



**EUROPEAN COMMISSION
SIXTH FRAMEWORK PROGRAMME 2007-2010
SPECIFIC TARGETED RESEARCH PROJECT**



**NOVEL, HETEROATOMIC BORON, NITROGEN AND CARBON NANOTUBES
(033350)**

**FINAL PUBLISHABLE ACTIVITY REPORT
1.2.2007-31.7.2010**

Period covered: from 1.2.2007 to 31.7.2010

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Revision 1

Dissemination level: PU

PU: public

RE: restricted to a group specified by the partners of the BNC Tubes project

CO: confidential, only for partners of the BNC Tubes project

Abbreviations

BN-SWNT – boron nitride single-walled nanotubes
BN-SWCNT – boron- and nitrogen-doped single-walled carbon nanotubes
B-MWCNT – boron-doped multi-walled carbon nanotubes
BN-MWCNT – boron- and nitrogen-doped multi-walled carbon nanotubes
CNT – carbon nanotubes
CVD – chemical vapour deposition
DWNT – double-walled nanotubes
EELS – electron energy loss spectroscopy
FE – field emission
HRTEM – high-resolution transmission electron microscopy
MWCNT – multi-walled carbon nanotubes
N-MWCNT – nitrogen-doped multi-walled carbon nanotubes
N-SWCNT – nitrogen-doped single-walled carbon nanotubes
OA – optical absorption
PL – photoluminescence
PM – person-month
SWCNT – single-walled carbon nanotubes
SEM – scanning electron microscopy
TEM – transmission electron microscopy
XPS – X-ray photoelectron spectroscopy

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1. Project execution

The Heteroatomic boron, nitrogen and carbon nanotubes (BNC Tubes) project aimed to develop novel, continuous, chemical vapour deposition (CVD) based synthesis methods for three dimensional regular nanostructures in the form of heteroatomic nanotubes (NTs) composed of boron, nitrogen and carbon: BN, N-doped carbon, B-doped carbon and mixed B-N-C nanotubes. In doped nanotubes either or both boron and nitrogen atoms replace carbon atoms within the structure and are covalently bound. Important industrial potential was demonstrated by developing transparent, conductive, flexible nanotube mats. The optical (i.e. band gap), electrical conductivity, electron field emission as well as non-linear optical properties of produced nanotubes were explored. A significant dedicated modeling aspect was included. Nanotube synthesis was studied using system level computational fluid/aerosol dynamics methods and NT properties investigated based on detailed atomistic modeling using *ab initio* simulations. Metrology issues included the development as well as comparison of advanced transmission electron microscopic (TEM) and scanning tunneling (STM) methods to determine the atomic structure and non-linear optical properties of produced nanotubes.

The original project partners were the following:

1. Helsinki University of Technology (TKK; Coordinating partner)
2. Centre National de la Recherche Scientifique (CNRS)
3. University of Oxford (UOXF.DJ)
4. University of Namur (FUNDP)
5. HP Packard (Manufacturing) Limited (HP-DIMO) – resigned from the project
6. ARKEMA (ARK)
7. Beneq Oy
8. Oulu University (UOULU)
9. Natural Sciences Center of A. M. Prokhorov General Physics Institute of Russian (NSC GPI)

In 2009, the name of the Helsinki University of Technology was changed to Aalto University (AALTO) School of Science and Technology. The name AALTO will be used throughout.

During December 2007 HP-DIMO has resigned from the project. The HP-DIMO tasks were transferred to AALTO, UOXF.DJ and NSC GPI, and accordingly no changes with respect to project research plan and deliverables were necessary.

