Final report on

Nanotube 2001: II. International Workshop on the Science and Applications of Nanotubes

Inselhotel Postdam, Germany (22-25 July 2001)

Organizers:
Tobias Hertel (FHI Berlin), David Tomanek (Michigan State Univ.)
and Angel Rubio (DIPC San Sebastian)

General remarks

This truly successful workshop provided an essential platform for the presentation and interchange of the latest results and ideas in the field of nanotube science and its applications. At the same time this workshop continues to be the only meeting worldwide with its focus exclusively on nanotubes. Ten years after the key discovery of carbon nanotubes by Sumio Iijima it therefore satisfies the need of this community to exchange ideas and allow lively discussions on a broad range of issues - ranging from synthesis over properties to applications - in an informal atmosphere. We thus believe that the meeting has played and will continue to play an increasingly important role in shaping this strongly growing community. The success of this workshop with its 133 participants from 19 countries has also prompted the organization of the following meeting *Nanotube 2002* which is to be held in Boston, USA and is planned to accommodate a significantly larger number of participants.

1 Organization

1.1 Board of advisors

The board of advisors played an decisive role for the preparation of the meeting, in particular for the selection of invited speakers. The organizers had asked 6 internationally renown scientists - all of them key figures of this field - to serve as advisors for Nanotube 2001. All of these scientists accepted under the premise that none of them would be invited to give a scientific presentation at the meeting – to avoid any conflict of interest.

Dr. Phaedon Avouris, IBM T.J. Watson Research Center, USA
Prof. Patrick Bernier, Universite de Montpellier II, France
Prof. Marvin Cohen, University of California at Berkeley, USA
Prof. Mildred Dresselhaus, Massachusetts Institute of Technology, USA
Prof. Philippe Lambin, Facultes Universitaires N-D Paix, Belgium
Prof. Susumo Saito, Tokyo Institute of Technology, Japan
Prof. Richard Smalley, Rice University, USA

Prof. Mildred Dresselhaus gave an after dinner speech on the second day of the meeting.

1.2 Invited speakers

23 invited internationally renown speakers were chosen to give account of the current status of the field of nanotube science. The emphasis on synthesis and transport properties as well as on chemical properties and potential applications very much reflects the interest of the majority of groups working in this field. A detailed list of invited speakers and titles of their presentations is attached to this report (Attachment I).

1.3. Participants

To keep the meeting as productive as possible and to avoid parallel sessions we have restricted the number of participants to below 140. The demand for participation at the meeting has been overwhelming with nearly twice as many applications (~ 250) than we were able to accommodate. The capacity of the hotel and its facilities also forced us to limit the number of participants to less than 140. The overwhelming majority of participants (with only a handful of exceptions) gave either invited or a poster presentations. The final number of participants of 133 was slightly below the hotels capacity due to a number of last minute cancellations which could not be compensated by new admissions. The number of students, including PhDs was estimated to be about 20. Participants originated from 19 different countries which made this a truly international meeting. More specifically: Western Europe excluding Germany (44), USA and Canada (33), Germany (28), Japan (15), Eastern Europe (6), Korea (6), Israel (2), Mexico (1). A detailed list of participants is attached to this report (Attachment II).

Some governement offices as well as industrial companies have show interest in this field as it is clear form the participation of people from Samsung, Infinion, Air Force, NASA.....

1.4 Financial support

Financial support was provided by a number of organizations. Major contributions were made by the Office of Naval Research International Field Office, the Deutsche Forschungsgemeinschaft and the Max-Planck-Society. We were also able to attract a number of other sponsors such as scientific networks, small firms or publishers. More specifically:

- Office of Naval Research International Field Office, Office of Naval Research Headquaters, USAF European Office of Aerospace Research and Development
- Detusche Forschungsgemeinschaft
- Max-Planck-Society
- Brandenburg Ministry of Culture, Education and Science
- NEC Corporation
- Asian Technology and Information Program (ATIP)
- PHANTOMS network of the European Union

- Springer Verlag Heidelberg
- Institute of Physics Publishing
- Nanolab Boston

1.5 Organization of the program and timetable

The program of this 4 day meeting was organized to provide the optimum time for invited presentations and the 4 poster sessions. At the same time we tried to provide enough room for informal discussions during poster sessions as well as during breaks between invited talks. Invited talks were scheduled to last 45 minutes which included 10 minutes for discussion. Two sessions in the morning and one after lunch were used for 2 invited presentations each while the remainder of the afternoons was reserved for poster sessions. The two large poster sessions with about 40 posters each were extended into the evening.

