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E-MRS Spring Meeting 2003
June 10 - 13, 2003

SYMPOSIUM L

Carbon materials for active electronics

Symposium Organizers:

J.-Ch. Arnault, IPCMS-GSI, Strasbourg, France

E. Kohn, University of Ulm, Germany

S. Roth, Max-Planck-Institut, Stuttgart, Germany

M. Schreck, University of Augsburg, Germany

Papers will be published in Diamond and Related Materials

E-MRS 2003 SPRING MEETING

SYMPOSIUM L

Tuesday, June 10, 2003
Mardi 10 juin 2003

Morning
Matin

9:00 Welcome

Session I: Nanotube circuits and devices

Session chair: G. Duesberg

- L-I.1** 9:10 -Invited- OPTICAL AND STRUCTURAL PROPERTIES OF NANOTUBES
Angel Rubio, Dpto. Fisica de Materiales, Facultad de Quimicas U. Pais Vasco, Centro Mixto CSIC-UPV/EHU and Donostia International Physics Center (DIPC) Apdo. 1072, 20018 San Sebastian/Donostia, Spain
We will present recent calculations performed to understand the spectroscopic properties of C and BN nanotubes, in particular optical, transport and vibrational properties. Those studies are relevant for characterisation of the nanotube samples as well as for their potential applications in devices.
Work done in collaboration with: L. Wirtz, L. Reining, T. Marinopoulos, N. Vast, A. Loiseau, S. Roth
Support: EC-RTN program COMELCAN (HPRN-CT-2000-00128)
- L-I.2** 9:45 -Invited- LOGIC CIRCUITS WITH CARBON NANOTUBE TRANSISTORS
A. Bachtold, Laboratoire de Physique de la Matière Condensée, Ecole Normale Supérieure, Paris, France, P. Hadley, T. Nakanishi, C. Dekker, Department of applied physics, TUDelft, 2628CJ Delft, The Netherlands
Carbon nanotubes are one-dimensional conductors, which are either metallic or semiconducting depending upon their structural details. In this talk, experiments on logic circuits with nanotube transistors will be discussed. We have attached nanofabricated electrodes to individual semiconducting nanotubes to measure their conductance. The originality of our layout lies in the gate that is local and that provides an excellent capacitive coupling with the tube. The transistors show favorable device characteristics such as high gain (10), a large on-off ratio, and room-temperature operation. Importantly, the local-gate layout allows for integration of multiple devices on a single chip. Indeed, we demonstrate one-, two-, and three-transistor circuits that exhibit a range of digital logic operations, such as an inverter, a logic NOR, a static random-access memory (SRAM) cell, and an ac ring oscillator. I will also discuss transport experiments through single nanotubes. Our new device layout also allows to probe new physical phenomena that are unique to nanotubes by measuring the transconductance. Strong electrostatic doping of the nanotube from p-doping to n-doping is achieved, which enables the study of the long-range screening of charge along these one-dimensional conductors.
- 10:20 **BREAK**

- L-I.3** 10:40 -Invited- NANOTUBE SPINTRONICS: MAGNETOTRANSPORT AND MAGNETISM IN CARBON NANOTUBE-BASED SYSTEMS
C.M. Schneider, B. Zhao, R. Kozhuharova, S. Zotova, T. Muehl, M. Ritschel, I. Moench, H. Vinzelberg, D. Elefant, A. Graff, A. Leonhardt, Inst. of Solid State and Materials Research IFW Dresden, Dresden, Germany, H. Lichte, Inst. of Applied Physics, Technical University Dresden, Dresden, Germany
 Carbon nanotubes (CNT) are extensively investigated as possible components in future molecular electronics. Additional functionality of CNT-based systems can be created by taking into account the electron spin. The spin functionality can be introduced in two ways. Firstly, CNTs may be contacted by ferromagnetic electrodes. For this arrangement, substantial spin-dependent transport effects have been observed at low temperature [1,2]. The maximum magnetic field induced resistance changes we have observed on multiwall CNT / Co contacts reach $\rho_R/\rho_0 > 50\%$ (4.2K). These findings suggest a quasi spin-ballistic transport to take place through multiwall CNT over several hundred nanometers separation of the electrodes. The results also show the magnetoresistance to be strongly affected by the properties of the nanotube/electrode interface. Secondly, CNTs may be filled with or covered by a magnet. A very efficient filling of multiwall CNT with magnetic elements is achieved by means of dedicated CVD techniques involving metallorganic precursors [3]. Using this approach, we have been able to prepare multiwall CNT filled with Fe, Co, Ni, or intermetallic compounds of these elements. Macro - and microscopic magnetic studies reveal unique magnetic properties of the filled tubes which may also become of interest in nanotube spintronics.
 [1] B. Zhao et al., Appl. Phys. Lett., 80 (2002) 3144.
 [2] K. Tsukagoshi et al., Nature, 401 (1999) 572.
 [3] N. Grobert et al., Appl. Phys. Lett., 75 (1999) 3363.
- L-I.4** 11:15 EFFECTS OF HEAVY-ION RADIATION ON THE ELECTRON FIELD EMISSION PROPERTIES OF SULFUR-DOPED NANOCOMPOSITE CARBON FILMS
 Adolfo González-Berríos, Joel De Jesús, Iris M. Vargas, Department of Physics, University of Puerto Rico, San Juan PR, USA, Oscar O. Ortiz, Department of Chemical Engineering, Polytechnic University, San Juan PR, USA, Brad R. Weiner, Department of Chemistry, University of Puerto Rico, San Juan PR, USA, Gerardo Morell, Department of Physical Sciences, University of Puerto Rico, San Juan PR, USA
 The effects of heavy ion radiation over the electron field emission (EFE) properties of sulfur-doped nanocomposite carbon (n-C:S) films were investigated. Two identical sets of n-C:S films were prepared in a hot filament chemical vapor deposition (HFCVD) system using CH₄, H₂ and H₂S. Films with various sp³ C and sp² C fractions were present within each set, which were obtained by varying the substrate temperature (300-900 oC), the CH₄ concentration (0.3 and 2.0%) and the H₂S concentration (0 and 500 ppm). Raman spectroscopy revealed the characteristic diamond (tetragonal sp³ C) band at around 1332 cm⁻¹ and the graphitic (trigonal sp² C) D and G bands at around 1350 and 1590 cm⁻¹, respectively, evidencing the composite nature of the films. One set of films was submitted to a 20 Krad dose of energetic Si and Fe ions at Brookhaven National Laboratory's Alternating Gradient Synchrotron (AGS). It was found that there is an enhancement of the current density (J) and threshold field (E_c) as result of irradiation for some n-C:S materials, while others did not show significant variations in their EFE properties. These changes depend critically on the initial aggregation state of trigonally-bonded carbon within the films, which was evaluated through a quantitative analysis of the corresponding Raman spectra. A comprehensive analysis of the results suggests that long-term stable electron field emitters can be fabricated using nanocomposite carbon materials that would remain unchanged in their EFE properties while absorbing ionizing radiation. Such behavior goes beyond the concept of radiation hardness and into radiation insensitiveness.
- L-I.5** 11:40 ELECTRON EMISSION FROM CARBON NANOTUBES AND CARBON NANOSTRUCTURES (DIAMOND DOPED WITH NITROGEN, GRAPHITIC FIBERS, ...).
CS Cojocaru(a), F. Le Normand(a), J.Q. Li(b), Y. Nedellec(c), L. Gangloff(c), H. Lezec(d), T.W. Ebbesen(d), P. Legagneux(c), (a)IPCMS, UMR 7504 CNRS, Po Box 43, Bat 69, 23, rue du Loess, 67034 Strasbourg Cedex, France, (b)University of Lanzhou, People's Republic of China, (c), (d)
 Field emission is one of the most promising potential applications of carbon nanotubes (CNTs) and carbon nanostructures when these nanostructures combine positively a geometrical effect (local exaltation of the electric field due to a strong curvature radius) and an electronic effect (weak work function). In addition they may display strong chemical inertness and thermal conductivity, which open the way to the realization of convenient electrons sources for vacuum electronics such as flat panels, cold cathodes. Field emission measurements obtained on CNTs, carbon fibers grown on SiO₂/Si(100) substrates and diamond doped with nitrogen deposited on Si(100) by a CVD process showed that the thresholds of emission were strongly dependent on the nature of the material. Therefore they were within the range 1-4 V/μm for CNTs. By contrast they ranged above 10 V/mm either for carbon nanofibers or doped diamond. However the current densities were quite variable and often reached a rapid saturation both due to screening of the field by the high density of CNTs and to conductivity limitations of the substrate. Therefore we used patterned surfaces to grow array of CNTs emitters. Patterned surfaces were obtained by controlled deposition of metallic spots by a combination of lithographic techniques, using either photons, electrons or ions beams.

