webster, Sakutaro Hoshi, and David L. Carroll, School of Materials Science and Engineering, Clemson, SC.

Nanocomposites of conjugated polymers and single wall carbon nanotubes (SWNTs) have shown promise for modifying charge transport in organic light emitting diodes (OLEDs) and organic photovoltiacs (OPVs) with the promise of increased efficiencies and lifetimes. Poly (9, 9-dioctylfluorene) (PFO) and its derivatives are considered to be some of most promising materials for use in commercial OLEDs, and similarly poly(N-octylthiophene) (P3OT) shows promise in OPVs. In this study, we have sought to determine the carrier transport properties of PFO- SWNT and P3OT-SWNT composites using time-of-flight (TOF) and dark injection. TOF was preformed on composites varying from 0% by weight SWNTs to the percolation threshold. The drift mobility of the composites was strongly influenced by trap formation as a result of the inclusion of SWNTs in the polymer matrix.

10:45 AM M7.6
SYNTHESIS, ANALYSIS, TRANSPORT AND FIELD EMISSION MEASUREMENTS OF COMPOUND B-C-N NANOTUBES. Dmitri Golberg, Yoshio Bando, Pavel Dorozhkin, Zhen-Chao Dong, Cheng-Chun Tang, Keiji Kurashima, Masanori Mitome, National Institute for Materials Science, Tsukuba, JAPAN.

Multiwalled B-C-N nanotubes of various morphologies and chemical compositions were synthesized by reacting C-based nanotubes with boron oxide and nitrogen at 1573-2173 K. The nanotubes were thoroughly analyzed using a high-resolution 300 kV transmission electron microscope (TEM), an energy-filtered 300 kV electron microscope (Omega filter), an electron energy loss spectrometer and an energy dispersion X-ray detector. Transport and field emission properties of the nanotubes were studied using a low energy electron point source microscope and via in-situ measurements in TEM equipped with a scanning tunnelling microscope (STM) unit. The following results were documented: (i) the compound nanotubes frequently assemble in long ropes (several micrometers) containing dozens of individual tubes; (ii) a BN/C atomic ratio of nanotubes increases as the synthesis temperature rises; (iii) island crystallization of BN domains and BN/C fragment separation, or growth of homogeneous B-C-N nanotubular shells are both possible depending of growth kinetics (temperature, use of synthesis catalysts/promoters etc.); (iv) transport properties of the compound nanotubes may be smoothly tuned from metallic to semiconducting or insulating depending on relative BN/C fractions; (v) thermally and chemically stable BN-rich C nanotube ropes are excellent field emitters with a field emission current per rope reaching 2.5 microampers; (vi) BN-insulated nanotube cables may be realized via controlled metal filling of BN-based nanotubes or preparation of sandwich-like BN/B-C-N compound nanotubes.

11:00 AM M7.7
FABRICATION OF FIELD EMITTER ARRAY OF CARBON NANOTUBES ON PATTERNED SUBSTRATES USING SELF-ASSEMBLY MONOLYAER. Ok-Joo Lee, Soo-Hwan Jeong, Kun-Hong Lee, Pohang Univ. of Science and Technology (POSTECH), Dept. of Chemical Engineering, Computer and Electrical Engineering Division, Pohang, KOREA.

Field emissions from single-walled carbon nanotubes (SWNTs) attached on various patterned substrates such as silicon wafer and polymer film, are reported. SWNTs were cut into sub-micron length by sonication in an acidic solution. The SWNT emitters were aligned on Au surface at room temperature by self-assembly monolayer technique. The field emission measurement in a silicon wafer and a polymer film showed that the turn-on field was 2.8 V/μm and 3.9 V/μm at the emission current density of 10 μA/cm^2, respectively. The current density was 0.9 mA/cm^2 and 1.6 mA/cm^2 at 6.0 V/μm. This room temperature process is suitable for the fabrication of flexible field emission devices with carbon nanotubes.

11:15 AM M7.8
RAMAN SPECTROSCOPY AND OPTICAL PROPERTIES OF NITROGEN DOPED MULTIWALLED NANOTUBES. Scott Webster, Richard Czerw, Jiwen Liu, and David L. Carroll, Laboratory for Nanotechnology, School of Materials Science and Engineering, Clemson University, Clemson, SC; Mauricio Terrones and Humberto Terrones, Advanced Materials Department, IPICyT, San Luis Potosi, MEXICO; N. Grobert, Max-Planck-Institut für Metallforschung, Stuttgart, GERMANY.

Doping of carbon nanotubes can greatly modify their electronic and optical properties paving the way to the creation of novel nanoscale devices. *N*-type multi-walled nanotubes were synthesized by nitrogen doping using melamine or pyridine in chemical vapor deposition, and their donor states were verified by Scanning Tunneling Spectroscopy. Nitrogen is present in the lattice of these MWNTs as pyridine structures and CN_X structures. The doped materials were studied by Raman scattering at 1.58 eV, Fourier Transform Infrared Spectroscopy, and Absorption Spectroscopy. Nonlinear optical techniques, including optical limiting at optical geometries ranging from f/5 to f/50 and Z-scan, were performed. These results are compared to un-doped MWNTs. N-MWNTs are found to have low optical damage thresholds, and α-Fe_2O_3 has been observed by Raman as a result of the liberation of catalyst by the incident laser irradiation.

11:30 AM M7.9
SPINNING AND CHARACTERIZATION OF HIGH PERFORMANCE MULTIFUNCTIONAL CARBON NANOTUBE FIBERS. Steve Collins, Alan Dalton, Edgar Munoz, Bog G. Kim, Joselito Razal, Ray Baughman, University of Texas at Dallas, Dept of Chemistry and NanoTech Institute; Jonathon Coleman, Trinity College Dublin, Dept of Physics.

Exploiting the extraordinary properties of carbon nanotubes has remained somewhat elusive due to the inability to process the as produced insoluble soot into functional macroscopic assemblies. To this end we have developed a simple but effective method to produce continuous, homogeneous fibers containing carbon nanotubes having as-spun mechanical properties that compare very favorably to recognized synthetic and natural "super fibers" such as Kevlar and spider silk. By using novel spinning apparatus, spinning solutions, and spinning coagulants, we have spun nanotube fibers having record lengths, record tensile strengths, and a much higher energy-to-break (toughness) than the highest performance natural and synthetic fibers. Moreover, due to the potential multi- functionalities of nanotube fiber, such as structural elements in fabrics to make composites and textiles used for military clothing, coupled with the ability to produce fundamentally limitless lengths, the implications for this advance are wide ranging.

SESSION M8: DEVICES AND PROPERTIES

Chairs: Phaedon Avouris and Thierry Ondarcuhu
Thursday Afternoon, April 24, 2003
Nob Hill A/B (Marriott)

1:30 PM *M8.1
ALL CARBON TRANSISTORS. Po-Wen Chiu, Ursula Dettlaff, Siegmar Roth, Max-Planck Institut für Festkörperforschung, Stuttgart, GERMANY.