We tried to group invited talks and poster sessions with particular focus on one or two topics per day. The first day was thus mostly devoted to the synthesis and purification of nanotubes accompanied by a few presentations on their properties. The second day was primarily on transport properties and related phenomena. The last two days where primarily devoted to chemical properties and applications of nanotubes, respectively.

Poster sessions were accompanied by so called Poster-PLUS session in which each presenter was asked to give a 2 minute- (2 viewgraph or Power-Point slides) presentation of the key results of his poster. This was intended to allow other participants to make a pre-selection of the posters they were particularly interested in.

Arrival & departure:

Saturday, July 21	Sunday-Wednesday, 22-25	Thursday, July 26
Arrival, Welcome reception (18:00-21:00)	Scientific Program	Breakfast (6:30-10:00), Departure

Program timetable:

<table>
<tr><th></th><th>Sunday, July 22</th><th>Monday, July 23</th><th>Tuesday, July 24</th><th>W-day, July 25</th></tr>
<tr><td>6.30 – 8.30</td><td>BREAKFAST</td><td>BREAKFAST</td><td>BREAKFAST</td><td>BREAKFAST</td></tr>
<tr><td>8.30 – 10.00</td><td>Welcome Address
&
Session Su1</td><td>Session Mo1</td><td>Session Tu1</td><td>Session We1</td></tr>
<tr><td>10.00 – 10.30</td><td>COFFEE BREAK</td><td>COFFEE BREAK</td><td>COFFEE BREAK</td><td>COFFEE BREAK</td></tr>
<tr><td>10.30 – 12.00</td><td>Session Su2</td><td>Session Mo2</td><td>Session Tu2</td><td>Session We2</td></tr>
<tr><td>12.00 – 13.30</td><td>LUNCH</td><td>LUNCH</td><td>LUNCH</td><td>LUNCH</td></tr>
<tr><td>13.30 – 15.00</td><td rowspan="2">Session Su3</td><td rowspan="2">Session Mo3</td><td>Session Tu3</td><td rowspan="2">Session We3</td></tr>
<tr><td>COFFEE BREAK</td></tr>
<tr><td>15.00 – 15.30</td><td>COFFEE BREAK</td><td>COFFEE BREAK</td><td rowspan="3">Poster-PLUS
contributed talks
and posters
PoS Tu</td><td>COFFEE BREAK</td></tr>
<tr><td>15.30 – 18.30</td><td>Poster-PLUS
contributed talks
and posters
PoS Su</td><td>Poster-PLUS
contributed talks
and posters
PoS Mo</td><td>Poster-PLUS
contributed talks
and posters
PoS We</td></tr>
<tr><td>18.30 – 20.00</td><td>DINNER</td><td>DINNER</td><td rowspan="3">Boat/Bus trip
&
Banquet

(ends 22-24:00)</td><td>DINNER</td></tr>
<tr><td>20.00 – 21.00</td><td rowspan="2">Poster Session
PoS Su
(continued)</td><td>After Dinner
Presentation</td><td rowspan="2">Poster Session
PoS We
(continued)</td></tr>
<tr><td>21.00 – 22.00</td><td></td></tr>
</table>

1.6 Book of abstracts, proceedings, workshop CD

A book of abstracts is attached to this report (Attachment III). A workshop proceedings with contributions from invited speakers only is scheduled to be published as special issue of Applied Physics A. In order to provide a snapshot of the current status of the field and all presentations given at the meeting we compiled and distributed a compact disc (CD) during the last day of the meeting. This disk includes viewgraphs from the majority of invited presentations as well as photographs or electronic versions of nearly all poster presentations. The effort to produce this CD during the meeting was considerable but we hope that it will be beneficial to all participants. A copy of this CD is also attached to the report (Attachment IV).

2 Overview of results and highlights

The issues discussed at the meeting focussed on the understanding of electronic, mechanical and structural properties of carbon and other nanotubes. The fascinating properties and potential technological applications of these materials together with their well defined low-dimensional structure offer a diversity of issues for research of both fundamental and practical interest. While the majority of the work in this field is being performed on carbon nanotubes, we also heard presentations on other inorganic nanotubes such as boron-nitride, boron, carbon nitride, molybdenum di-sulfide and other types of nanotubes.