12:05

LUNCH

Tuesday, June 10, 2003
Mardi 10 juin 2003

Afternoon
Après-midi

Session II: Diamond doping and applications in devices
Session chair: J. Isberg

- L-II.1** 14:00 -Invited n-TYPE DOPING OF DIAMOND AND THE DEVICE APPLICATIONS
Satoshi Koizumi(a) and **Milos Nesladek**(b), (a)Advanced Materials Laboratory, National Institute for Materials Science, 1-1 Namiki, Tsukuba 305-0044, Japan ,(b)Institute for Materials Research (IMO), Limburg University, 3590 Diepenbeek, Belgium
n-Type diamond thin films were successfully formed by optimizing the growth condition of chemical vapor deposited diamond under phosphorus doping to obtain better crystalline perfection. Phosphorus atoms can be incorporated in {111} oriented surface during the growth and the concentration can be controlled within the range of $1E17 \sim 5E19 \text{ cm}^{-3}$. Phosphorus forms a donor level at 0.6 eV below the conduction band minimum that is confirmed by Hall measurements, photocurrent and infrared absorption (FTIR). The maximum electron mobility is $400 \text{ cm}^2/\text{V}\cdot\text{sec}$ at room temperature obtained from lightly doped samples ($3E17 \text{ cm}^{-3}$). Cathodoluminescence of phosphorus doped films show strong bound exciton luminescence at 5.19 eV at low temperatures and free exciton luminescence (5.27 eV) can be observed even at room temperature. Applying the n-type diamond growth technique, pn-junction has been formed with boron-doped p-type diamond. The pn-junction has shown good rectification property. The diode characteristics and the behavior of pn-junction interface have been characterized by temperature dependent IV and CV measurements. By forward bias operation, the diode shows ultraviolet light emission at 235 nm that attributes free exciton luminescence. The diode also shows photoelectric response against ultraviolet light with the wavelength shorter than 225 nm that corresponds the band-gap of diamond. It is expected these characteristics of diamond pn-junction will be applied for the next generation opto-electrical devices.
- L-II.2** 14:35 PREPARATION AND ELECTROCHEMICAL PROPERTIES OF SULFUR-BORON-CODOPED N-TYPE DIAMOND FILMS
S.C. Eaton, J.C. Angus, Case Western Reserve University, Cleveland OH 44106, USA and Yu.E. Evstefeeva, Yu.V. Pleskov, Frumkin Institute of Electrochemistry, Leninskii pr. 31, 119071 Moscow, Russia
Electrochemical properties of the n-type diamond films are studied for the first time using methods of electrochemical impedance, open-circuit photopotential, and potentiodynamic curves in $\text{Fe}(\text{CN})_6^{3-/4-}$ redox solutions. The films of sulfur-doped synthetic diamond were chemical-vapor-deposited using codoping with sulfur and boron. The sulfur, which was more heavily concentrated in the near-surface region, was detected with particle-induced x-ray emission, x-ray photoelectron spectroscopy, and secondary ion mass spectroscopy. Electrochemical, thermoelectric and Hall measurements showed that the sulfur-containing films grown from a gas phase lean in boron are n-type, whereas those grown with higher boron content are overcompensated, hence, p-type. The impedance-spectroscopy and kinetic behaviour of n-type semiconductor diamond electrodes appeared anti-symmetrical to that of p-type diamond.
This work was carried out financed in part by NEDO
International Joint Research Grant Program (Project no. 01MB9)
and Russian Foundation for Basic Research (Project no. 01-03-32045).
- L-II.3** 15:00 DIAMOND-BASED HIGH POWER SWITCHES: CONTROLLING PHOTOCONDUCTIVE GAIN FOR LOW RESISTANCE ON-STATE
Stephane Curat, Oliver Gaudin, Oliver A Williams and Richard B Jackman, Electronic and Electrical Engineering, University College London, Torrington Place, London WC1E 7JE, U.K.
The extreme electronic properties of diamond suggest that it may be an ideal substrate for the formation of high power switches. For example, diamond can possess resistances in excess of 10^{11} Wcm , enabling high voltages to be blocked. However, if a conventional approach to switching is adopted through the formation a diode structure, tunnel currents will severely reduce this blocking capability if high doping levels are used, and with low doping levels useful on-currents will only be achieved at high voltages where power losses become a significant concern. An alternative strategy is to use intrinsic diamond such that a high blocking capability is achieved and photo-inject carriers to generate a low resistance on-state. To obviate the need for high intensity light sources, whose use is not realistic within the envisaged applications for these switches, high levels of photoconductive gain are required, such that many carriers can be measured (on-current) for the injection of modest numbers of photo-generated carriers.
This paper will present recent results on the control of photoconductive gain within single crystal and polycrystalline CVD diamond for high power switching applications. Control of the material parameter $\mu\tau$ (mobility-lifetime product) is essential if switches are to be designed with the desired characteristics. It will be shown that whilst diamond 'quality' and grain size (in the case of polycrystalline material) play a role in determining the value of $\mu\tau$, post-growth defect passivation treatments can also be used to good effect. $\mu\tau$ values in the range 10^{-6} to 10^{-2} will be reported. The effect of varying the wavelength of the light used will be described (UV-VUV-X-ray), and kV levels of switching shown.

L-II.4 15:25 **LOW ENERGY X-RAY LINEAR DOSIMETRY BY THIN POLYCRYSTALLINE DIAMOND FILM BASED DEVICES**
P. Ascarelli, E. Cappelli, D.M. Trucchi, Consiglio Nazionale delle Ricerche (CNR), Istituto di Metodologie Inorganiche e dei Plasmi (IMIP), Via Salaria km 29,300, 00016 Monterotondo Scalo, Rome, Italy and G. Come, M.C. Rossi, Dept. of Electronic Engineering, University of Rome "Roma Tre", Via delta Vasca Navale 84, 00146 Rome, Italy
The suitability of the use of thin polycrystalline diamond films (40-80µm) as X-ray dosimeters has been verified by field analysis of the photo-generated signal dependence both on the applied voltage and on the radiation incident flux. It has been possible to demonstrate both the linearity of the detector response to the radiation absorbed flux and the reconstruction of the source emission spectrum. Through the absorber method (a simple technique for changing the radiation intensity in a controlled way), there is the possibility to characterize the devices illuminated by a low energy (8-40 keV) X-ray beam. A linear signal dependence on the incident radiation intensity has been verified and a model has been proposed in order to explain the influence of the polarization voltage on the charge carrier collection processes. Further, through a mathematical treatment of the signal intensity as a function of the absorber thickness, it has been possible to reconstruct the source energy spectrum. Thus the association of the absorber method to the radiation dose measurement allows the use of the diamond based detectors not only as dosimeters but as simple spectrometers.

15:50

BREAK

Session III: Surface conductivity of hydrogenated diamond surfaces

Session chair: E. Kohn

- L-III.1** 16:10 -Invited- **INFLUENCE OF EPITAXY ON THE SURFACE CONDUCTION OF DIAMOND FILM**
Makoto Kasu and Naoki Kobayashi, NTT Basic Research Laboratories, NTT Corporation, 3-1 Morinosato-Wakamiya, Atsugi 243-0198, Japan
Surface conduction due to H termination is obtained in CVD-grown or H-plasma-exposed, poly- and single-crystalline diamond layers. The surface conduction seems the easiest p-type doping method, and has been used to field effect transistors. However, it seems still unclear how electric properties of the surface conduction depend on various structural properties of diamond surface and bulk.
In this presentation, we focus on the study of electric properties of microwave-plasma CVD-grown H-terminated homoepitaxial diamond layers on HPHT diamond substrates. We have investigated the electric and structural properties of homoepitaxial diamond layers grown on both (001) and (111)-oriented HPHT diamond substrates in various growth conditions, and clarified how structural properties, such as unepitaxial crystals, stacking faults which contain many twins, grain boundaries, step bunching, and residual impurities affect its electric properties. In addition, we confirmed that the density of physically-adsorbed species from the air changes the hole sheet concentration and surface conduction, although the physics of the surface conduction has not been completely understood. This suggests the environment of device processing will affect its electric properties.
- L-III.2** 16:45 **IMPROVING THE STABILITY OF THE ELECTRICAL CONDUCTIVITY OF HYDROGENATED DIAMOND SURFACES**
E. Snidero, D. Tromson, C. Mer, P. Bergonzo, LIST (CEA - Recherche Technologique)/DIMRI/SIAR, CEA/Saclay, France
In order to improve the reliability of the H surface layer properties and their long-term stability required for electronic device fabrication, in-situ measurements of the surface conductivity were performed after hydrogen plasma treatments, to assess the parameters that are most affecting the conductivity. By using an optimised in-situ configuration, the influence of the gaseous environment after plasma treatment, as well as the temporal aspects of the rise of the surface conductivity were analysed. The importance of each step influencing the surface properties can be independently studied, in order to check its effect, and namely the type and duration of several treatments, surface temperature, gaseous environments, and electrical biasing of the contacts, this being responsible for attracting or repulsing ions from the diamond surface. Further, the dynamical aspects of the variation in conductivity are also addressed, and concern the time to reach the surface conductivity with respect to the sample environments.
- L-III.3** 17:10 **DIAMOND BIOELECTRONICS: PATTERNED GROWTH OF NEURONS ON SINGLE CRYSTAL AND CVD DIAMOND FILMS**
Oliver A Williams(a), Christian Spec(b), Ralf Schoepf(b) and Richard B Jackman(a), (a)Electronic engineering, University College London, Torrington Place, London, WC1E 7JE, U.K., (b)Department of Pharmacology, University College London, U.K.
Diamond is one of a very small number of materials that are truly biocompatible. It is also probably the only semiconductor that is biocompatible, and this is essential in the application of in-vivo bioelectronics. The fact that diamond is optically transparent is also an attribute which is often overlooked when discussing biomaterials.
In this paper, the formation of ordered networks of mouse hippocampal neurons will be demonstrated on diamond surfaces, and compared with those on silicon and glass. Proteins and peptides were patterned using micro contact printing, and images formed using immunofluorescence, SEM and standard inverted microscopy techniques. The suitability of interfacing neurons with devices fabricated on the surface conductive layers on diamond films, formed through hydrogenation, will be discussed.