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The projects main objectives were

1. the development of novel synthesis methods for heteroatomic (N- and B- doped carbon and BN) nanotubes based on floating catalyst and aerosol CVD, laser evaporation and substitution thermochemical reaction
2. the characterization of heteroatomic nanotubes by advanced techniques based on high resolution transmission electron microscopy (HRTEM), electron energy loss spectroscopy (EELS), scanning tunnelling microscopy (STM), optical absorption (OA), photoluminescence (PL) and field emission (FE) to determine their structure and properties
3. the development of both atomic and reactor level descriptions of nanotube formation mechanisms and investigation of heteroatomic nanotube properties based on detailed atomistic modelling using *ab initio*, molecular dynamics and Monte Carlo simulations
4. the development and characterisation of a highly transparent, conductive and flexible thin nanotube mats.

The project was originally planned for three years, but was extended for 6 months in early 2010. Therefore the project is divided here into three periods: Period 1 (Year 1, 1.2.2007 – 31.1.2008), Period 2 (Year 2, 1.2.2008 – 31.1.2009), and Period 3 (1.2.2009 – 31.7.2010).

A more detailed description of objectives and progress beyond the state-of-the-art as well as the milestones corresponding to each objective on a period-by-period basis are given in Tables 1 and 2.

Table 1: More detailed description of the major objectives and expected progress beyond the state-of-the-art on a period-by-period basis.

Objective	Period 1	Period 2	Period 3
1. Synthesis	Design of floating catalyst and aerosol CVD reactors	N- and B-doped carbon nanotube CVD synthesis methods operational for	Single walled N- and B- doped carbon as well as BN nanotube synthesis methods developed
2. Characterisation	Atomic structure of BNNT produced with laser determined	Field emission and optical properties of BN nanotubes	Atomic structure, optical and transport properties of heteroatomic tubes
3. Modeling	Understanding of catalyst particle dynamics in synthesis reactor	Understanding of surface reactions and transport of C atoms at catalyst surface during growth	Atomic level description of heteroatomic tube transport properties; reactor level predictions of tube production
4. Nanotube mats	Control of dispersion into solvents of 10 ml volume	Method to deposit 1 cm ² nanotube mat from dispersions developed	Method to produce 1 cm ² conductive,transparent and flexible nanotube mat developed

Table 2: Major milestones for each objective on a period-by-period basis.

Objective	Period 1	Period 2	Period 3
1. Synthesis	Floating catalyst and aerosol CVD reactors operational	N- and B-doped carbon nanotube CVD synthesised	Single walled N- and B- doped C and BN nanotube synthesized
2. Characterisation	BN nanotubes characterized with HRTEM and EELS	Field emission, PL and Raman measurements of BN tubes	Heteroatomic tubes fully characterized for structure and properties
3. Modeling	Population balance modeling of catalyst size behaviour	Kinetic representation of precursor surface reactions and carbon atom transport	MD calculations of transport properties; reactor level calculations of synthesis
4. Nanotube mats	10 ml stable dispersions produced	1 cm ² nanotube mat deposited and characterized	Nanotube mat properties optimised

1.1 Synthesis

The research work was carried out in 4 work packages: synthesis, characterization, modeling and demonstration of applications. Here we briefly describe the highlight results from each package.

During the project we produced B-, N- and BN- doped, single- and multi-walled carbon nanotubes using six different methods: floating catalyst, aerosol CVD, fluidized bed CVD, laser evaporation, arc discharge and thermo-chemical substitution. The production methods used during the project, the partners responsible for the work and the type of nanotubes produced by them are summarised in Table 3.

During the first project year, UOXF.DJ developed aerosol CVD method for the synthesis of N-doped MWCNTs and produced several samples, as well as initiated the studies to grow N-SWCNTs with this method. In CNRS, laser evaporation method was successfully used to produce SWCNTs doped with N and B, as well as BN-SWNTs (Figure 1). Floating catalyst reactors were designed at Beneq in collaboration with AALTO. In addition, another high temperature physical method, arc discharge, was used to produce N-SWCNTs at NSC GPI.