We believe that the meeting with its focus on synthesis, low energy transport properties, chemical modification and mechanical properties of nanotubes has given the scientists working in this field the perfect opportunity to exchange ideas in a concerted effort and to develop the foundations for future research.

- First, we got very lively discussion after each talk, in most cases questions were left to the coffee break, lunch or the poster sessions. This is a very important remark as many conferences lack of the life-discussion environment so important when discussing new achievements as the ones presented in Potsdam.

- Second, it created the proper atmosphere for interaction among people that have opened up possibilities for future (or even present) new collaborations. We have got very positive remarks from most participants.

- Third, the ample time dedicated for the poster sessions with not a high number of posters per day, helped to promote deep discussions in each panel among different participants.

Program and highlights: ==========

The program and the discussions have been centered around several main questions (both theoretically and experimentally) related to Synthesis, growth and purification of nanotubes, Low energy excitations and electronic transport properties, Mechanical properties and Applications.

2.1.1 Synthesis and characterization of nanotubes and hybrid systems

1) Production and characterization of single-wall and multi-wall nanotubes and nanotubes filled with peopods. Nowadays different techniques allow for high-yield production of nanotubes (both carbon and BN in particular). The synthesis of nanotubes by chemical vapor

deposition (CVD) has been shown to be extremely useful for the production of large quantities of high purity material as well as for the controlled deposition of nanotubes on patterned substrates.

2.1.2 Transport properties

Potential use of carbon nanotubes as molecular wires or as novel electronic devices has been the focus for a large portion of workshop (both as invited speakers and poster presentations). New electronic transport phenomena of multi-wall nanotubes (MWNT), SWNT and assembled collections, or ropes, of SWNT were discussed in detail. Carbon nanotube based devices have been shown to exhibit Coulomb blockade, or have been demonstrated to act as field effect transistors.

2.1.3 Applications:

The most striking in-market application is the use of nanotubes for field emission displays. Current issues are the long term stability and reproducibility of field emission sources. In this respect BN nanotubes offers interesting possibilities compared to carbon-based materials. The use of carbon-materials for catalysis and hydrogen-storage have also been addressed. Many potential application for nanoelectronics have been envisioned as well as the use of the high mechanical strength of nanotubes for new compound materials.

2.1.3 Chemical sensitivity of nanotubes

There is an important role of the environment in the electronic properties of the tubes. This needs still to be understood properly and quantified. A large effort has been shown in the meeting towards this goal.

5) Temperature effects: coalescence of fullerenes inside tubes to form in a control way two-wall carbon nanotubes (if was proposed that this could be also done in BN tubes to get a double layer insulator-metal system). Similarly at high enough temperatures SWNT-ropes coalesce into MWNT. This established a limit for the applicability of tubes under extreme conditions.

5) Theory: there has been a ample presentation of modellization of transport, mechanical and electronic properties of different nanotubes. Role of defects, packing and substrate interaction were presented. The analysis of the structural and electronic properties of a great variety of inorganic nantoubes (many of them still to be synthesized) has been presented in the workshop. Maybe the most exciting aspect of theoretical predictions is electron correlation in these systems: existence of superconductivity, charge and spin density waves, Luttinger liquid response for specific metallic tubes. The experimental realization of the theoretical predictions have been attempted with great however in some cases the interpretation of results remains still ambiguous.

Concluding remarks

Feedback from participants is great.

Attachment I

List of speakers and titles of their presentations (in order of appearance)

Sumio Iijima (Meijo University and NEC)
Single-Wall Graphite Sheets as Molecule Adsorption

Annick Loiseau (LEM, Châtillon)
Root Growth Mechanism for Single Wall Nanotubes

Jim Hone (CalTech)
Thermal Properties and Quantized Phonon Spectrum of Single-Walled Carbon Nanotubes

Laszló Fórró (EPF Lausanne)
Disorder and Pressure Effect on the Physical Properties of Carbon Nanotubes

Marc Bockrath (Harvard)
Transport in Carbon Nanotubes

Reinhold Egger (Universität Düsseldorf)
Spin Transport and Coulomb Blockade in Nanotubes

David Luzzi (UPenn)
Carbon Nanotube-Based Hybrid Materials

Robert Schlögl (Fritz-Haber-Institut)
Carbon Nanomaterials in Heterogeneous Cataylsis