L-III.4 17:35

DIAMOND-BASED ELECTRONICS FOR RF APPLICATIONS

A. Aleksov(a), M. Kubovic(a), M. Kasu(b), D. Grobe(c), M. Schreck(d), B. Stritzker(d), E. Kohn(a), (a)Department of Electron Devices and Circuits, University of Ulm, Albert-Einstein-Allee 45, 89081 Ulm, Germany, (b)NTT Basic Research Laboratories, Kanagawa, 243-0198 Japan; currently with the Department of Electron Devices and Circuits, University of Ulm, 89081 Ulm, Germany, (c)present address: GFD, Gesellschaft für Diamantprodukte mbH, 89081 Ulm, Germany, (d)Institut fuer Physik, Universitaet Augsburg, 86135 Augsburg, Germany

Due to its exceptional properties diamond may be considered an ideal material for high power, high temperature, high frequency electronics. However, diamond does not possess a natural single-crystalline substrate of relevant size and the possibilities of active doping are still severely restricted. Within this restricted field of parameters however, high frequency / ultra-high power applications seem in reach based on p-channel FETs and MMICs including waveguide components. Only recently a single-crystal diamond quasi-substrate grown on an Ir-coated SrTiO₃ substrate was used for diamond FETs, the size of 1 cm² opening up the perspective of a monolithic circuit integration.

The status of discrete surface p-type FETs (using the H-induced surface channel) will be discussed for a HTHP single-crystal (including a homoepitaxial buffer layer) and a single crystal quasi-substrate. Using a new processing scheme current instabilities usually observed with diamond surface channels could be minimized, enabling first RF-power measurements. Up to now only devices with small gatewidth have been fabricated (without air bridges etc.), nevertheless DC, small signal RF and RF-power measurements could be performed. Although the mobility in the H-induced surface channel is still below the bulk mobility at 0.2 μm gate length f_{max} cut-off frequencies above 30 GHz could be extracted. At 1 GHz a maximum output power of up to 0.35 W/mm could be measured. However, the RF-power measurement does not reflect the maximum power handling capability due to incomplete matching, but rather the RF large signal characteristics. Thus, it appears that there is indeed a window for the development of high power diamond RF FET devices.

Proper device matching in an amplifier is generally performed by the MMIC passive waveguide network, preferably being integrated on the identical substrate. Indeed diamond is an ideal microwave substrate with low attenuation in coplanar waveguides. First integration concepts will be discussed.

L-III.5 18:00

STUDY OF THE STABILITY OF SCHOTTKY DIODES ON HYDROGEN TERMINATED DIAMOND

D. Tromson, C. Mer, E. Snidero, P. Bergonzo, LIST (CEA - Recherche Technologique)/DIMRI/SIAR, CEA/Saclay, France, F. Houzé, J.P. Kleider, J. Alvarez, Laboratoire de Génie Electrique de Paris (UMR 8507 CNRS), Ecole Supérieure d'Electricité, Plateau de Moulon, 91192 Gif-sur-Yvette Cedex, France, V.N. Amosov, Trinit, Division of Physics of Thermonuclear reactors, Troitsk Moscow, Russia

One of the most fundamental steps for the fabrication of Schottky diodes on diamond surface is the elaboration of the conductive surface layer that can be obtained from hydrogen plasma treatment under micro-wave excitation. This hydrogen terminated diamond exhibits a p-type behaviour that allows the elaboration of Schottky contacts from the evaporation of aluminium. The rectifying properties of the diode strongly depends on the H-terminated surface (homogeneity, stability), but also on the properties of the diamond-aluminium interface which can include defective regions that degrade the diode quality.

The stability of the H₂ layer conduction properties has been characterised by in-situ measurements during the H-plasma process and the resulting surface coverage was investigated by micro-analysis techniques. The time evolution of the aluminium contact in air has been evidenced by means of conducting probe AFM characterisations and correlated with the degradation of the diode quality. Complementary measurements with encapsulated aluminium contact as well as measurements in neutral atmosphere have been made in order to focus on the stabilisation of the diode properties.

L-III.6 18:25

STATIONARY SECONDARY ELECTRON EMISSION FROM DIAMOND FILMS

P. Ascarelli, A. Cali, E. Cappelli, CNR-IMIP, P.O.B. 10, 00016 Monterotondo Scalo, Rome, Italy, S. Zoffioli, CNR-IMM, via Gobetti 101, 40129 Bologna, Italy

Aiming to applications in stable electron multipliers and to the realization of image enhancing devices for scanning electron microscopy, a study of the stationary secondary electron emission from CVD diamond films is presented. An extensive analysis of the secondary electron emission yield d as a function of the primary electron beam energy E has been performed on polycrystalline CVD samples of different microstructure.

The experimental results are analysed according to a theoretical model [1] which allows the separation of the bulk properties (related to the electron transport) from the surface effects (which substantially influence the probability of electron emission into the vacuum). By means of the electron current intensities usually operated in the scanning electron microscopy, it is shown that the mean free path of the secondary electrons inside the sample is the electron transport microstructural parameter which mainly influences the electron yield $d(E)$. The scaling property of this function, already pointed out in previous works, also applies to the model presented here and is verified by the results of the electron emission data obtained from the diamond samples which have been studied in this work. [1] P. Ascarelli, E. Cappelli et al., J Appl. Phys 89, 689 (2001)

Wednesday, June 11, 2003
Mercredi 11 juin 2003

Afternoon
Après-midi

Session IV: Nanotubes junctions
Session chair: V. Skakalova

- L-IV.1** 14:00 -Invited- ALL-CARBON TRANSISTORS
Po-Wen Chiu, Martti Kaempgen, Ursula Dettlaff and Siegmur Roth, Max-Planck Institut für Festkörperforschung, Heisenbergstr. 1, 70569 Stuttgart, Germany
In this contribution we present investigations of transistors consisting of carbon nanotubes only (and a tripropylentetramin linker molecule which takes the role of the oxide layer in conventional field-effect transistors). The active area is confined to a few nanometers in all three dimensions and gain values of 100 and above are obtained. We observe transistor behavior not only for a semiconducting but also for a metallic tube as channel. This effect is explained by electromechanical coupling ("actuator", "artificial muscle").
- L-IV.2** 14:35 -Invited- CARBON NANOTUBE Y-JUNCTIONS: GROWTH AND PROPERTIES
L.P. Biró, Z.E. Horváth, G.I. Márk, Z. Osváth, A.A. Koós, Research Institute for Technical Physics and Materials Sciences, POB 49, 1525 Budapest, Hungary, A.M. Benito, W. Maser, Instituto de Carboquímica (CSIC), C/Miguel Luesma Castañ 4, 50015 Saragossa, Spain, Ph. Lambin, Laboratoire de Physique du Solide, Facultés Universitaires Notre-Dame de la Paix, Rue de Bruxelles 61, 5000 Namur, Belgium
The possibility of growing Y-branched carbon nanotubes by inserting non-hexagonal rings in the junction region has been predicted [1, 2] shortly after the discovery of the nanotubes. More recently, several methods have been reported to produce carbon nanotube Y-junction [3, 4, 5]. These novel carbon nanoarchitectures are extremely promising for building extended nanocircuitry and due to their shape, they can be used more efficiently than straight carbon nanotubes for composite reinforcement, too. In the present paper a critical overview of the various growth methods is given. Theoretical model calculations of charge transport through Y-junctions will be compared to experimentally available data and STM images.
[1]. G.E. Scuseria, Chem. Phys. Lett. 195, 534 (1992).
[2]. L.A. Chernozatonskii, Phys. Lett. A 172, 173 (1992).
[3]. J. Li, C. Papadopoulos, J.M. Xu, Nature 402, 253 (1999).
[4]. L.P. Biró, et al., Mat. Sci. Eng. C 19, 3 (2002).
[5]. Z. Osváth, et al., Chem. Phys. Lett. 365, 338 (2002).
- L-IV.3** 15:10 CLASSIFICATION, GROWTH AND TRANSPORT PROPERTIES OF CARBON NANOTUBE Y- AND T- JUNCTIONS
A. Andriotis(a), L. Chernozatonskii(b), M. Menon(c), S.Lisenkov(b), I.Ponomareva(b), D. Srivastava(d), (a)Institute of Electronic Structure and Laser, Foundation for Research and Technology-Hellas, P.O. Box 1527, 71110 Heraklio, Crete, Greece, (b)Institute of Biochemical Physics, Russian Academy of Sciences, Moscow 119991, Russia, (c)Center for Computational Sciences, University of Kentucky, Lexington, KE 40506-0045, USA, (d)NASA Ames Research Center, CSC, Mail Stop T27-A1, Moffett Field, CA 94035-1000, USA
Carbon nanotubes are the most promising materials for the fabrication of nanotechnology devices in the future. The NT junctions have recently emerged as excellent candidates for use as building blocks in the formation electronic devices. Connecting different NTs to form three terminal nanotube heterojunctions have been proposed recently (G. Scuseria 1992, L. Chernozatonskii 1992, M. Menon, D. Srivastava 1997). Between them high-yield fabrication of Y junctions have been obtained by using template-based chemical vapor deposition (CVD) [1], and pyrolysis of organometallic precursor [2]. These Y junctions have shown intrinsic nonlinear and asymmetric I-V behavior at room temperature [3]. Theoretical calculations have supported these experimental findings [4].
We consider: - topological classifications of planar Y ("folk"-, "slingshot"-, "bough"- types), and T junctions which require the presence of topological defects in the form of pentagons, heptagons and octagons; - energy optimization different types of Y and T junctions (metal or semiconductor branches and stem, symmetric or asymmetric branches) using the molecular-dynamic methods [5, 6]; - the growth mechanism of Y-junctions in developing template-based CVD and pyrolysis techniques [5,6]; - coalescence of two/or three nanotubes into T- and Y- junctions, comparison with experiments [7].
[1]. J. Li, C.Papadopoulos, and J. Xu, Nature 402, 253 (1999)
[2]. B.C. Satishkumar, et al., Appl. Phys. Lett. 77, 2530 (2000).
[3]. C.Papadopoulos, et al. Phys. Phys. Lett 85, 3476 (2000).
[4]. A. N. Andriotis et al., Phys. Rev. B 65, 165416 (2002).
[5]. M. Menon, et al., Phys.Rev. B 57, 4063 (1998).
[6]. D. W. Brenner, Phys. Rev. B 42, 9458 (1990).
[7]. M. Terrones, et al., Phys. Rev. Lett. 89, 075505 (2002).