During the second project year, UOXF.DJ continued to further develop the aerosol CVD method for the synthesis of N-MWCNTs (Figure 2), as well as initiated studies to grow B-MWCNTs and N-SWCNTs. Floating catalyst reactors were used in AALTO to produce nanotubes and to deposit nanotube mats for conductive, transparent electrode manufacturing. Especially, AALTO succeeded – for the first time – to produce N-SWCNTs with the continuous floating catalyst CVD reactors.

During the third period of the project, ARK used the FB-CVD technology to produce at a large scale CNT doped with nitrogen. Fluidized bed Chemical Vapor Deposition technology (FB-CVD) is a promising method for large-scale production of CNT. The good heat and mass transfer inside the fluidized bed are ideal conditions for the growth of CNT and the possibility of an easy scale up makes this method ideal for industrial applications. This study was made on a quartz reactor of 2.5 cm diameter for adapting the FB-CVD for N-MWCNT production.

Also in the third period, CNRS performed the synthesis of single-walled nanotubes (NTs) made of boron, carbon and nitrogen (B-N-C) using the thermochemical substitution reaction method.

Table 3: Production methods and products.

Prod. Method	Group	Product
Floating catalyst CVD	<i>AALTO</i>	N-, B-SWCNT
Aerosol CVD	<i>UOXF.DJ</i>	N-SWCNT; N-,B-, BN-MWCNT
Fluidized bed CVD	<i>ARK</i>	N-MWCNT
Laser evaporation	<i>CNRS</i>	N- SWCNT, BN-SWNT
Arc discharge	<i>NSC GPI</i>	BN-SWCNT
Thermochemical substitution reaction	<i>CNRS</i>	BN-SWCNT

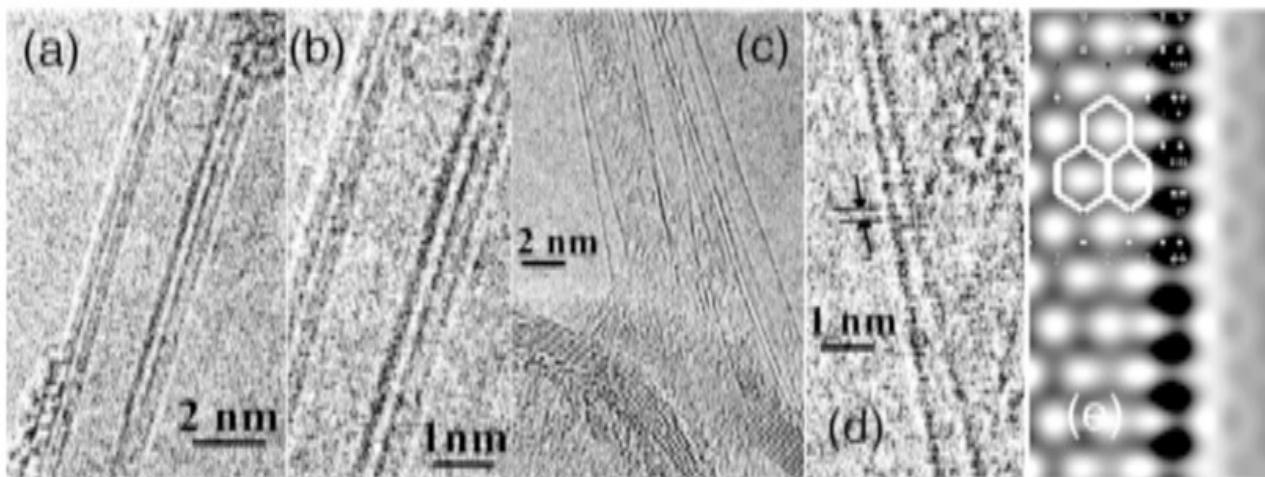


Fig. 1: (a) (b) and (c) HRTEM of BN-MWNT and SW-BNNT. (d) Enlargement of the contrast observed in the area indicated by the rectangle in (c). (e) Image simulation of a BN-SWNT having the zigzag configuration. The hexagonal network of the tube is drawn in white lines.