Carbon nanotube T-junctions were formed by coupling chemically functionalized nanotubes with molecular linkers. A well-shaped junction deposited on Si chip was selected in the AFM and gold leads were applied by electron beam lithography. The nonconductive linker at the junction is used for a gate oxide and the end-connected nanotube can hence function as a third terminal (in-plane gate) in this all-carbon transistors. The active part of the device is now truly confined to a region of a few nanometers in all three dimensions. We will show that a gain value 100 can be easily obtained in this new generation nanotube devices.

2:00 PM M8.2
CARBON NANOTUBE PHOTODETECTOR DEVICES. Matthew S. Marcus, Univ of Wisconsin-Madison, Dept of Physics, Madison, WI; Todd R. Narkis, Univ of Wisconsin-Madison, Dept of Materials Science and Engineering, Madison, WI; J.M. Simmons, Univ of Wisconsin-Madison, Dept of Physics, Madison, WI; M.G. Lagally, Univ of Wisconsin-Madison, Dept of Physics and Dept of Materials Science and Engineering, Madison, WI; M.A. Eriksson, Univ of Wisconsin-Madison, Dept of Physics, Madison, WI.

Optical fields have been a valuable tool for characterizing carbon nanotube properties such as structure, band gap, and critical features in the density of states. We report photocurrent measurements on nanotube devices consisting of a single bundle of (or individual) nanotubes. Photocurrents (of order 1nA) and photovoltages are measured at zero applied bias at wavelength 633 nm. Due to the small size of the nanotube, the incident power is tiny, and a naive calculation gives a large sensitivity (greater than 10 A/W) at zero bias. At finite bias voltages the sensitivity increases dramatically.

2:15 PM M8.3
NONLINEAR OPTICAL THIN FILM DEVICES USING SATURABLE ABSORPTION OF SINGLE WALL CARBON NANOTUBES. Youichi Sakakibara, Aleksey G. Rozhin, Madoka

Tokumoto, National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, JAPAN; Hiromichi Kataura, Yohji Achiba, Tokyo Metropolitan University, Graduate School of Science, Tokyo, JAPAN; Sze Y. Set, Hiroshi Yaguchi, Mark K. Jablonski, Yuichi Tanaka, Alnair Labs Corporation; Kazuro Kikuchi, The University of Tokyo, Research Center for Advanced Science and Technology, Tokyo, JAPAN.

Carbon nanotubes (CNTs) are unique nanostructures with fascinating electrical, mechanical, and chemical functions. However, so far, little promising optical functions attracting extended attentions have been known. Here we present detailed properties of saturable absorption of single wall carbon nanotubes (SWNTs) that function effectively at optical telecommunication wavelength (∼1550 nm) [1]. Diameter-selective SWNTs with a mean diameter at ∼1.1 nm were grown by laser ablation method. The SWNTs were sprayed onto the surface of a 1 mm thick quartz substrate forming a thin film of SWNTs (∼1 μm). The film had a strong exciton absorption band ranging from 1400 nm to 2000 nm with a peak at 1680 nm. Saturable absorption properties were investigated, using a mode-locked fiber laser operating at 1550 nm with 1 ps pulses [2], by the z-scan method [3] and by observing the spectral variation of the transmitted pulses. The z-scan experiments clearly showed an increase in the transmitted laser power when the CNT-film was placed at around the focal point, where the laser intensity was at its maximum. This phenomenon clearly showed occurrence of saturation of the excitonic absorption. High-resolution spectral transmission measurements were also carried out, showing a reduction in absorption over the spectral region of the pulse source, with a double-hump absorption feature. This result indicates that the sample has an inhomogeneously broadened absorption, which can respond to pulses on a timescale of 1 ps. Based on these results, we will discuss the potentials of SWNT thin films for implementing optical telecommunication devices such as an ASE noise suppresser for EDFA and an optical switch. [1] Y. Sakakibara et al., Japan Patent No: 2001-320383, filed on 18 October 2001. [2] S.Y. Set, et al., OECC 2000, Yokohama, paper 12D3-2, pp. 632-633. [3] M. Sheik-Bahae, et al., IEEE J. Quant. Electron., 26 (1990) 760.

2:30 PM *M8.4
CARBON-NANOTUBE ENGINEERING FOR PROBES AND TWEEZERS OPERATING IN SCANNING PROBE MICROSCOPE. Yoshikazu Nakayama and Seiji Akita, Osaka Prefecture Univ, Dept. of Physics and Electronics, Osaka, JAPAN.

We have developed a series of processes for preparing carbon-nanotube devises of probes [1] and tweezers [2] that operate in scanning probe microscope (SPM). The main developments are a nanotube cartridge where nanotubes are aligned at a knife-edge to be easily picked up one by one and a scanning-electron-microscope manipulator by which a nanotube is transferred from the nanotube cartridge onto a substrate under observing its view. The recent additional developments are the electron ablation of nanotube to adjust its length and the orthopedic treatment of multiwalled nanotube to extract its inner layer with or without an end cap. For the orthopedic treatment, the free end of nanotube protruded from a knife-edge was attached onto a metal-coated Si tip and the voltage was applied to the nanotube. At a high voltage giving the saturation of current, the current decreased stepwise in a temporal variation, indicating the sequential destruction of individual nanotube layers. The nanotube was finally cut at the middle of the nanotube bridge, and its tip was sharpened to have an inner layer with an opened end. Pulling down the silicon tip before cutting enables us to extract the inner layer with an end cap. SPM installed with these tips has provided a high-resolution. The calculation based on the current steps shows that each layer has the quantum conductance of 2G0 and the interlayer resistance depends on the diameter of the layer. The force for extracting the inner layer with ∼2nm diameter is estimated to be less than 12 nN from the force measurement. In conclusion, the electron ablation and orthopedic treatment are promising ways for providing a high quality nanotube probes and annotube tweezers for SPM. 1) H. Nishijima et al., Appl. Phys. Lett. 74 (1999) 4061. 2) S. Akita et al., Appl. Phys. Lett. 74 (1999) 4061.

3:30 PM *M8.5
PROBING THE ONE-DIMENSIONAL ELECTRONIC STATES OF NANOSCOPIC PEAPODS. Ali Yazdani, Dept of Physics, University of Illinois at Urbana-Champaign.

Nanoscopic peapods, which consist of encapsulated arrays of C_{60} molecules nested inside single wall nanotubes (SWNTs), represent a new class of nanoscale materials having potentially tunable properties. We report on electronic measurements of this system using a scanning tunneling microscope (STM). Our results demonstrate that the encapsulated C_{60} modify the local electronic structure of the SWNT cage. Furthermore, our measurements and calculations show that a periodic array of C_{60} molecules gives rise to a new hybrid electronic band, which derives its character from both the SWNT states and the C_{60} molecular orbitals. Work done in collaboration with D.J. Hornbaker, S. Kahng (UIUC), B.W. Smith, D. Luzzi, E.J. Mele, and C. Kane (University of Pennsylvania).