L-IV.4 15:35

FREQUENCY DEPENDENT ELECTRICAL TRANSPORT PROPERTIES OF CONJUGATED POLYMER ONTO SELF-ASSEMBLED ALIGNED CARBON NANOTUBES

L. Valentin(a), I. Armentano(a), E. Frulloni(a), J. Biagiotti(a), L. Lozzi(b), S. Santucci(b), J.M. Kenny(a), (a)Materials Engineering Center, Università di Perugia, 05100 Terni, Italy, (b)Dipartimento di Fisica - Unità INFN, Università dell'Aquila, 67010 Coppito (AQ), Italy

This work focuses on the combination of the complementary properties of self-assembled aligned carbon nanotube (CNT) thin films and poly3-octylthiophene (P3OT), following a dielectric route to the characterization of a novel composite material. A simple fabrication method allows us to obtain a micrometer-scale conducting network made of self-assembled aligned carbon nanotubes thin films deposited by pulsed plasma enhanced chemical vapour deposition technique. The structural and electrical characterization of CNTs/P3OT hybrid system performed by differential scanning calorimetry, Raman and impedance spectroscopy show interesting effects, including the tendency of the nanotube structure to nucleate crystal growth and substantial changes in the dielectric behavior of the composite due to the effect of the polymer on the nanotubes conformation. In particular the curve peak of the imaginary part of the impedance spectra show a shift to lower frequency demonstrating that the crystallization of the polymer onto the nanotube results into different relaxation onto the composite's electronic structure. These results promise controlled modification of the outer surface of CNTs to provide selectable functionalities. Raman spectroscopy is finally applied to suggest that in the composite film the changes in the dielectric properties can be explained in terms of a reduced vibrational freedom of the polymer chains as a consequence of the intercalation of the polymer matrix.

L-IV.5 16:00

SYNTHESIS AND CHARACTERISATION OF CARBON NANOTUBES-CONDUCTING POLYMER THIN FILMS

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Heterostructures as thin films of carbon nanotubes - conducting polymer have been obtained on transparent substrates: single walled carbon nanotubes (SWCNT) were deposited on a transparent substrate (plexiglass or quartz) and used as electrode to grow electrochemically a thin film of conducting polymer (CP) on it. The resulting heterostructure could be enough transparent and electrically conducting to be used for interesting applications. We obtained different films SWCNT-CP using polypyrrole or polyaniline as conducting polymers, varying the chemical and electrochemical conditions, and characterize them by spectroscopy and transport properties. We measured the optical absorption and electrical conductivity, with the aim of optimise the obtaining conditions to reach films with either high electrical conductivity and transparency. We analyse the obtained thin films by optical, SEM and Raman spectroscopy in order to characterize them. Raman spectroscopy show an evidence of the possible interaction between carbon nanotubes and conducting polymer.

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Diamond

- L-V/P.01** EARLY STAGES OF DIAMOND BEN- HFCVD ON IRIIDIUM BUFFER LAYERS
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 Three barriers have to be surmounted to achieve highly oriented diamond films in heteroepitaxy: the growth mode, the film adhesion and the doping control. At the present time, the most promising substrate remains iridium, Schreck et al. reported polar and azimuthal components of the film misorientation included between 0.4 and 0.6° [1]. To realize further progress in the crystalline quality, new improvements of CVD techniques have to be combined with a deeper knowledge of the mechanisms responsible for the diamond orientation. However, the mechanisms involved in the oriented growth and the interface formation are not yet well understood [2, 3].
 This study attempts to provide answers concerning the effects of BEN step on diamond nucleation on iridium buffer layers by the use of in situ electron spectroscopies (XPS, AES, EELS). Moreover, the morphology of the samples was further characterised by ex situ AFM and SEM FEG. Raman and Nano-Auger investigations provide informations about the chemical nature of the crystals. Effects of each step of the process (etching, BEN and CVD growth) on the chemical state as well as on the surface topography will be discussed. References
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- L-V /P.02** withdraw
- L-V /P.03** IN-SITU STUDY OF C-ATOMS INTERACTION WITH NATURAL DIAMOND AND UDD
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 The fundamental goal of surface science techniques is to identify the chemistry occurring during CVD growth. In the course of the diamond growth interaction of the C-atoms, hydrocarbon radicals and hydrocarbon molecules with the surface chemical states Cd and CdH takes place. To look into the CVD process in detail only the elementary reaction of surface Cd sites with C-atoms from gas-phase was studied. The surfaces (at T > 700K) of Ultra dispersion diamond (UDD) and natural diamond (ND) were treated by H-atoms. According to CKVV data the chemical state was the same in both cases. The carbon atoms were prepared by decomposition of CH₄ on W hot-filament at 2300 K. The CKVV Auger spectra did not show any modification of chemical state on UDD and ND surfaces up to deposition of about 4 monolayers. Obviously, the results point to incorporation of carbon atoms into diamond structure. The possibilities of catalysis of CVD diamond growth by the Cd chemical state are discussed. Under deposition of carbon atoms on SiO₂-substrate at the same conditions the growth of graphite takes place.
- L-V /P.04** CHEMICAL STATE OF CARBON ATOMS ON SURFACES OF ULTRA DISPERSION DIAMOND (UDD) AND NATURAL DIAMOND AFTER H-TREATMENT
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 At present time the UDD seeding frequently is used for a nucleation of diamond growth. The N(E) CKVV Auger spectroscopy with X-ray excitation of Auger emission were used for identification of the chemical state of carbon atoms on surface of UDD particles. The next peculiarities of the CKVV spectra of UDD were established: a) difference from standard spectra of carbon atoms with sp₂, sp₃ and mixture sp₂/sp₃ bonds; b) coincidence with spectrum of natural diamond after H-treatment (ND H-t). The b) statement allows to suppose about the same chemical state on UDD and ND H-t surfaces (denote it as Cd). The simulation of the CKVV spectrum by self-convolution of graphite valence band shows that opposite to graphite in UDD case the pi-pi and pi-sigma transitions are absent. So, this implies that on UDD and ND H-t surfaces there is only monolayer with pi-bonds of carbon atoms. The Cd state is inactive to ambient air that allows ex-situ study of CVD process. The power of the N(E) CKVV Auger spectra in combination with C1s and valence band XPS are discussed.
- L-V /P.05** HIGH DENSITY DIAMOND NUCLEATION ON A LARGE SCALE BY A DC HF CVD PROCESS
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 A DC HF CVD process is described that is quite convenient for diamond nucleation with a high density (10¹¹ cm⁻²) and on a large scale. The process is designed in an ultra high vacuum chamber directly connected to a surface analysis chamber provided with XPS, AES, ELS probes for the determination of the carbon nature and surface cleaning and deposition tools (ion beam, thermal vacuum evaporation, ...) for surface preparation. The DC HF CVD process combines the activation of a gas mixture (CH₄:H₂) both by a plasma created between two electrodes and by hot filaments, whereas the substrate was negatively biased relative to the cathode (extraction potential). Thus both ions and neutral radicals are focussed onto the substrate with a high density. The plasma was probed by emission of the visible light. Many deposition parameters were investigated as the temperature, methane concentration, electrical and geometrical parameters of the process, nucleation time. Nucleation occurs after very short nucleation times (< 10 min), and the nature of the deposit was strongly dependent on the extraction potential. The variation of the extraction current density with time was recorded and allowed to monitor the nucleation process.

L-V /P.06 TRANSPORT ANISOTROPY IN CVD DIAMOND ELUCIDATED BY DC AND AC CONDUCTANCE MEASUREMENTS

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In the last few years the necessity of realizing electronic devices for high temperature, high power, high frequency and, more recently, resistance to high energy radiation beams has increased. Owing to the limitations shown by other conventional semiconductors, the exploration of new wide bandgap materials has started. Among them, CVD diamond promise excellent performance in high power and high frequency electronics, the best figure of merit, but practical applications are presently limited by the polycrystalline nature of deposited films which leads to large concentrations of electrically active defects at the grain boundaries (GBs). Very strong anisotropies are generally evidenced owing the columnar structure of the material. Surface conductivity is related to hydrogen terminated bonds whereas bulk one to a-Carbon phases at the GBs. The role played by GBs in determining the electronic properties has been studied, till now, on very thin films and the influence on the electronic properties not clear, yet. Aim of this work is to report results recorded during the analysis of 40-90 nm thick free-standing films able to be exploited in radiotherapy dosimeters development. The possibility to use such kind of material for dosimeters with a linear response to ionising radiation beams has already been demonstrated and a deeper understanding of GBs role in determining such response is the focus of this contribution. IP. Ascarelli et al. Diamond Rel. Mater. in press.