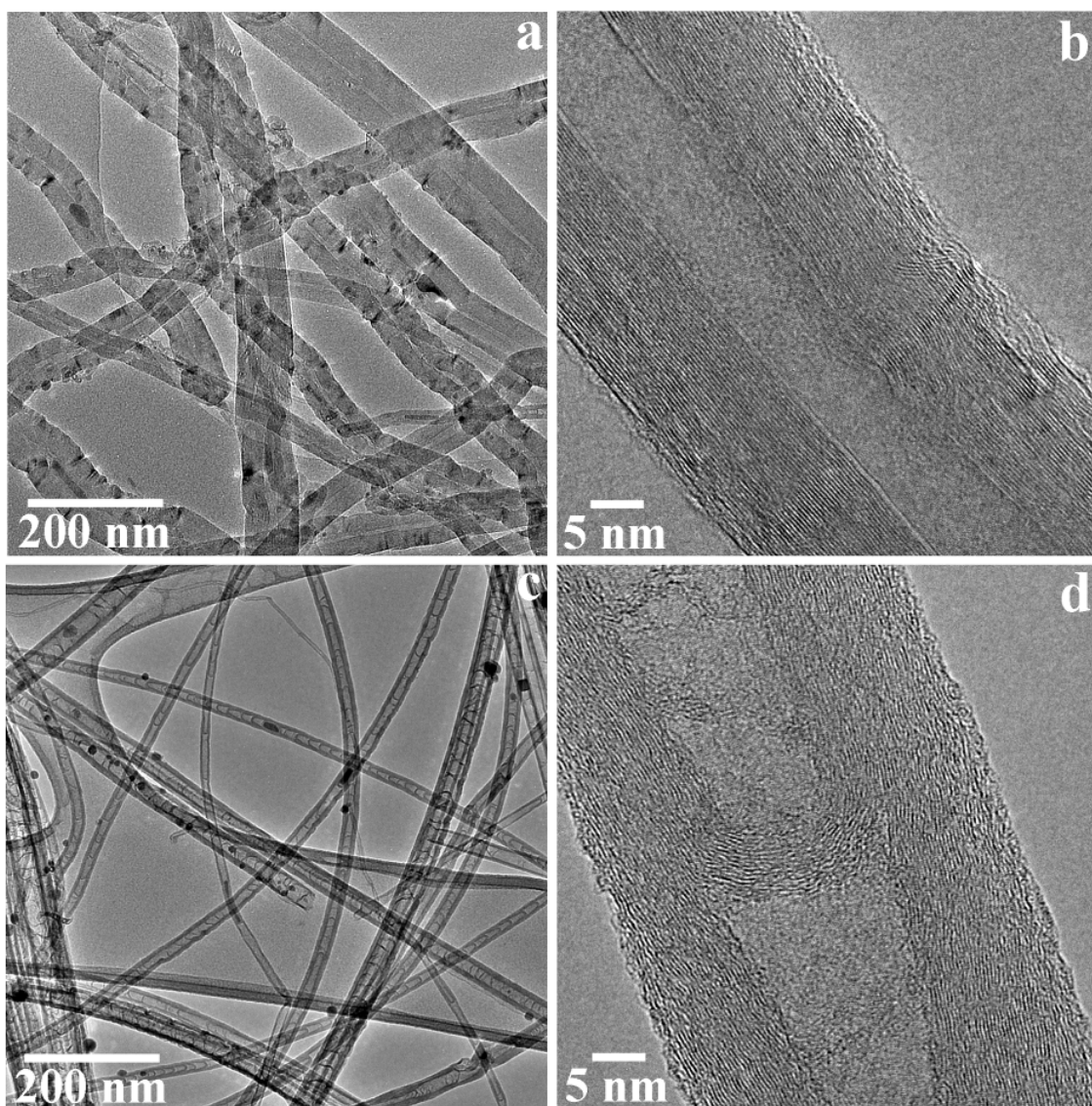


Fig. 2: TEM images of N-MWCNTs made by aCVD from a-b) acetonitrile c-d) benzylamine.