4:00 PM M8.6
COMBINING ELECTRON TRANSPORT AND TRANSMISSION ELECTRON MICROSCOPY ON INDIVIDUAL SINGLE-WALLED CARBON NANOTUBE STRUCTURES. S. Paulson, Dept. of Physics and Astronomy; Satishkumar Chikkannanavar and D.E. Luzzi, Dept. of Material Science and Engineering; A.T. Johnson, Dept. of Physics and Astronomy, University of Pennsylvania, Philadelphia, PA.

We have developed a technique for measuring electronic transport and performing Transmission Electron Microscopy (TEM) on individual chemical vapor depostion (CVD) grown Single-walled Carbon Nanotube (SWNTs) structures. TEM shows that we have been successful in creating C60 filled peapods from CVD nanotubes, and we report synthesis techniques and transport data from these devices. In addition to a characterization tool giving us sub-nanometer structural information, the TEM can be used to interact with the sample. By tuning the electron beam energy, we can introduce defects into the SWNT in a somewhat controlled fashion. We observe changes in both the structure and the electronic behavior of the SWNT as a result of this controlled damage.Finally we will present results electronic behavior and modification of SWNT/SWNT junctions.

4:15 PM M8.7
ON DETERMINING THE MECHANICAL PROPERTIES OF CARBON NANOTUBES AND VERTICALLY ALIGNED CARBON NANOTUBE FORESTS USING NANOINDENTATION. Hang Qi, Mary C. Boyce, Dept of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA; Ken Teo, John Robertson, William Milne, Dept of Engineering, University of Cambridge, Cambridge, UNITED KINGDOM; Ken Lau, Karen K. Gleason, Dept of Chemical Engineering, Massachusetts Institute of Technology, Cambridge, MA.

The ability to grow vertically aligned carbon nanotube (VACNT) forests on a substrate has been demonstrated by several research groups. Various growth conditions enable impressive control over the CNT diameter, length and areal density. Thus, this growth process has the potential to be a tremendous source for well defined CNTs. Additionally, the VACNT forest coatings have attracted a great deal of interest for numerous applications ranging from field emission devices to hydrophobic coatings. Although the VACNT forests are a subject of intense research regarding optimization of processing conditions and structural parameters for specific applications, little attention has been given to the mechanical properties of these forests even though the stiffness and mechanical integrity will be important issues in their ultimate success. Here, we study the mechanical stiffness of VACNT forests using nanoindentation. The resistance to indentation is obtained by the penetration of a Berkovich indentor into the forests using atomic force microscopy nanoindentation. The resistance to indentation, a penetration force penetration depth curve, is measured for a range in VACNTs where CNT diameter, height and areal density are varied. In a homogeneous material, measurements of the resistance to indentation have been successfully used on thin coatings as a measurement technique to determine the elastic modulus and yield stress of the coating material when combined with elasticity analysis of the stress and strain fields that lead to the force-depth curves. For our case of VACNT forest coatings, such analysis does not apply and therefore cannot be used to assess an effective modulus of the VACNT forest coatings. However, micromechanical modeling of the interactions between the indentor and the tubes as the indentor penetrates into the forest and successively bends each tube encountered during penetration is shown to result in a novel approach for determining not only the dependence of the resistance to indentation on the key structural features of the forest (CNT diameter, length and areal density), but also provides a measure of the stiffness of the constituent carbon nanotubes. Indeed, the use of nanoindentation together with the proposed micromechanical model of the successive bending of the tubes as the indentor penetrates into the forest is shown to provide a relatively easy measure of the bending stiffness and axial modulus of the constituent nanotubes. Several cases are used to demonstrate the technique whereby the model is compared to experiments for VACNT forests of various diameters, lengths and areal densities.

4:30 PM M8.8
LOCALIZED FABRICATION OF METAL CONTACTS AND ELECTRICAL MEASUREMENTS ON MULTIWALLED CARBON NANOTUBES. J. Ziroff, J. Rullan, G. Agnello, K. Dovidenko, School of NanoSciences and NanoEngineering and UAlbany, Institute for Materials, The University at Albany-SUNY.

The ability to measure electrical conductivity of Multiwalled Carbon Nanotubes (MWNTs) is crucial for their future device applications. A few different methods have been traditionally used to measure their conductivity, with the high contact-resistance between the nanotube and metal usually posing a serious obstacle. In this study, a four-point-probe method is used to eliminate the influence of the high contact resistance. We have used Focused Ion Beam (FIB) microscope to deposit platinum contacts (typically, four 200nm-wide contacts providing 6 possible electrode combinations) on MWNTs dispersed over the silicon dioxide surface with pre-fabricated Al pads for electrical testing. FIB-assisted metal deposition is an approach alternative to e-beam lithography-assisted contacts fabrication, and has certain advantages and disadvantages. The main advantage is the ease of locating and contacting the desired nanotube at the desired locations. The main disadvantage is the difficulty to control the surface modification typically produced by 30 kV Ga ions used in FIB. Correlation between the nanotube structure (studied by Transmission Electron Microscopy), surface modification and the observed electrical properties is discussed. We have developed techniques to minimize surface modification and damage of the nanotubes due to the ion beam exposure, and are working on a technique to avoid such undesirable effects. One of the problems is the formation of thin Pt layer in the region closely surrounding the electrodes, making a conductive surface area around those. The ways to remove the undesired platinum regions as well as to model their conductivity vs. deposition parameters in order to deconvolute their contribution to the measured conductivity will be discussed.

4:45 PM M8.9
DIRECT INTEGRATION OF SINGLE-WALLED CARBON NANOTUBES WITH SILICON: A NOVEL APPROACH USING THE UHV SCANNING TUNNELING MICROSCOPE.
Peter M. Albrecht and Joseph W. Lyding, University of Illinois at Urbana-Champaign, Dept. of Electrical and Computer Engineering, Beckman Institute for Advanced Science and Technology, Urbana, IL.

We have used ultrahigh vacuum scanning tunneling microscopy and spectroscopy to study the direct integration of single-walled carbon nanotubes (SWNTs) with silicon. In these experiments, a high quality Si(100)2x1:H surface is initially prepared in UHV. Next, we remove the sample from UHV and solution deposit SWNTs ultrasonically dispersed in an organic solvent. We have shown previously that the UHV hydrogen-terminated Si(100) surface is exceptionally robust under ambient exposure, with up to 40 hours needed before an oxide peak appears in XPS analysis [1]. Following a mild degas upon return to UHV, atomic resolution topographic imaging is routinely achieved on both the SWNTs and the substrate. On n-type silicon, dI/dV spectroscopy of semiconducting SWNTs elucidates the silicon valence band edge and the SWNT conduction band edge. The remaining band edges are obscured by the zero conductance regions of the SWNTs and the substrate. Precise cutting of SWNTs and ropes has been performed in a manner analogous to that demonstrated on metal surfaces [2], although with notably different parameters. Furthermore, we have determined that SWNTs and ropes can be reliably manipulated on the Si(100)2x1:H surface in UHV using the STM probe. Experimental results will be presented in which SWNT manipulation is combined with atomic scale lithography (selective hydrogen desorption) to explore the bonding mechanisms between SWNTs and silicon. Progress will also be reported on the *insitu* binding of individual molecules to reactive sites on modified SWNTs. One of our foremost goals is to further the development of hybrid SWNT/Si devices and architectures, incorporating the many attractive properties of carbon nanotubes into the silicon-based electronic paradigm. [1] M.C. Hersam, D.S. Thompson, N.P. Guisinger, J.S. Moore, and J.W. Lyding, *Appl.Phys.Lett.* **78**, 886 (2001). [2] A. Rubio, S.P. Apell, L.C. Venema, and C. Dekker, *Eur.Phys.J.B* **17**, 301 (2000).