L-V /P.07 NON DESTRUCTIVE DETERMINATION OF THE BORON CONCENTRATION OF HEAVILY DOPED METALLIC DIAMOND THIN FILMS FROM RAMAN SPECTROSCOPY

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Metallic conductivity for diamond films is needed for all electrical devices (low resistance ohmic contacts, efficient diamond electrodes for reduction or oxidation, ...). It can be obtained by heavy incorporation of boron (boron concentration $> 3E20$ cm⁻³) in homoepitaxial as well as polycrystalline films by Microwave Plasma Chemical Vapor Deposition. Unfortunately, Infra Red transmission cannot be used for non destructive determination of their boron content as the films are metallic and are no longer transparent. However, this metallic conductivity induced drastic effects on their Raman spectra, with new wide bands around 500 and 1240 cm⁻¹ and a "fano" deformation of their characteristic "1332 cm⁻¹" line. In fact, the "500 cm⁻¹" band exhibits a systematic shift versus the boron concentration which is used here for an easy non destructive measurement of the boron concentration in this heavy doping range.

L-V /P.08 MODIFICATION OF ALUMINIUM MASKS DURING THE ETCHING BY AN ECR OXYGEN PLASMA OF DIAMOND FROM X RAY DIFFRACTION AT GLANCING INCIDENCE

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Etching is a basic process for the achievement of any devices. It presents a good efficiency with an oxygen plasma and a good selectivity against Al masks. Instead of the usual 13.6 MHz Reactive Ion Etching, we use here an Electron Cyclotron Resonance at 2.45 GHz assisted by a variable self-induced DC polarization from a 13.6 MHz voltage applied to the sample. This gives a very high concentration of atomic oxygen which increases additionally the efficiency of the plasma, but also oxidized the "bulk" of the mask. The new composition of the "Al" mask is studied after one hour of etching with a Microwave power of 1 Watt cm⁻² and a DC voltage of - 100 V, for increasing Al thicknesses of 100, 200 and 300 nm by X rays diffraction under glancing incidence. It shows the formation on a thickness of about 200 nm of various Al sub-oxides according to the thickness of the original Al film.

L-V /P.09 A 3.4 eV POTENTIAL BARRIER HEIGHT IN SCHOTTKY DIODES ON BORON DOPED DIAMOND THIN FILMS

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Diamond has a wide band gap of 5.45 eV but rather low Schottky barrier heights up to now (0.7 to 1.9 eV). Here, boron doped diamond films were grown by MPCVD at 830°C on Ib substrates. Under Ultra High Vacuum, one monolayer of Ti was deposited on the free (100) surface and annealed at 400°C. Subsequently, a 200 nm thick Ag layer was deposited. After lithography and etching, some titanium carbide probably remained in between contacts, resulting in extra surface currents. After annealing at 225°C under fore vacuum, the surface conduction disappeared, and below 225°C, the reverse current became intrinsic and undetectable in our set-up. After such a treatment, the direct current varies exponentially over more than 5 decades up to 700°K. Boron doping is testified both from the conductivity of the diamond layer and the series resistance of the diodes. The ideality factor of the diode is high (over 5) at 300°K, because of the presence of recombination or residual leakage currents. Then it decreases to 1.6 at 500-600°K, then increases up to 2.45 at 700°K. A potential barrier height of 3.4 eV is calculated from the variation of the saturation current (extracted from the forward current extrapolated at zero bias voltage) with reciprocal temperature. The possible origins of this very high potential barrier of 3.4 eV is discussed and compared with data obtained from ultra-violet and X-rays electron spectroscopies performed on the same sample.

Nanotubes

L-V /P.10 ELECTRO-MAGNETIC PROPERTIES OF DOPED CARBON NANOTUBES

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The conductance, thermoelectric power and magnetic susceptibility of different types of carbon nanotubes (metallic single- and multi-walled carbon nanotubes) after their doping/intercalation by cobalt atom were studied in a wide temperature range. The structural characteristics and phase composition were investigated using the electron microscopy, X-ray diffraction, Ouge and Raman spectroscopy. The correlation between the morphology, doping/intercalation concentration and behaviour of electro-magnetic properties were discussed in detail. The geometrical and electronic structures, and also the electrical resistance, thermoelectric voltage and magnetic susceptibility of doped/intercalated carbon nanotubes were studied theoretically using the molecular-dynamics and quantum-chemical calculations. In particular, the different stable structures of these carbon systems were found depending on the internal and inter-tube infilling. This work was partly supported by STCU grant (N 1618).

- L-V /P.11** ELECTRON EMISSION FROM CARBON NANO-FIBERS PREPARED BY HOT FILAMENT ASSISTED SPUTTERING
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Carbon films were deposited by hot filament assisted sputtering system. The film consisted of carbon nano-fibers. The film showed good field emission characteristics.
The target was a graphite disk of 50 mm in diameter. The sputtering gas was pure Ar (99.9995%) and no H₂ was added to the sputtering gas. No catalytic metal was deposited on the substrate prior to the sputtering. The hot filament was made from W wire, and was formed to a coil. The temperature of the filament was about 2000 degree C. The film was characterized by using TEM, SEM and X-ray diffraction. The SEM and TEM images showed that the film consisted of carbon nano-fibers. The fibers formed the structure like chestnut shells or sea urchin shell. Each fiber was found to be not hollow but solid by TEM observation. The field emission characteristics were measured in a vacuum chamber evacuated by an oil diffusion pump system to about 10⁻⁴ Pa. Distance between anode and filed emission plate was 0.5 - 0.6 mm. The turn on field was 5 - 20 kV/mm. The current transport was explained by FN tunneling model.
- L-V /P.12** COMBINED RAMAN AND TRANSPORT MEASUREMENTS ON CARBON NANOTUBES
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Raman spectroscopy has proven to be a powerful technique for characterizing carbon nanotubes. By probing the vibrational normal modes of single-walled nanotubes it is possible to determine both the diameter as well as the chirality of the tubes. In the present work electronic transport measurements on carbon nanotubes are combined in situ with micro-Raman investigations. Combining these two measurements is useful in making sure that the semiconductor/metallic regime is correctly assigned, but is also of deeper interest regarding the electron-phonon couplings in nanotubes. Since the resonant Raman effect in carbon nanotubes depends on the positions of the van Hove singularities in the electronic density of states the influence on the Raman spectra of introducing a gate voltage to manipulate the position of the Fermi level is also investigated.
- L-V /P.13** CHARACTERIZATION OF GAMA-IRRADIATED SINGLE-WALL CARBON NANOTUBES
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Individual single-wall carbon nanotubes (SWNT) have excellent mechanical and electrical properties. On the other hand, due to weak intermolecular interactions, in bulk material (buckypaper) these properties are several orders of magnitudes lower. In order to enhance the intermolecular interactions, chemical functionalization of SWNT or mixing with appropriate polymers have been used. We have been studying the effect of gamma-irradiation on paper made from SWNT. Changes in Young modulus and electrical conductivity were observed, with maximum values for a dose of 165 kGy. Structural changes after irradiation were characterized by Raman and optical spectroscopy. Effects of irradiation on the properties of the SWNT-paper were compared with those of gamma-irradiated graphite.
- L-V /P.14** SYNTHESIS OF CARBON NANOTUBES WITH HOT FILAMENT PLASMA ENHANCED CHEMICAL VAPOR DEPOSITION METHOD
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We prepared metal oxide clusters formed by spin coating an iron (III) nitrate ethanol solution onto silicon substrate for carbon nanotube growth, and also we prepared silicon substrate with Ni catalyst layer. We were able to get highly oriented carbon nanotubes with a HFPECVD(Hot Filament Plasma Enhanced Chemical Vapor Deposition) method. Ammonia(NH₃) and acetylene(C₂H₂) gas were used for the dilution gas and a carbon precursor for the growth of the carbon nanotubes. The relationship between the cluster density and the nanotube density was observed with AFM(Atomic Force Microscopy) and SEM(Scanning Electron Microscopy) images. The cluster density was controlled by the iron (III) nitrate ethanol solution. TEM(Transmission Electron Microscopy) images show multi-walled carbon nanotube and Raman spectroscopy of nanotubes show that G-band and D-band peak around 1370 cm⁻¹ and 1590 cm⁻¹, respectively
- L-V /P.15** MICRO-RAMAN ANALYSIS OF CARBON NANOTUBES OBTAINED BY ARC-METHOD USING METALLIC AND OXIDE CATALYSTS
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Single-wall carbon nanotubes (SWCNT) were produced by arc method (He atmosphere) using different catalysts, based on transition metal and rare earth elements. The samples were collected from two regions of reactor, collar and walls zones. Transmission electron microscopy and micro-Raman spectroscopy were used as characterization tools. Raman bands of SWCNT, occurring in the frequency region of carbon D, G and G’ bands, were used to estimate the sample composition in terms of carbon phases. Different content of SWCNT were generally found in correspondence to powder aggregates so obtained. In some cases, quite different kinds of carbon were found within the same aggregate, within a spatial resolution of the order of micrometer. For the materials obtained via Ni-Co catalysts, the effect of the acid treatment was, also, analysed.
A special care was taken to the comparative analysis between different yields of SWCNT, when metallic Ni/Y₂O₃ and oxide NiO/Y₂O₃ catalysts were used, and the raw material obtained was submitted to ultrasonic and filtration treatments, using a surfactant aqueous solutions (Sodium Dodecyl Sulfate). Micro-Raman analysis allowed to establish some correlation between such treatments and the content of nanotubes vs. amorphous carbon or graphite within the powders. In particular, the presence of oxygen in catalyst increases the carbon nanotube component, and the surfactant treatment further reduces the amorphous carbon or graphite content in the raw material.