1.2 Characterization

The heteroatomic nanotubes were characterized by advanced techniques based on high resolution transmission electron microscopy (HRTEM), electron energy loss spectroscopy (EELS), electron diffraction, scanning tunneling microscopy (STM), optical absorption (OA), photoluminescence (PL) and field emission (FE) to determine their structure and properties.

In the first year of the project CNRS characterised BN-SWNT samples by HRTEM, EELS and electron diffraction for their morphology, chirality and composition. Electron diffraction studies showed that BNNTs have dominantly zigzag chirality. In addition, optical (both cathode- and photoluminescence) as well as STM measurements of BNNTs were initiated. BN-SWCNT made by arc discharge were extensively characterised at NSC GPI by HRTEM, Raman, optical absorption as well as electron field emission (Figure 3). Analysis of their current-voltage characteristics showed that the threshold field and the slope of Fowler-Nordheim plot increase by a factor of 2 with the rise of BN percentage in the mixture.

In the second year, AALTO developed an electron diffraction method for the determination of the chiral angle for nanotube assemblies, i.e. for single walled tube bundles and for multiwalled tubes. Scanning tunnelling microscopy (STM) was adapted to determine the atomic structure and local density of states for N-SWCNTs produced by laser evaporation. NSC GPI performed a detailed Raman study of the BN-SWCNTs.

In the third period of the project, CNRS demonstrated a method of deducing the intrinsic electronic properties of SWCNTs from STM measurements, allowing the experimental results obtained by STM and optical absorption to be conciliated (Figure 4). Also, FUNDP performed electronic structure modelling to help understand the atomic resolution images and local spectra obtained by STM/STS that evidenced the appearance of specific states at the defect sites of N-SWCNTs synthesized at AALTO. In only one particular case, a good match is obtained with the expected local conductance (similar to the Density of States) of a simple N substituted nanotube (Figure 5). Most experimental configurations were very complex and did not match the simple simulated configurations. AALTO demonstrated simple and effective (n,m) -selective growth of SWCNTs in the aerosol floating catalyst CVD process by introducing a certain amount of ammonia (NH_3).