SESSION M9: POSTER SESSION MOSTLY PROPERTIES

Thursday Evening, April 24, 2003
8:00 PM
Salon 1-7 (Marriott)

M9.1
WATER-BASED, SINGLE-WALLED NANOTUBE-FILLED POLYMER COMPOSITE WITH ULTRA-LOW PERCOLATION THRESHOLD.
Jaime C. Grunlan and Ali R. Mehrabi, Avery Research Center, Pasadena, CA.

In an effort to improve ease of processing and lower the percolation threshold of single-walled nanotube (SWNT)-filled polymer composites, an emulsion-based polymer has been used as the polymer matrix starting material. When cast as a film, this unique composite system exhibits a percolation threshold of approximately 0.03 wt% of SWNT's. A comparable carbon black-based composite has a percolation threshold that is more than two orders of magnitude greater and the best SWNT-filled solution-based polymer system exhibits a threshold that is nearly an order of magnitude greater. This lowered percolation threshold for the emulsion-based system is most likely due the combination of excluded volume during composite film formation, lack of polymer - nanotube interaction, and the large aspect ratio of the nanotubes. With a loading of only 4 wt% SWNT's, an electrical conductivity of 0.2 S/cm is achieved. This novel composite system offers the potential for conductive polymers that are inexpensive, mechanically robust, environmentally stable, and easy to process.

M9.2
EFFECT OF ALIGNMENT ON TRANSPORT PROPERTIES OF CARBON NANOTUBE/METALLIC JUNCTIONS.
Buzz Wincheski and Min Namkung, NASA LaRC, Hampton, VA; Jan Smits, Lockheed Martin Engineering and Sciences Corporation, Hampton, VA; Phillip Williams, National Research Council, Hampton, VA; Robert Harvey, Christopher Newport University, Newport News, VA.

Ballistic and spin coherent transport in single walled carbon nanotubes (SWCNT) are predicted to enable high sensitivity single-nanotube devices for strain and magnetic field sensing. Based upon these phenomena, electron beam lithography procedures have been developed to study the transport properties of purified HiPCO single walled carbon nanotubes for development into sensory materials for nondestructive evaluation. Purified nanotubes are dispersed in solution and then deposited on the device substrate before metallic contacts are defined and deposited through electron beam lithography. This procedure produces randomly dispersed ropes, typically 2 - 20 nm in diameter, of single walled carbon nanotubes. Transport and scanning probe microscopy studies have shown a good correlation between the junction resistance and tube density, alignment, and contact quality. In order to improve transport properties of the junctions a technique has been developed to align and concentrate nanotubes at specific locations on the substrate surface. Lithographic techniques are used to define local areas where high frequency electric fields can be concentrated. Application of the fields while the substrate is exposed to nanotube-containing solution results in nanotube arrays aligned with the electric field lines. A second lithography layer is then used to deposit metallic contacts across the aligned tubes. Experimental measurements are presented showing the increased tube alignment and improvement in the transport properties of the junctions. Transport experiments are compared with a spin-coherent quantum transport theory based on a nonequilibrium Greens function method with good agreement.

M9.3
MECHANICS OF DEFORMATION OF SINGLE AND MULTIWALL CARBON NANOTUBES.
Antonio Pantano, David M. Parks, Mary C. Boyce, Massachusetts Institute of Technology, Department of Mechanical Engineering, Cambridge, MA.

Single wall and multi-wall carbon nanotubes (CNTs) hold substantial promise for use as superstiff and strong nanofibers, catalysts, and as components of novel electronic and thermal devices. Despite the potential impact of carbon nanotubes in many areas of science and industry, a robust understanding of their mechanical behavior is lacking and thus limits the design and optimization of CNT-enhanced materials. The deformation behavior of CNTs has been the subject of numerous experimental, molecular dynamics (MD), and elastic continuum modeling studies. Experiments at this lengthscale are themselves still under development and thus have resulted in a range of values for various mechanical properties. Furthermore, consistent interpretation of tube geometry when reducing data to properties is still an issue. This is particularly important when studying multiwall nanotubes (MWNTs). Spectroscopy, micrography and MD simulations have accurately mapped out the structure of MWNTs. MD simulations have also been effective in simulating the deformation of CNTs in tension, bending and torsion. However, the computational expense of MD simulations limits the size of the CNTs that can be studied with this technique and a direct analysis of MWNTs seems prohibitive at the present. Despite the robustness of the laws of continuum mechanics, elastic models cannot be easily applied to MWNTs due to the presence of the interlayer Van der Waals forces. In this paper, we present a novel finite element (FE) approach to model the structure and the deformation of single and multiwall CNTs. Individual tubes are modeled using shell elements where the importance of the lengthscale of the discretization in accurately predicting the deformation response is identified. In the case of multiwall nanotubes, the crucial effects of the tube-tube Van der Waals interactions are simulated by the construction of special interaction elements. The success of this new CNT modeling approach is verified by first comparing simulations of deformation of SWNTs with MD results on axial compression, bending and torsion available in the literature. The approach was then applied to the bending of MWNTs, where the deformed configurations from the novel FE approach were compared to correspondent high-resolution images from experiments. The FE approach was able to successfully predict the experimentally observed wavelengths and shapes of the wrinkles that develop in bent MWNTs, a complex phenomenon dominated by interlayer interactions. The model was found to predict the dependence of wrinkling wavelength on the number of walls, and on the inner and outer diameters. Present results demonstrate that the proposed FE technique could provide scientists with a valuable tool for studying the mechanical behavior of MWNTs as single entities as well as their effectiveness as load bearing entities in nanocomposite materials.

M9.4
GREEN'S FUNCTION METHOD FOR MODELING PHONON MODES IN SINGLE-WALL NANOTUBES CONTAINING DEFECTS. Vinod K Tewary, Natl Inst of Standards and Technology, Materials Reliability Division, Boulder, CO.