- L-V /P.16** CARBON NANOTUBES GROWTH BY HFCVD: EFFECT OF THE PROCESS PARAMETERS AND CATALYST PREPARATION
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Carbon nanotubes were grown on Nickel catalysts by hot-filament chemical vapour deposition (HFCVD) using H₂ and CH₄ as precursors. CNTs with different characteristics were observed varying some growth parameters, such as total pressure, methane concentration and substrate temperature. CNTs untangled and with smooth walls were obtained at the lowest pressure tested, their density was found mainly dependent on the carbon content. The substrate temperature affected the purity, in term of presence of other carbonaceous phases. Catalyst nanoparticles were obtained from clustering of Ni thin films deposited by RF sputtering and Langmuir-Blodgett techniques. The clusters distribution and size influenced the density and the diameter of CNT that ranged between 5 and 50 nm. Catalytic layers and grown carbon nanotubes were characterized by SEM and XPS.
- L-V /P.17** VISCOELASTIC PROPERTIES OF MULTIWALLED CARBON NANOTUBE SOLUTIONS
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We have prepared solutions of multiwalled carbon nanotubes in very low pressure vapor solvents (a mixture of polychlorinated biphenyls). The solutions are very stable and have shown no sign of precipitation for months. Rheological measurements using annular and Sogel-Pochetino geometries have been performed. We obtained the real and imaginary part of the complex viscosity coefficient in a frequency range covering eight orders of magnitude and a temperature range from 5 to 50°C. The data shows unexpected changes in the solution with temperature: for T below 20°C there appears to be substantial reorganization or clustering, suggesting incipient formation of a liquid crystalline phase (the solution concentration is at least 1000 times the overlap concentration of the nanotubes). This self-organization could result in a useful technique to improve the electronic properties of polymer/carbon nanotubes composites used in electronic devices, specially organic photovoltaic cells.
- L-V /P.18** FORMATION OF CARBON NANOTUBES BY CATALYSIS OF TRANSITION METALS OBTAINED FROM MOLECULAR PRECURSORS
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There is considerable interest to achieve a selective growth of carbon nanotubes from distinct nucleation centers on specific substrates, since they display a huge range for new applications. It is known that transition metals act as catalysts for the formation of carbon nanotubes. For this reasons the influence of catalytically active metals supplied in a nanodisperse form by thermal decomposition of transition metal compounds on silicon substrates was studied. By this novel method, catalytically active transition metal complexes were used to generate nucleation centers on silicon substrates for the formation of carbon nanotubes. A CVD route using methane was used to supply activated carbon species from the gas phase. Since the transition metals used for this investigation are catalyzing dehydrogenation reactions, the effects of the presence of those metals on the morphology of the deposits were studied in correlation with the process parameters (pressure, substrate temperature, precursor concentration). The deposits were characterized with SEM, infrared- and raman spectroscopy.
- L-V /P.19** PROJECTED RF PERFORMANCE OF SUB- μ m FIELD EMITTING DEVICES BASED ON CARBON NANOTUBES
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In this paper a theoretical study of a projected RF-performance of sub- μ m lateral field emitting structures based on carbon nanotubes is presented. The basic structure for the analysis is a planar cantilever structure representing a carbon nanotube emitter embedded into a cathode electrode and two parallel metal gates on the substrate surface adjusted to the emitter - anode spacer. The field emitting characteristics and mechanical deflection of the nanotube cantilever are investigated as a function of the geometrical layout of the structure, and nanotube material properties.
The calculations of the RF characteristics are based on the concept of intrinsic transit time. It is shown that a field emitting structure scaled to nm- dimensions may exhibit the f_r cut-off frequency as high as 100 GHz, due to the extremely small emitter-to-gate capacitance. The effects of the nanotube series resistance, gate configuration and the substrate material on the RF device performance are investigated.
- DLC**
- L-V /P.20** HIGH DENSITY PLASMA CHEMICAL VAPOR DEPOSITION OF AMORPHOUS CARBON FILMS
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This work investigated the influence of the plasma parameters on the characteristics of amorphous carbon films (a-C:H) deposited by High Density Plasma Chemical Vapor Deposition, using inductively coupled methane plasmas. These films show several good characteristics like high electric resistivity, low dielectric constant, high breakdown field, low stress, high density, hardness and chemical inertness. Today, this material has important applications in the mechanic, optic, chemistry and microelectronic areas.
For these studies, we used a methane gas with different process parameters (pressure and RF power). After deposition, we submitted the films to the following measurements: the thickness was measured with a height step meter and an ellipsometer; Fourier Transformed Infrared and Raman Spectroscopy were used to identify the sp² and sp³ hybridization of C and CH bonds and other possible bonds that can appear because of the hydrogen presence; Atomic Force Microscopy was used to measure the film roughness and I x V and C x V measurements to determine the dielectric constant; the electric resistivity and the breakdown electric field.

L-V /P.21**THE INFLUENCE OF NITROGEN ON ELECTRIC CHARACTERISTICS OF DIAMOND-LIKE CARBON FILMS**

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The combination of electric, optic and mechanic properties of nitrated diamond like carbon (a-C:H:N) films have motivated its studies during the last years. In addition, the possibility of growing these films at low temperature by reactive sputtering, allows their use as semiconductor and dielectric material for microelectronic applications. The variation of the electrical conductivity because of the Fermi level shift induced by the change in doping concentration is an obvious evidence of a doping effect. The minority of the dopant atoms can self-adjust substitutionally in the tetrahedral N4 site and the majority forms non-doping trigonal N3 sites. In the highly doped regime, the predominant C-N bond is a trigonal bond. This can be interpreted as increasing N sites in the C amorphous network causing a reduction of the energy barrier for sp3 to sp2 transition to a small value, so the graphitization proceeds around the N site. This result leads to a broadening of the * and ** bands and to a narrowing of the band gap.

In this paper a-C:H:N films with up to 28 at.% of nitrogen were deposited by reactive magnetron sputtering with a graphite target in a mixed methane/argon/nitrogen plasma. The nitrogen content in the deposited films increased systematically when increasing the nitrogen content. Raman analysis was performed to study the chemical bonding structure. Rutherford Backscattering Spectrometry (RBS) was used to investigate the chemical composition. Electrical properties were measured through current-voltage (I-V) curves and related to the composition and structure of the films.

L-V /P.22**INFLUENCE OF ADDITIVES ON ELECTRIC CHARACTERISTICS OF DIAMOND LIKE CARBON FILMS DEPOSITED BY REACTIVE SPUTTERING**

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In this work we studied the influence of the plasma composition on the characteristics of Diamond Like Carbon (DLC) films deposited by reactive magnetron sputtering. DLC is a material that shows several good characteristics like high electric resistivity, low dielectric constant, high breakdown field, low stress, high density, hardness and chemical inertness. This material is important today in mechanic, optic, chemistry and mainly in microelectronic areas.

For these studies, we used a mixture of methane with different flows of nitrogen or carbon tetrafluoride or argon. After deposition, we analyzed the films by the following measurement techniques: the thickness was measured with a height step meter and an ellipsometer; Fourier Transformed Infrared (FTIR) and Raman Spectroscopy identified the sp2 and sp3 hybridization of C, CH and other possible bonds that can appear because of the argon, fluorine or hydrogen presence; Atomic Force Microscopy (AFM) was used to measure the surface roughness and I x V and C x V measurements determined the dielectric constant, the electric resistivity, the breakdown electrical field and possible semiconductor properties. Films deposited with pure methane were compared with films deposited using different gas mixtures. The characterizations allowed to relate the chemical bond structure to the electric characteristics of the films. Argon addition decreased the resistivity and increased the surface roughness. The addition of nitrogen increased the conductivity and for some plasmas the DLC film became a semiconductor. On the other hand, carbon tetrafluoride addition increased the resistivity of the films and reduced the dielectric constant.

L-V /P.23**EFFECT OF THE BIAS VOLTAGE ON THE STRUCTURE OF CARBON NITRIDE FILMS**

A. Champj, UNICAMP, Brazil, F.C. Marques, UNICAMP, Brazil

In this work we study the effect of the bias voltage on the mechanical, electrical and structural properties of amorphous carbon nitride films deposited by the plasma decomposition of methane (CH4) and nitrogen (N2) atmosphere. Two series of films were deposited under different bias voltage in order to investigate the effect of the nitrogen incorporation in a-C:H films with different structures. The first series of films was deposited under the condition in which diamond-like a-C:H films is obtained, i.e. bias of -200 V, and pressure of 1.0Pa. On the other hand, the second series of films was deposited under the condition graphitic-like films is obtained, i.e. bias of -800 V, and pressures of 10 Pa. The N2 partial pressure was the only parameter varied in both series. In order to investigate the effect of these conditions on the properties of the films, a number of analyses were undertaken: FTIR, nanohardness, Raman, EPR, SEM, EELS, field emission and stress. The efficiency of nitrogen incorporation was strongly affected by the initial condition adopted. However, it was observed that the incorporation of nitrogen reduces the deposition rate, band-gap, hardness, the elastic constant of the films, and increases the sp2/sp3 ratio, in both series of films. The use of high pressure and high bias allowed the preparation of stable and thick (~1 micron) nitrogen-carbon films, with high hardness (17 GPa), and low stress (0.8 GPa) deposited at relatively high deposition rate (0.3 nm/s).