Philip G. Collins (IBM, T.J. Watson Research Center)
Controlling the Electronic Properties of Carbon Nanotube Bundles

Walt A. de Heer (Georgia Tech)
When are Carbon Nanotubes Ballistic Conductors

Cees Dekker (Delft University of Technology)
Recent Transport and STM Results on Carbon Nanotubes

Steven G. Louie (Berkeley)
Theoretical Study of the Quantum Conductance of Nanotube Structures: Defects, Junctions, and Peapods

Mauricio Terrones (University of Sussex & UNAM)
Novel Layered Nanomaterials: Controlled Synthesis, Electronic Properties and Applications

Hiromichi Kataura (Tokyo Metropolitan University)
Optical Properties of Fullerene- and Non-Fullerene-Peapods

Mark Golden (IFW Dresden)
The Optical Properties and Electronic Structure of SWCNT: Empty, Stuffed or Surrounded by Dopants

Peter C. Eklund (Penn State University)
Molecule/SWNT Interactions: Effects on Electronic and Phonon Properties

Robert C. Haddon (Riverside)
Chemistry of Single-Walled Carbon Nanotubes

Wongbong Choi (Samsung)
Carbon Nanotube and its Application to Nanoelectronics

Louis Schlapbach (Universite Fribourg & EMPA)
Carbon Nanostructures: Growth, Electron Emission, Interactions With Hydrogen

Reshef Tenne (Weizmann Institute)
Inorganic Nanotubes and Inorganic Fullerene-Like Materials of Metal Dichalcogenides

Jie Liu (Duke University)
CVD Synthesis of Single-Walled Carbon Nanotubes on Aerogel Supported Catalyst

Jerry Bernholc (North Carolina State University)
Theoretical Studies of Quantum Transport, Pyro- and Piezo-Electric Effects and Lithium Intercalation

Hongjie Dai (Stanford)
Carbon Nanotube Molecular Wires: Recent Progress in Synthesis, Characterization and Devices

Attachment II
List of participants

Dr.	Markus E	Ahlskog	Finland
Dr.	Joerg	Appenzeller	USA
Dr.	Alexis	Baratoff	Switzerland
Prof.	Jerry	Bernholc	USA
Dr.	Holger F	Bettinger	Germany
Dr.	L szl¢ P.	Bir¢	Hungary
Prof.	Marc	Bockrath	USA
Dr.	Kim	Bolton	Sweden
Mr.	Mark R	Buitelaar	Switzerland
Dr.	Lyubov G.	Bulusheva	IRussia
Dr.	Marko	Burghard	Germany
Ms.	Silke	Burkart	Germany
Mr.	Peter R	Butzloff	USA
Dr.	Davide	Ceresoli	Italy
Prof.	Leonid A	Chernozatonskii	Russia
Dr.	Hyoung Joon	Choi	USA
Dr.	Wongbong	Choi	Korea
Dr.	Phil	Collins	USA
Mr.	Mirco	Croci	Switzerland
Mr.	Mihail D.	Croitoru	Germany
Prof.	Hongjie	Dai	USA
Prof.	Walt A.	deHeer	USA
Prof.	Cees	Dekker	The Netherlands
Dr.	Ursula	Dettlaff	Germany
Dr.	Michel J.-P.	Devel	FRANCE
Prof.	Mildred S.	Dresselhaus	USA
Mr.	Orest	Dubay	Austria
Dr.	Caterina	Ducati	UK
Dr.	Kristina	Edström	Sweden
Prof.	Reinhold	Egger	Germany
Dr.	Sebastian	Eggert	Sweden
Prof.	Peter C.	Eklund	USA
Mr.	Joerg	Engstler	Austria
Dr.	Yuwei	Fan	Germany
Dr.	Laszlo	Forro	Switzerland
Ms.	Steffi	Friedrichs	United Kingdom
Prof.	Michael S	Fuhrer	USA
Dr.	W.	Gerlach	Germany
Dr.	Harald	Goering	Germany
Dr.	Dmitri V.	Golberg	Japan
Dr	Mark	Golden	Germany
Prof.	Robert C.	Haddon	USA
Prof.	Pertti J	Hakonen	Finland
Mr.	Anders	Hansson	Sweden
Dr.	Abdou	Hassanien	Japan
Dr.	Tobias	Hertel	Germany
Dr.	Kaori	Hirahara	Japan
Mr.	Mattias	Hjort	Sweden
Dr.	Holger	Hoffschulz	Germany
Mr.	Michael	Holzinger	IGermany
Dr.	James	Hone	USA