Study of phonon spectra through Raman spectroscopy is a powerful technique for characterization of nanotubes and calculation of their physical parameters like thermodynamic functions and thermal conductivity. Most of the calculations on the phonon spectra of nanotubes are based upon the assumption of ideal nanotubes that have full translation symmetry. Recently many configurations have been experimentally identified in which extra atoms are attached to some atoms of a nanotube. Such atoms can be regarded as defects in otherwise perfect nanotubes. In practical nanotube based devices, it would be necessary to identify and characterize such defects because they can affect the efficiency of the devices. We will describe a phonon Green's function method for modeling defects and for calculating the frequencies of perturbed phonon modes and changes in the thermodynamic functions of single-wall nanotubes with arbitrary chirality. The unperturbed Green's function is defined in terms of the dynamical matrix of the Born von Karman model. The local change in the mass and force constants at the defect defines the perturbation and the defect space. The defect Green's function is obtained by solving the Dyson equation using the matrix partitioning technique. Finally, the perturbed frequencies are given by the poles of the Green's function in the frequency space. The thermodynamic functions of the nanotube are obtained by using the phonon frequency spectrum which is given by the diagonal element of the imaginary part of the phonon Green's function. Numerical results will be presented for perturbed phonon modes in a carbon SWNT containing a defect. The main advantage of the Green's function method, in contrast to methods based upon molecular dynamics, is that it is semianalytical and computationally efficient.

M9.5
IDEAL NANO-ANTENNA, NANO-EMITTERS AND PANEL NANO-DEVICES USING 2D CRYSTALS OF SUPERCONDUCTING NANO-TUBES. V. Pokropivny and A. Pokropivny, Institute for Problems of Materials Science of UNAS, Kiev, UKRAINE; A. Vaseashta, Dept of Physics, Marshall University, Huntington, WV.

Unique applications of high-T_c (HTC) and room-T_c (RTC) superconductivity in two-dimensional (2D) bundles and ropes of carbon and non-carbon nanotubes (NTs), and nanotubular crystals (NTCs) are presented. Unique properties of NTs stem from phase transition connected with the change in the aspect ratio i.e. by reducing of tube diameter to nanoscale dimension. A nanotube becomes a quantum quasi -1D cylinder, nanoscopic in diameter while macroscopic in length. Lattices of 2D ordered bundles or ropes of NTs are expected to be more unique in characteristics. Combining Little and Ginsberg's theory with the recent advances in NTs, an ideal superconductor with record RTC can be produced on base of a 2D lattice of quasi-1D superconducting NTs. Mechanism of superconductivity was proposed on the basis of a whispering mode of phonon vibration, which is shown to be responsible for a strong enhancement of electron-phonon interaction and for an increase of T_c and J_c. Coherent and low attenuated vibrations of all atoms pairs on diameter-opposite walls of NTs induce coherent states of their nearest electrons pairs with opposite impulses (**-k,k**) that provide an ideal conditions for Cooper pair formation and peculiar Bose-Einstein condensation. Unique resonant Bose-Einstein condensate appearing in such crystals is suggested to recognize as a novel universal peculiar structural state of matter, that can manifest itself not only in the enhancement of superconductivity but also for the acoustoelectronic and other effects. Evidently in such state, an NTC would be able to transform the energy of external electromagnetic waves without losses into the vibrational energy of natural acoustic hyper-sound phonons acting as an ideal nano-antenna vibrator. Such superconducting NTCs also appear to act as 2D photonic crystals, noiseless field emitters with applications in flat panel displays, photovoltaic devices, etc. An overview of synthesis methods along with several alternate methods to synthesize such superconductors based of MgB_2, C, $NbSe_2$ and other simple compounds will be presented.

M9.6
FIELD EMISSION CHARACTERISTICS OF CARBON NANOTUBES AND THEIR APPLICATIONS IN PHOTONIC DEVICES. A. Vaseashta, C. Shaffer, M. Collins, A. Mwuara, Dept of Physics, Marshall University, Huntington, WV; V. Pokropivny, Institute for Materials Sciences of NASU, Kiev, UKRAINE; D. Dimova-Malinovska, Bulgarian Academy of Sciences, Sofia, BULGARIA.

The dimensionality of a system has profound influence on its physical behavior. With advances in technology over the past few decades, it has become possible to fabricate and study reduced-dimensional systems, such as carbon nanotubes (CNTs). Carbon nanotubes are especially promising candidate for cold cathode field emitter because of their electrical properties, high aspect ratio, and small radius of curvature at the tips. Electron emission from the carbon nanotubes was investigated. Based upon the field emission investigation of carbon nanotubes, several prototype devices have been suggested that operate with low swing voltages with sufficient high current densities. Characteristics that allow improved current stability and long lifetime operation for electrical and opto-electronics devices are presented. The aim of this brief overview is to illustrate the useful characteristics of carbon nanotubes and its possible application.

M9.7
NANOSCALE JUNCTIONS AND NAOASSEMBLY OF STRUCTURES. Sathyajith Ravindran, Mihri Ozkan, University of California Riverside, Dept of Chemical and Environmental Engineering, Riverside, CA; Brooke Colburn, Cengiz Ozkan, University of California Riverside, Dept of Mechanical Engineering, Riverside, CA.

Carbon Nanotubes have attracted attention in the fabrication of transistors, and sensors. However, the challenge has been in ordered placement, orientation and manipulation of these nanotube devices. Conventional patterning strategies must be augmented by new techniques in order to truly take advantage of the quantum nature of novel nanoscale devices. In our research, we are developing a bottom-up approach to fabricate building blocks, which can be used to assemble nanostructures and devices. This involves the assembly of atom- and molecule-like nanostructures into functional 2-D and 3-D units. This will take advantage of the unique optical, electronic, and size-tunable properties of nanostructures and permit the use of these properties for "real" applications in a larger system ($>$ 10 nm and $<$ 1 um). Here, we demonstrate a novel technique for the fabrication of nano-assemblies of carbon nanotubes (CNT) and quantum dots (QD) (CNT-QD conjugates) for the first time using a zero length cross-linker. CNT's are primarily functionalized with carboxylic end groups by oxidation in concentrated sulfuric acid. Thiol stabilized QD's in aqueous solution with amino end groups were prepared in the laboratory. The ethylene carbodiimide coupling reaction was used to achieve the CNT-QD conjugation. Sulfo-N-Hydroxysuccinimide (sulfo-NHS) was used to enhance this coupling procedure. We present EDS and FTIR data for the chemical modification and SEM images of the first nano-building blocks. Current work includes the more complex 3-D assembly of particles and nanotubes into nanodevices. Potential future applications of our method include the fabrication of novel electronic and photonic devices, crystal displays and biosensors.

M9.8
FABRICATION OF TRIODE STRUCTURE FIELD EMITTER ARRAY USING ANODIC ALUMINUM OXIDE TEMPLATE ON Si SUBSTRATE. Jong Hyung Choi, Mun Ja Kim, Jae-Hee Han, Jin Seung Lee, Ji-Beom Yoo and Chong-Yun Park Center for Nanotubes and Nanostructured Composites, Sungkyunkwan University, Suwon, KOREA; Taewon Jung, SeGi Yu, In Taek Han and J.M. Kim, FED Projects, Samsung Advanced Institute of Technology, Suwon, KOREA; T.S. Oh, Department of Materials Science and Engineering HongIk University, Mapo-Gu, Seoul, KOREA.