Thursday, June 12, 2003
Jeudi 12 juin 2003

Morning
Matin

Session VI: Diamond homoepitaxial and heteroepitaxial growth
Session chair: M. Kasu

- L-VI.1** 9:00 -Invited- SINGLE CRYSTAL DIAMOND FOR ELECTRONIC APPLICATIONS
Jan Isberg, Division for Electricity Research, Box 539, 75121 Uppsala University, Sweden, Daniel J. Twitchen, Geoffrey A. Scarsbrook, Andrew J. Whitehead and Steve E. Coe, Element Six Ltd, King's Ride Park, Ascot, Berkshire SL5 8BP, U.K.
There is significant academic and industrial interest in developing electronic devices for high frequency, high power and high temperature applications. This interest has generated considerable research efforts in wide bandgap semiconductors. Of these materials diamond has by far the most intriguing and extreme properties, i.e., mechanical, optical, thermal as well as electronic. Diamond exhibits the highest breakdown field and thermal conductivity of any material and has the highest carrier mobilities of any wide bandgap semiconductor, thereby enabling the development of electronic devices with superior performance with regards to power efficiency, power density, high frequency properties, power loss and cooling. Nevertheless the breakthrough of diamond-based electronics has not yet happened, largely due to the difficulty of synthesising high-quality single crystal diamond. We will describe recent advances in growing intrinsic and boron doped single crystal diamond intended for electronic applications. The intrinsic material was grown under conditions of extreme purity, resulting in films of exceptionally low defect densities. In the intrinsic material we have measured room temperature drift mobilities of $4500 \text{ cm}^2/\text{Vs}$ for electrons and $3800 \text{ cm}^2/\text{Vs}$ for holes. These mobility values were determined by using the time-of-flight technique on thick intrinsic diamond plates. The high values for the electron and hole mobility, as well as a measured carrier lifetime in excess of 2 ns , indicates a huge improvement in the electronic quality of free-standing, single crystal CVD diamond [Science 297 (2002) p1670]. Although an efficient n-doping of diamond is still lacking we argue that efficient unipolar devices can be made.
[1] J. Isberg et al., Science, 6 Sept, 297 (2002) p1670.
- L-VI.2** 9:35 HOMOEPITAXIAL GROWTH FOR SURFACE CONDUCTIVE DEVICE APPLICATIONS
Oliver A Williams and Richard B Jackman, Department of Electronic and Electrical Engineering, Torrington Place, London WC1E 7JE, U.K.
Diamond has many properties which surpass those of all other materials in the field of electronic devices. Unfortunately, doping to date has been problematic resulting in high activation energies, such as 0.37 eV for boron, yielding less than 1% of the substitutional acceptors being activated at room temperature. Hydrogen terminated diamond exhibits p - type surface conductivity with high carrier concentration and mobility values. High performance devices have been demonstrated on this layer, with FETs operating in the GHz regime, high power schottky diodes and single hole transistors. However, it has been shown that these devices can be unstable with relation to the ambient environment and that mobility and carrier concentration values vary widely with surface treatments. This work aims to investigate these stabilities by focusing on "as deposited" material, which generally exhibits higher mobilities presumably due to the reduced exposure to hydrogen plasma etching. The focus of this approach is on the growth of diamond on single crystal HPHT Ib 100 diamond substrates, although some interesting work on polycrystalline HFCVD will also be mentioned. High mobilities have been reproducibly obtained in the region of $140 \text{ cm}^2/\text{Vs}$ at $2.5 \times 10^{12} \text{ cm}^{-2}$. It is also possible to control these values by adjusting the growth process parameters. The mechanism behind these exciting results will be discussed
- L-VI.3** 10:00 RAMAN IMAGING OF INTERNAL STRESSES IN HOMOEPITAXIAL CVD DIAMOND LAYERS AND DEVICES
M. Mermoux(a), B. Marcus(a), A. Tajani(b), C. Baron(b), E. Gheeraert(b), E. Bustarret(b), (a)LEPMI, INPG-CNRS, BP 75, 38042 St Martin d'Hères cedex, France, (b)LEPES, CNRS, BP 166, 38042 Grenoble cedex 9, France
Undoped and doped diamond thin films grown by Microwave Plasma-enhanced Chemical Vapor Deposition on {111}-oriented diamond substrates have been studied by confocal micro-Raman spectroscopy and confocal imaging. We detected a distinct Raman peak, broader than the substrate phonon line and about 6 cm^{-1} below the nominal relaxed diamond frequency. The substrate itself yielded a peak almost 1 cm^{-1} higher than this value. This indicated that the homoepitaxial layers were under an intense tensile strain, in many cases greater than 2 GPa . The dependences of the magnitude of this strain on the film thickness and on the doping level are discussed. Confocal Raman imaging showed that a network of oriented cracks and a few delamination regions observed by Optical and Scanning Electronic Microscopy brought a local relief (in the film as well as in the substrate) to this internal strain during the growth of the thicker layers. After examining whether this strain is a feature specific to {111} CVD diamond homoepitaxial growth, we present some results on p/n junctions resulting from the successive growth of boron-doped layers and of a phosphorus-doped film and discuss briefly the potential limitations brought to the performance of these devices by the structural defect creation mechanism driven by such intense tensile internal strains.

10:25

BREAK

- L-VI.4** 10:45 -Invited- **DIAMOND HETEROEPITAXY ON IRIIDIUM BUFFER LAYERS**
M. Schreck, S. Gsell, F. Hörmann, T. Bauer, B. Stritzker, Universität Augsburg, Institut für Physik, 86135 Augsburg, Germany
The availability of large area diamond films or wafers with electronic and structural properties close to single crystals is a key issue for the future realisation of diamond based devices. Heteroepitaxial growth by chemical vapour deposition (CVD), currently the only promising concept to reach this aim, has therefore been a topic of major scientific interest during the last decade. Though epitaxial diamond grains with a high degree of alignment have successfully been nucleated on a variety of monocrystalline surfaces (Si, SiC, TiC, Pt ...), only for diamond on iridium the transition to single crystal films has been demonstrated up to now. The present contribution describes the recent progress in the heteroepitaxial deposition on iridium by the bias enhanced nucleation (BEN) procedure. In particular the contribution deals with a) the uniquely high nucleation densities of epitaxial grains (up to 10^{11}cm^{-2}), b) the arrangement of the grains in defined islands, c) the extremely early stage of first coalescence of the grains after few minutes (thickness 10 nm) d) the specific nature of the nucleation structures and e) the furrows in the iridium which are usually formed during BEN. The alignment of the latter can be drastically changed by the CVD parameters. It is shown that epitaxial nucleation on Ir(001) and Ir (111) can be achieved under identical conditions. Finally, the role of textured growth and different concepts for future upscaling are considered.
- L-VI.5** 11:20 **HRTEM STUDY OF BEN-HFCVD DIAMOND SYNTHESIS ON THINNED SI(111) SAMPLES**
S. Pecoraro, J.C. Arnault, J. Werckmann, F. Le Normand, CNRS – IPCMS, 23 rue du Loes, BP 43, 67034 Strasbourg Cedex 2, France
Heteroepitaxy of diamond CVD films is a great challenge for future applications in high temperature and high power electronic devices. However, the crystalline quality of heteroepitaxied diamond films is a significant obstacle to succeed in electronic applications.
The widely used bias enhanced nucleation (BEN) method has been successively improved to produce highly oriented diamond films on Si. However, further progress in diamond film quality and interface control could not be achieved without an accurate knowledge of the nucleation elemental mechanisms. Our major aims are the understanding of the BEN-effects on the nucleation, the identification of the crystallographic structure as well as the chemical nature of diamond precursor and the characterisation of the epitaxial relationship between the diamond crystals and the silicon substrate. In this way, a sequential study on localised thinned areas has been performed by plan-view HRTEM observations in order to compare the early stages of the HFCVD diamond nucleation including or not a BEN step. This study has been completed by cross-section observations of the interface. In both cases, a mosaic of b-SiC crystals which present a pseudo-epitaxial relationship b-SiC {220} // Si {220} has been observed. For the HFCVD growth preceded by BEN step, the diffraction pattern reveals an increase of the nucleation density and a preferential orientation of diamond crystals in agreement with Si substrate. The several epitaxial relationships which have been studied using nanodiffraction experiments, will be discussed.
- L-VI.6** 11:45 **NANOCRYSTALLINE DIAMOND FILMS DEPOSITION FOR SURFACE ACOUSTIC WAVE DEVICES ACHIEVEMENT**
E. Mohasseb(a), F. Bénédic(a), M.B. Assouar(b), O. Elmazria(b), P. Alnot(b) and A. Gicquel(a), (a)Laboratoire d'Ingénierie des Matériaux et des Hautes Pressions, UPR CNRS 1311, Université Paris 13, Av. J. B. Clément, 93430 Villetaneuse, France, (b)Laboratoire de Physique des Milieux Ionisés et Applications, UMR CNRS 7040, Université Henri Poincaré - Nancy I, BP 239, 54506 Vandoeuvre les Nancy, France
The increasing demand for large volume data transmission requires electronic systems, such as Surface Acoustic Wave (SAW) devices, operating at high frequency (GHz range). Nowadays, high frequency SAW devices based on CVD Poly-Crystalline Diamond (PCD) combined with piezoelectric material can be achieved. However, the rough grow-side of PCD films must be smoothed by a time-consuming mechanical polishing process, in order to enhance the wave propagation and to fulfill the requirements of the photolithographic process. Therefore Nano-Crystalline Diamond (NCD), owing to a very low thickness-independent roughness of the as-grown film surface, would be an interesting alternative to PCD.
In this work we report on a study dealing with the deposition of NCD films suitable for SAW devices realization. The NCD films were deposited on silicon substrate by MPACVD process at various experimental conditions. The properties of the films were investigated using SEM, AFM, XRD and Raman spectroscopy. SAW devices based on AlN/NCD/Si layered structure were then achieved using selected high quality NCD films of several thickness. The high frequency characterization of the devices was accomplished with a network analyzer. It showed that operating layered structures was successfully achieved and confirmed that the NCD layers present a high surface acoustic velocity similar to that of PCD films. This shows that it is possible to realize high frequency NCD-based SAW devices which does not require the polishing step necessary when PCD films are used.