Mr.	Fumiyuki	Hoshi	Japan
Prof.	jisoon	Ihm	Korea
Prof.	Sumio	Iijima	Japan
Dr.	Ahraf M.	Imam	USA
Dr.	Oliver	Jost	Germany
Dr.	Akinobu	Kanda	Japan
Dr.	Tapas	Kar	USA
Dr.	Hiromichi	Kataura	Japan
Prof.	Krzysztof	Kempa	USA
Dr.	Gyu-Tae	Kim	Germany
Mr.	Yong-Hyun	Kim	Korea
Mr.	Alex	Kleiner	Sweden
Dr.	Steven E.	Kooi	Germany
Dr.	Petr	Kral	Israel
Prof.	Philipe	Lambin	Belgium
Mr.	Freek	Langeveld	The Netherlands
Dr.	Christophe	Laurent	France
Prof.	Cheol Jin	Lee	Korea
Ms.	Jeongo-O	Lee	Korea
Dr.	Seung Mi	Lee	Germany
Dr.	Maik	Liebau	Germany
Dr.	Jie	Liu	USA
Mr.	Xianjie	Liu	Germany
Prof.	Annick	Loiseau	France
Dr.	Maria J	Lopez	Spain
Prof.	Steven G.	Louie	USA
Prof.	David E	Luzzi	USA
Dr.	Apostolos G.	Marinopoulos	France
Dr.	Richard	Martel	USA
Dr.	Klaus	Mauthner	Austria
Dr.	Gregory C	McIntosh	Korea
Dr.	Enzo	Menna	ITALY
Dr.	Alf	Mews	Germany
Prof.	Stephen C.	Minne	USA
Dr.	Yoshiyuki	Miyamoto	Japan
Mr.	Gunnar	Moos	Germany
Prof.	Nobukata	Nagasawa	Japan
Dr.	Takeshi	Nakanishi	The Netherlands
Dr.	Fumiyuki	Nihey	Japan
Dr.	Pavel	Nikolaev	USA
Mr.	Jesper	Nygard	Denmark
Dr.	Michael J.	O'Connell	USA
Dr.	Alexander V.	Okotrub	Russia
Dr.	Ruth	Pachter	USA
Prof.	Juan J.	Palacios	Spain
Mr.	J.S.	Park	Germany
Dr.	Phillip A.	Parrish	United Kingdom
Dr.	Michael F.	Pestorius	USA
Dr.	Günther E	Philipp	Germany
Dr.	Thomas	Pichler	Austria
Dr.	Lu-Chang	Qin	Japan
Dr.	Burkhard	Renker	Germany
Prof.	Daniel E	Resasco	USA
Dr.	Stephan	Roche	FRANCE
Prof.	Alain	Rochefort	Canada
Dr.	Frank	Rohmund	Sweden
Dr.	Anatoly I	Romanenko	Russia
Prof.	Angel	Rubio	SPAIN

Prof.	Susumu	Saito	Japan
Mr.	Jan	Sandler	United Kingdom
Dr.	Masahito	Sano	Japan
Dr.	Jean-Louis M.	Sauvajol	France
Prof.	Louis	Schlapbach	Switzerland
Prof.	Robert	Schlögl	Germany
Dr.	Ulrich S.	Schwarz	Germany
Prof.	Gotthard	Seifert	Germany
Dr.	Milo S.P.	Shaffer	UK
Ms.	Priscilla	Simonis	Belgium
Prof.	Gregory Ya.	Slepyan	Belarus
Mr.	Olivier	Smiljanic	Canada
Dr.	Shekhar	Subramoney	USA
Mr.	Saikat	Talapatra	USA.
Prof.	Reshef	Tenne	Israel
Prof.	Mauricio	Terrones	England
Dr.	Michael	Thorwart	The Netherlands
Prof.	David	Tomanek	USA
Ms.	Susana	Trasobares	France
Mr.	Hendrik	Ulbricht	Germany
Mr.	N.J.	van Druten	Netherlands
Prof.	Kazuyuki	Watanabe	Japan
Mr.	Glenn	Wright	USA
Prof.	Shi-Yu	Wu	USA
Dr.	Liu	Yang	US
Dr.	SeGi	Yu	Korea
Dr.	Masako	Yudasaka	Japan
Mr.	Renju	Zacharia	Germany