Earlier work reported the use of an anodized aluminum oxide (AAO) film, having highly ordered pore arrays, as a nanotemplate to control the geometry of subsequently grown carbon nanotubes (CNTs). The devices using CNTs in the AAO/Si substrate can show designed special quality by more complete electrical isolation between them. In this study, we used the through hole AAO membrane as a cathode channel and then CNTs were grown in the pore by thermal chemical vapor deposition without catalytic metal as an emitter. C2H2 and NH3 were used as a source gas. The geometric parameters of the resulting nantubes, such as diameter and length, are controllable with the template structure. SiO2 was deposited as a dielectric layer between gate metal (Cr) and CNTs grown in AAO template using plasma enhanced chemical vapor deposition. Fabricated nano-channel CNTs triode using AAO template generates a high emission current at the low gate voltage. Field emission scanning electron microscopy was employed for the analysis of morphology and microstructure. Emission characteristics of triode were measured in a vacuum chamber (10-6 Torr).

M9.9
ELECTRICALLY CONDUCTIVE POLYANILINE MICRO/ NANOTUBE BLENDS. Alan R. Hopkins, Russell A. Lipeles, and Wei H. Kao, The Aerospace Corporation, El Segundo, CA.

Since the discovery of conducting polymers in 1977, there has been substantial interest in the scientific and engineering communities in understanding their intrinsic properties and finding applications for their unique properties. Recently, one such polymer that has shown to be both processable and conducting when cast from solution is polyaniline (PANI). This electrically conducting polymer has shown significant promise for a wide range of electronic, optoelectronic and charge dissipation applications. The flexibility of its chemical design and synthesis makes it possible to tune PANI's end chemical and physical properties. Moreover, PANI has recently been fabricated into micro and nanotubes that offer very interesting conducting properties. The natural processing advantages of a polymer, together with its tube geometry, make these conductive polymer tubes an attractive material for charge dissipation applications. In this work, we investigate the synthesis and characterization of these polyaniline tubes which were fabricated by a template free synthesis. Futhermore, the processing techniques used to blend these conductive tubes with a series of insulating host materials will be presented.

M9.10
MAGNETIC PROPERTIES OF CARBON NANOTUBE PEAPODS. Dirk Obergfell, Po-Wen Chiu, Siegmar Roth, Max-Planck-Institut fuer Festkoerperforschung, Stuttgart, GERMANY.

By inserting single guest atoms of transition metals like gadolinium or dysprosium into carbon cages one can get metallofullerenes. It is possible to further encapsulate those metallofullerenes into a carbon nanotube, forming a one-dimensional fullerene array inside the tube (a so-called nanotube peapod). We have fabricated single-walled carbon nanotubes which encage Dy@C_{82} metallofullerenes. By using Magnetic Force Microscopy (MFM), we investigate the magnetic properties of carbon nanotube peapods and can observe magnetic signals for our samples. The results will be discussed in terms of long range magnetic ordering between the Dy ions in the peapods.

M9.11
FIELD EMISSION PROPERTIES OF CARBON NANOTUBES SYNTHESIZED BY HIGH TEMPERATURE ARC METHOD AND LOW TEMPERATURE CVD METHOD. Hong-Jen Lai, Sheng-Chin Kung, Chin-Ming Hsu, Bean-Jon Li, Ching-Cheng Lin, Materials Research Laboratories, Industrial Technology Research Institute, Chutung, Hsinchu, TAIWAN, R. O. C.

The field emission properties of carbon nanotubes (CNTs) are investigated for the application of field emission display. Comparisons of the microstructure and field emission properties are made between those carbon nanotubes synthesized by high temperature arc methods and low temperature chemical vapor deposition methods. CNT deposits are examined using scanning electron microscopy (SEM) and high-resolution transmission electron microscopy (HRTEM) to determine microstructure. Carbon structure is studied using Raman spectroscopy. Electron field emission characteristic is measured with diode method in 10-6 torr pressure. The results of HRTEM observations and Raman spectra show the high temperature arc process can produce CNT that has perfect graphitic layer structure and high I(G)/I(D) ratio. The ratio of G-line(sp2 bond) and D-line(sp3 bond) is about 2.8-3.5. From field emission measurement, the low onset fields are about 1.4-2.4 V/gm and can be attributed to highly sharp tips and high electric conductivity of CNTs.

M9.12
FIELD EMISSION STABILITY OF COATED CARBON NANOTUBES AND NANOWIRES. SeGi Yu, Taewon Jeong, Jungna Heo, Sang Hyun Lee, Wonseok Kim, Changsoo Lee, Jeonghee Lee, and J.M. Kim, Samsung Advanced Institute of Technology, NCRI Center for Electron Emissions, Suwon, KOREA; Whikun Yi, Hanyang University, Department of Chemistry, Seoul, KOREA; Ji-Beom Yoo, Sungkyunkwan University, Center for Nanotubes and Nanostructured Composites, Suwon, KOREA.

Field emission stabilities were investigated for carbon nanotubes (CNTs), and GaN and GaP nanowires (NWs) under the oxygen environment, which might affect the lifetime of field emission displays. Uncoated CNTs exhibited several order of magnitude decrease in emission current upon introduction of an oxygen gas, and they failed to return to the initial values after evacuating oxygen. However, SiO2-, BN-, and MgO-coated CNTs showed rather mild current decreases during oxygen environment, and they returned to the initial value after removing oxygen. GaN NWs displayed current reduction upon introducing an oxygen gas while GaP NWs didn't. It was mainly caused by the fact that GaP NWs were found to be coated by an oxide layer while GaN NWs were not. Consequently, the coating layer on CNTs or NWs was consider to be very important for emission stability under oxygen environment. This finding is very promising, since it suggests one way of improving the lifetime of field emitters which might be useful for field emission displays, microwave sources, and etc.

SESSION M10: ACTUATORS AND SENSORS
Chairs: David L. Carroll and Ali Yazdani
Friday Morning, April 25, 2003
Nob Hill A/B (Marriott)

8:30 AM *M10.1
ENERGY TRANSFORMING CARBON NANOTUBE FIBERS. R.H. Baughman, S. Collins, A.B. Dalton, J.P. Ferraris, E. Munoz, S. Lee, J. Razal, V. Ebron, A.A. Zakhidov, B.J. Kim, Univ. of Texas at Dallas; G.M. Spinks, G.G. Wallace, C. Too, J.N. Barisci, Univ. of Wollongong, Wollongong, AUSTRALIA; Y. Gartstein, Xerox; M. Kertesz, Georgetown Univ.; R. Raj, S.R. Shaw, Univ. of Colorado at Boulder; J.N. Coleman, Trinity College, Dublin.

We show that carbon nanotubes can be used in energy transforming devices and materials that (a) transform electrical energy to mechanical energy in nanotube artificial muscles, (b) reversibly transform electrical energy to double-layer energy in fiber supercapacitors that are woven into electronic textiles, (c) transform mechanical energy to elastic energy and thermal energy in super-tough carbon nanotube composite fibers, and (d) transform waste thermal energy into electrical energy in electrochemical thermal energy harvesting devices. Each of these energy transformations will be both demonstrated experimentally and analyzed theoretically. These applications are facilitated by improved methods that we have developed for spinning nanotube fibers that are super tough and have high modulus and strength, which we will describe.