12:10

LUNCH

Thursday, June 12, 2003
Jeudi 12 juin 2003

Afternoon
Après-midi

Session VII: Nanotubes and hybrid circuits
Session chair: N. Ferrer-Anglada

- L-VII.1** 14:00 -Invited- WAYS TOWARDS THE SCALEABLE INTEGRATION OF CARBON NANOTUBES INTO SILICON BASED TECHNOLOGY
G.S. Duesberg A.P. Graham, F. Kreupl, M. Liebau, R. Seidel, E. Unger, W. Hoenlein, Infineon Technologies AG, CPR Nano Processes, Otto Hahn Ring 6, 81739 Munich, Germany
The outstanding performance of carbon nanotubes (CNTs) in interconnect applications and microelectronic devices has been shown in a number of experiments on hand-picked demonstrators. However, for implementation parallel manufacture, which involves the precise placement and the simultaneous control over the properties of millions of CNTs, with microelectronic compatible processes is required. Various concepts for the large-scale integration of CNT-based electronics are compared in this presentation. One of them, catalyst mediated CVD growth, allows the direct growth of CNTs on silicon substrates. Methods for structuring the substrates and the catalyst materials on wafer scale as well as the influence of the process parameters are discussed in terms of reproducibility and uniformity. Furthermore the synthesis of single, isolated CNTs with lithographically defined diameters and locations has been established. This resembles the creation of vertical interconnects consisting of individual and multiple multi-walled CNTs. From this base, a concept for the assembly of CNT based, vertical, surrounding-gate transistors is presented.
- L-VII.2** 14:35 NEARLY MONODISPERSED CARBON COATED IRON NANOPARTICLES FOR THE CATALYTIC GROWTH OF NANOTUBES
F. Dumitrache, **L. Morjan**, R. Alexandrescu, I. Voicu, I. Sandu, I. Soare, M. Ploscaru, C. Fleaca, National Institute for Lasers, Plasma and Radiation Physics, P.O. Box MG-36, 76900 Bucharest, Romania, V. Ciupina, G. Prodan, Ovidius University of Constanta, Bd. Mamaia 124, Constanta, Romania, B. Rand, R. Brydson, A. Woodward, Institute for Materials Research, School of Process, Environmental and Materials Engineering, University of Leeds, Leeds FS2 9TT, U.K.
Catalytic methods are now wide spread for producing high yield carbon nanotubes. Moreover, the methods allow for the fabrication of regular array of nanotubes, which has great potential for application in microelectronics. A uniform and controlled catalytic growth of carbon nanotubes should depend on a narrow size distribution of the catalysing particles. However, if we refer to highly reactive transition metals like iron, the obtaining of nanoparticles of controlled dimensions and chemistry is difficult to realize. The embedding of metal nanoparticles in carbon layers could confer stability and inertness to the entrapped nano-scale material. Iron-carbon composite nanopowders have been synthesized by the CO₂ laser pyrolysis of gas-phase reactants. Iron pentacarbonyl and ethylene-acetylene mixtures were used as iron and carbon precursors. In usual experimental conditions, the reaction products may present themselves as iron-based nanoparticles dispersed in a carbon matrix. By a careful control of experimental parameters and radiation geometries we demonstrate the feasibility of an efficient and well-controlled, single-step technique for the production of iron-based nano-cores embedded in carbon layers. Electron microscopy and Raman spectroscopy were used in order to analyse the structure and composition of the obtained nanopowders. The results indicate that the synthesized iron nanoparticles (4.5 - 6 nm mean diameter) present a low degree of agglomeration and are covered by carbon layers. HREM analysis of the Soxhlet toluene extracted residue shows well dispersed Fe particles, which seem to be embedded in a few graphitic sheets.
- L-VII.3** 15:00 OPTICAL CHARACTERIZATION OF PURIFIED SINGLE WALLED CARBON NANOTUBES DEPOSITED ON SILICON
Vincenzo Vinciguerra(a), Francesco Buonocore(a), Maria Fortuna Bevilacqua(b) and Salvo Coffa(a), (a)STMicroelectronics, Stradale Primosele 50, 95121 Catania, Italy, (b)STMicroelectronics, Via Remo De Feo 1, 80022 Arzano, Naples, Italy
Single walled carbon nanotubes (SWNTs) are among the most promising materials in the field of molecular electronics because of their unique conducting properties. Recently the observation of luminescence in the near IR region from semiconducting nanotubes has determined a great interest in the optical properties of SWNTs that may open new perspectives in the field of optoelectronics. For this reason we have undertaken a thorough experimental investigation on the optical properties in the UV-vis and near IR region, at room temperature, of purified SWNTs deposited on a (100) Si p- surface. Our investigation has been connected to several spectroscopic and structural techniques. The optical properties of SWNTs observed in the UV-vis and near IR region have been compared with the absorption properties in the IR region measured with the Fourier transformed infrared spectroscopy (FTIR) and also with the information collected by the Raman spectra. Structural characterizations have been obtained by using transmission electron microscopy (TEM) and scanning electron microscopy (SEM) techniques. We will show that SWNTs have a peculiar optical behaviour in the near IR region that can be ascribed to the energy gap of semiconducting SWNTs and we will also consider how this optical response can undergo ageing processes which are strongly influenced by the presence of absorbed gases. We give also a theoretical description of the optical properties that we have observed in SWNTs in terms of first principle calculations.

- L-VII.4** 15:25 CARBON NANOTUBES/NANOFIBERS FOR PARALLEL E-BEAM LITHOGRAPHY AND MICROWAVE AMPLIFIER DEVICES
P. Vincent, L. Gangloff, G. Pirio, E. Minoux, J.P. Schnell, D. Pribat and P. Legagneux, Thales Research and Technology, France, K.B.K. Teo, M. Chhowalla, D.G. Hasko, H. Ahmen, G.A.J. amaratunga and R. Lacerda, University of Cambridge, V. Semet and V.T. Binh, University Claude Bernard, Lyon, France, O. Groening, University of Fribourg, Switzerland, M. Castignolles and A. Loiseau, CNRS-ONERA and University of Montpellier, France
 Plasma Enhanced Chemical Vapor Deposition (PECVD) has been used to grow aligned carbon nanotubes at predetermined locations and with a precise control of their geometrical aspect ratio. Due to these properties such nanotubes are particularly interesting for many field emission applications of which two will be presented:
 Arrays of electron microguns for parallel lithography. In this case each microgun consists of an unique electron emitter (i.e. one carbon nanotube) an extracting electrode and a focusing lens that can be driven by an active CMOS pixel. The fabrication process of the cathode and the first field emission properties of these arrays will be discussed.
 High frequency cathodes for microwave amplifiers. In order to asses the suitability of nanotubes for this application, first field emission results from arrays of 100*100 nanotubes will be presented.

15:50

BREAK

Session VIII: Other carbon materials

Session chair: J.C. Arnault

- L-VIII.1** 16:10 INCAR-FULLERENE-CONTAINING CARBON PEAPODS AS MATERIALS FOR QUANTUM COMPUTATION
John Dennis and M. Kanai, Department of Chemistry, Queen Mary, University of London, Mile End Road, London E1 4NS, U.K., Kyriakos Porfyriakis, Andrei Lhlobystov, Gavin Morleyy, Arjang Ardavan, Simon Benjamin and Andrew Briggs, Department of Materials, University of Oxford, Parks Road, Oxford OX1 3PH, U.K.
Incar-fullerenes *iNC*₆₀ and *iNC*₇₀ have clear potential to act as qubit systems for quantum information processing. The two spin states of the unpaired electron on each incarcerated atom embody the actual qubits. The fullerenes merely act as containers for the qubits – shielding them from chemical reaction and environmental effects that would decrease superposition correlation times. Furthermore, *incarc*-fullerenes may be constrained to a self-assembled linear arrangement with a carbon nanotube. Thus, carbon peapods thus have clear potential to yield strings of qubits – a necessary requirement of a quantum computer. Furthermore, these systems are amenable to global addressing systems.
 We have performed the first full isolation of *iNC*₆₀ and *iNC*₇₀. We will present our progress on the spectroscopic characterisation of these *incarc*-fullerenes, and their potential in the physical realisation of quantum computation at the meeting
- L-VIII.2** 16:35 OPTICAL PROPERTIES OF CARBON MATERIALS FORMED BY PYROLYSIS OF NOVOLAC-RESIN/BIOMASS COMPOSITES
S. Theodoropoulou, L. Zoumpoulakis, I. Simitzis, National Technical University of Athens, School of Chemical Engineering, 15780 Athens, Greece and D. Papadimitriou, National Technical University of Athens, School of Applied Sciences, Department of Physics, 15780 Athens, Greece
 The optical properties of carbon materials formed by pyrolysis of novolac-resin/biomass composites using a low-cost method were studied by non-destructive, optical spectroscopic techniques in dependence of the temperature of pyrolysis and the heating rate. FTIR-, Raman, photoluminescence (PL) and (modulated) photoreflectance (MPR) spectroscopy were applied. Materials pyrolyzed at high temperatures (1000o C) are expected to be suitable for technological applications. The Raman spectra were composed of two bands: the graphitic G-band and the disordered graphitic D-band. The Raman band frequency was temperature independent, while the Raman bandwidth and the intensity ratio of the Raman D- to G-band, ID/IG, increased with the temperature. This is indicative of an increase in the fraction of sp²-bonded material and an increase in disorder. The optical band gap of the material was obtained by line shape-analysis of the MPR-spectra and was equal within the experimental error to the band gap of activated charcoal of 1.45 eV. The material pyrolyzed between 400o and 600o C exhibited a strong PL-emission, which was quenched at higher temperatures. This can be possibly explained by the presence of two different phases (novolac-resin and biomass), with different transition temperatures (towards a graphitic structure) and different number of defect states responsible for PL-emission. The MPR- and PL-spectra may be then associated with different material components.