9:00 AM M10.2
CARBON NANOTUBE ACTUATOR DEVICE DEVELOPMENT. Leonard S. Fifield, Anne M. Zipperer, Larry R. Dalton, University of Washington, Dept of Chemistry, Seattle, WA.

Carbon nanotubes represent an interesting material option for many applications including electromechanical actuators. This work attempts to improve actuation based on bulk samples of nanotubes, characterize the performance and mechanism of these nanotube actuators, and demonstrate the use of nanotube actuation in a fiber optic switch.

9:15 AM M10.3
NANODEVICES, NANOSENSORS AND NANOCANTILEVERS BASED ON SEMICONDUCTING OXIDE NANOBELTS. Z.L. Wang, W. Hughes, P.X. Gao, Center for Nanoscience and Nanotechnology, School of Materials Science and Engineering, Georgia Institute of Technology, Atlanta, GA; Michael S. Arnold and Phaedon Avouris, IBM Research Division, T.J. Watson Research Center, Yorktown Heights, NY; E. Comini, G. Faglia, G. Sberveglieri, INFM and Universitá; di Brescia, Brescia, ITALY.

This presentation addresses three novel applications of the semiconducting oxide nanobelts [1]: nano-size field-effect transistors (FETs), nano sensors and nanocantilevers. We have fabricated FETs based on single SnO_2 and ZnO nanobelts of thicknesses between 10 nm and 30 nm [2]. Switching ratios as large as six orders of magnitude and conductivities as high as 15 $(\Omega\text{-cm})^{-1}$ are observed. Annealing SnO_2 nanobelt FETs in an oxygen-deficient atmosphere produces a negative shift in gate threshold voltage, indicating doping by the generation of surface oxygen vacancies. This treatment provides an effective way of tuning the electrical performance of the nanobelt devices. ZnO nanobelt FETs are sensitive to ultraviolet light. Gas sensors have been fabricated using the single crystalline SnO_2 nanobelts [3]. Electrical characterization showed that the contacts were ohmic and the nanobelts were sensitive to environmental polluting species like CO and NO_2 as well as ethanol for breath analyzers and food control applications. The results demonstrate the potential of fabricating nano-size sensors using the intigrity of a single nanobelt with a sensitivity at the level of a few ppb. Finally, the nanobelts have been demonstrated as ultra-sensitive cantilever for AFM. [1] Z.W. Pan, Z.R. Dai and Z.L. Wang, Science, 291 (2001) 1947. [2] E. Comini, G. Faglia, G. Sberveglieri, Z.W. Pan, Z.L. Wang Applied Physics Letters, 81 (2002) 1869. [3] M. Arnold, P. Avouris, Z.L. Wang "Field-Effect Transistors Based on Single Semiconducting Oxides Nanobelts", J. Phys. Chem. B, in press (2002).

10:00 AM *M10.4
ELECTRONICS AND MECHANICS WITH CARBON NANOTUBES. Yuval Yaish, Ji-Yong Park, Ethan Minot, Vera Sazonova, Markus Brink, Sami Rosenblatt, Paul McEuen, Cornell University, Laboratory of Atomic and Solid State Physics, Ithaca, NY.

We explore the electronic, electrochemical, and electromechanical properties of carbon nanotubes (NT) using both transport and scanned probe measurements. First, a metallized atomic force microscope (AFM) tip is utilized as a local voltage probe to the potential profile within a NT transistor. Voltage pulses applied to the AFM tip are also employed to create electrical breaks, tunnel barriers, and quantum dots within nanotubes. An AFM tip is also used to apply tension to suspended NTs. We show that strain modifies the NT band gap and can convert a metallic tube into a semiconductor, and vice versa. Finally, we discuss measurements of NTs where an electrolyte serves as a very efficient gate. We will discuss possibilities for single molecule detection using these devices.

10:30 AM M10.5
SEMICONDUCTOR SWNTS AS CHEMICAL SENSOR. S. Auvray, E. Valentin, M. Goffman, S. Palacin, A. Filoramo, J.P Bourgoin, LEM Laboratoire CEA-MOTOROLA, d'Electronique Moleculaire Service de Chimie Moleculaire, CEA Saclay, Gif/Yvette, FRANCE.

Semi-conducting single-walled carbon nanotubes (SWNTs) are promising building blocks for chemical nanosensors and other electronic devices. To fabricate such devices systematically and reproducibly, we use self-assembly to control the placement of SWNTs [1] on silica surfaces. The SWNTs self-assembled on the substrates are subsequently contacted using e-beam lithography in a field-effect transistor. These devices allowed us to systematically study the effect of molecular adsorption on the SWNTs [2] on its electronic transport properties. A shift of several volts of the threshold voltage of the transistors has been observed in the transconductance curve (Ids vsVg). The mechanism underlying this shift is being investigated by masking the nanotube surface or the contacts to localize the adsorption of molecules. This makes it possible to study the chemical interactions between the adsorbed molecules and the surface of the nanotubes as well as the role played by the metallic contacts independently. We will present first promising results of a chemical sensor based on individual semiconductor SWNTs for the detection of molecules in the gas phase or in solution. The high sensitivity and fast time response of our devices will be discussed and compared with existing solid-state sensors at room temperature. [1] K.H. Choi, S. Auvray, J.P. Bourgoin, D. Esteve, G.S. Duesberg, S. Roth, M. Burgard ; Surf. Sci., 462 (2000)195 [2] Dai H.; Acc. Chem. Res.(2002).

10:45 AM M10.6
SELF-ALIGNED CARBON NANOTUBE NANO-ELECTROMECHANICAL SYSTEMS. Seung-Beck Lee, L.A.W. Robinson, D.G. Hasko, H. Ahmed, University of Cambridge, Cavendish Labordtory, Cambridge, UNITED KINGDOM; A.S. Teh, K.B.K. Teo, M. Chhowalla, G.A.J. Amaratunga, W.I. Milne, University of Cambridge, Dept of Engineering, Cambridge, UNITED KINGDOM.

Due to their superior chemical stability and mechanical strength, carbon nanotubes have been proposed as components of various nano-electromechanical systems (NEMS). To realize integrated on-chip NEMS applications using carbon nanotubes, a reliable method of placing individual adjacent control electrodes with nanoscale precision on suspended carbon nanotubes should be found. Here, we present a study on fabrication and implementation of self-aligned nano-electrodes on suspended carbon nanotubes for NEMS application. A single pattern in PMMA was used to suspend the nanotube and define control electrodes that were perfectly aligned. Nanotubes were dispersed on an oxidized Si substrate, and after mapping, contact electrodes were deposited. Then a thin line ($\sim$20 nm) was defined in PMMA perpendicular to the nanotube. When the substrate was chemically etched through this line, the nanotube was suspended ($\sim$50nm) and the resist had an undercut profile. The suspended nanotube acts as an evaporation mask for the control electrodes. After metal evaporation and lift-off, the metal island formed on the nanotube was removed due to poor adhesion, while the metal electrodes remained on the substrate. The self-aligned nano-electrodes now contain a nano-gap, and form split gate electrodes, separated by a few nanometers from the suspended nanotube. We will present results of self-aligned carbon nanotube NEMS fabrication and demonstrate electromechanical control of suspended carbon nanotubes.

11:00 AM M10.7
HORIZONTALLY ALIGNED CARBON NANOTUBE ARRAY AS A GAS SENSOR. Youngsik Song and Jaewu Choi, Wayne State University, Dept. of Electrical and Computer Engineering, Detroit, MI.

We fabricated horizontally aligned carbon nanotube array between electrodes. The electrodes have three-layer structure and catalyst layer is embedded between two metallic layers. The diameter of carbon nanotube was controlled by the thickness of catalyst layer. We obtained semiconducting carbon nanotube array by burning out metallic carbon nanotubes since the semiconducting carbon nanotube is intrinsically sensitive to the external perturbations. The semiconducting carbon nanotube array is desirable to implement a high sensitive nano-scale gas sensor. The significant change of the conductivity was observed with an extremely small amount of nitrous oxide. First, it is attributed to selective array of the semiconducting nanotubes instead of mixed metallic and semiconducting carbon nanotubes. Second, the direct lateral growth between electrodes reduces the contact potential between carbon nanotube and electrode. Finally, the lateral array of carbon nanotubes has large effective surface area and it increases the effective impinging crosssection of the nitrousus oxide to the carbon nanotubes.

11:15 AM M10.8
SINGLE-WALLED CARBON NANOTUBE BASED CHEMI-RESISTOR FOR GAS SENSING. Jing Li, Marty Cinke, Qi Laura Ye, Yijiang Lu, M. Mayyappan, Center for Nanotechnology, NASA Ames Research Center, Moffett Field, CA.

Single-walled carbon nanotube (SWCNT) has been used as a sensing material in an interdigitated electrode platform for gas sensing. Due to extremely high surface-to-volume ratio, efficient gas adsorption occurs on the surface of the carbon nanotubes. Gas adsorption causes the SWCNT to change its conductivity. The one-dimensional quantum wire nature makes its electronic properties very sensitive to the gas adsorption. SWCNT based chemiresistors have demonstrated high sensitivity to gases and vapors such as nitrogen dioxide, benzene, nitromethane and nitrotoluene. A high pressure CO disproportionation (HiPco) process produced SWCNTs are used in this study. Very high purity single-walled carbon nanotubes (SWCNTs) were obtained from this HiPco by a two-step purification process. The raw and purified samples were characterized using high resolution transmission electron microscopy, Raman spectroscopy and thermogravimetric analysis. The purified sample consists of $\sim$0.4% Fe and the process does not seem to introduce any additional defects. The nitrogen adsorption isotherm studies at 77K reveal that the total surface area of the purified sample increases to 1587 m2/g that is the highest value reported for SWCNTs. The adsorption properties to different analytes and pore structures of this purified SWCNT have been investigated. The polarity, electronegativity and vapor pressure of the analytes will be correlated to the sensor performance, such as response amplitude, response curve shape, response time and sensitivity, of SWCNT based chemiresistors.

11:30 AM M10.9
ELECTRON FIELD EMISSION FROM CARBON NANOTUBES EMBEDDED IN POLYMER MATRIX FOR ELECTRONIC SENSOR APPLICATIONS. C.H.P. Poa, R.C. Smith, S.R.P. Silva Advanced Technology Institute, School of Electronics and Physical Science, University of Surrey, Guildford, UNITED KINGDOM; P.C.P. Watts, W.K. Hsu, H.W. Kroto, D.R.M. Walton, School of Chemistry, Physics and Environmental Science, University of Sussex Brighton, UNITED KINGDOM.

Miniaturisation of microelectronic devices is driven by the need for higher specification devices. Although carbon nanotubes (CNTs) have been proposed as a future material for high specification devices, the design or architecture used to fabricate such a structure on a large scale is yet unknown. One of the most promising electronic applications for CNT based devices is in the area of electron field emission. Indeed, prototype field emission displays, luminescent tubes and x-ray sources have been published. However, to date no results based on CNT sensors have been proposed. Due to the exponential relationship between the emission current and the applied electric field, it can be envisaged that a high precision and high sensitivity sensor can be fabricated, to map the variations in the applied electric field. In addition, an added advantage in using a field emission based sensor is the high amplification of current density to variations in electric field. We have designed a novel sensor based on electron field emission from CNT. The field emission from CNTs embedded in a polystyrene matrix have been studied, with threshold fields as low as 1.6 V/micron observed. The technique used to fabricate our cathode material is simple and lends itself to screen-printing. We show that by subjecting our cathodes to differing stress loadings how a high performance transducer can be designed. The field emission property as a function of external applied stress is studied using a three-point bending technique. The threshold field decreases linearly as a function of the applied deformation to thin CNT cathodes. Results suggest that CNT emitters are promising as a future sensor material.

11:45 AM M10.10
SUPERCAPACITORS BASED ON CARBON NANOTUBE–NICKEL OXIDE COMPOSITES. Kui Liang, Kay Kyeok An, Chan Kim, Ji Yeong Lee, Seong Chu Lim, Dong Jae Bae, and Young Hee Lee, Sungkyunkwan Univ, Suwon, KOREA (SOUTH).

Carbon nanotubes (CNT)and nickel oxide(NiO) are two attractive electrode materials for supercapacitors. Carbon nanotubes may have high electric conductivity, but their way of forming capacitance is electric double layer capacitance and the corresponding specific capacitance is not high enough. The way of forming capacitance of supercapacitors based on nickel oxide is pseudocapacitance and the corresponding specific capacitance is high, but the electric conductivity of nickel oxide is too low. It is well known that the specific energy and the specific power are key parameters for supercapacitors, and dependant on the specific capacitance and electric conductivity of electrode materials of supercapacitors, respectively. That is to say, both carbon nanotubes and nickel oxide are not ideal electrode materials for supercapacitors. In this paper a composite electrode material is proposed and applied as an supercapacitor electrode material for the first time. This kind of composite consists of carbon nanotubes and nickel oxide, and is prepared by two ways: the first one is sol-gel way and the second one is chemically precipitating way. By the sol-gel way, the composite is obtained when carbon nanotubes are mixed with nickel hydroxide sol, followed by drying and annealing at different temperature and time. By the chemically precipitating way, the composite is obtained when carbon nanotubes are employed as templates of hydroxide precipitating, followed by drying and annealing. X-ray diffractometry (XRD), field-emission scanning electron microscopy(FE-SEM), nitrogen adsorption(BET) and four-probe techniques are employed to characterize the structure, morphology, surface area and electric conductivity of this composite. Percolation phenomenon is observed in this composite material. Charge-discharge, ac impedance and cyclic voltammetry test are executed to characterize supercapacitors. Supercapacitors based on carbon nanotubes and nickel oxide composite not only have high specific capacitance, but also have low equivalent serial resistance. Good frequency response ability can be observed for the supercapacitors.