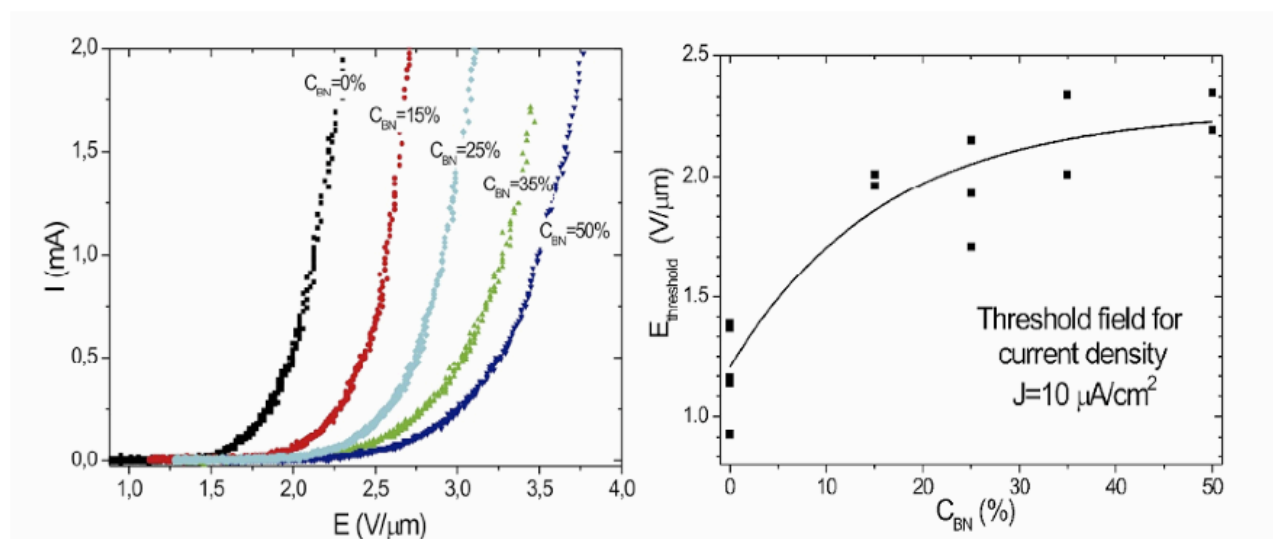


Fig. 3: I - V curves measured for nanotubes grown from different BN:C mixtures (left), dependence of the emission threshold field on the BN concentration in the initial mixture (right).

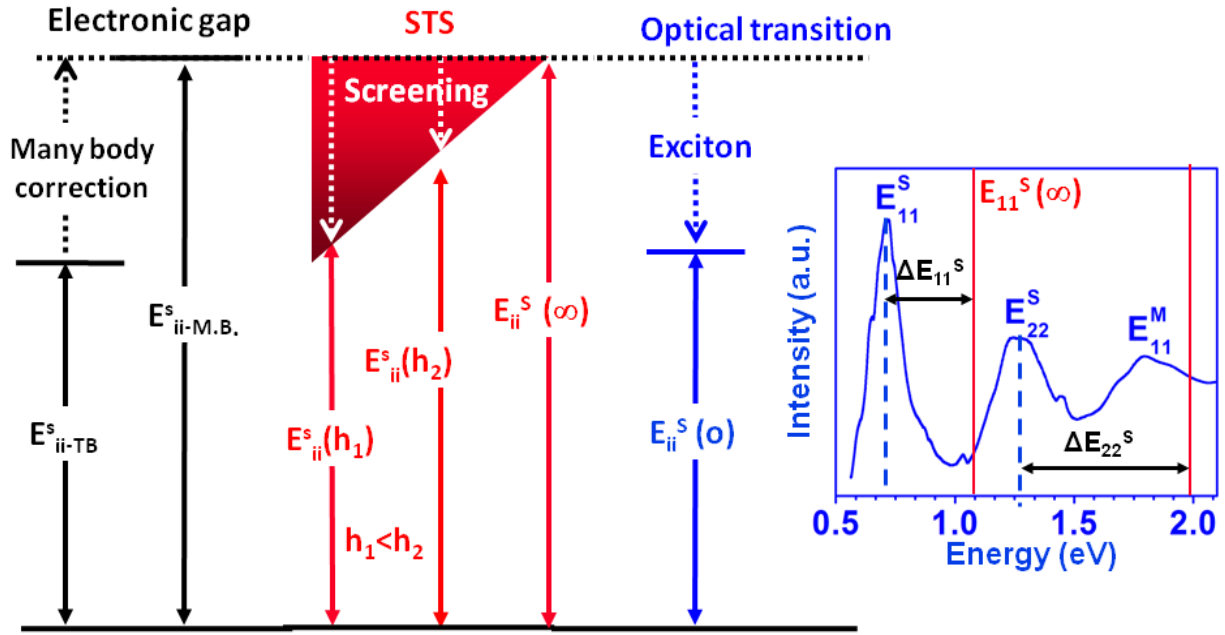


Fig. 4: Comparison of predicted or measured CNT. The electronic gap in many-body theory corresponds to the gap as predicted by the zone-folding tight-binding model enlarged by the self-energy. The experimental gap measured in STS experiments corresponds to the many-body gap reduced by the screening resulting from the metal substrate. The optical transition corresponds to the many-body gap reduced by the value of the exciton binding energy. The differences between optical transition and estimated intrinsic gap ΔE_{11}^S and ΔE_{22}^S correspond to an estimate of the exciton binding energy.

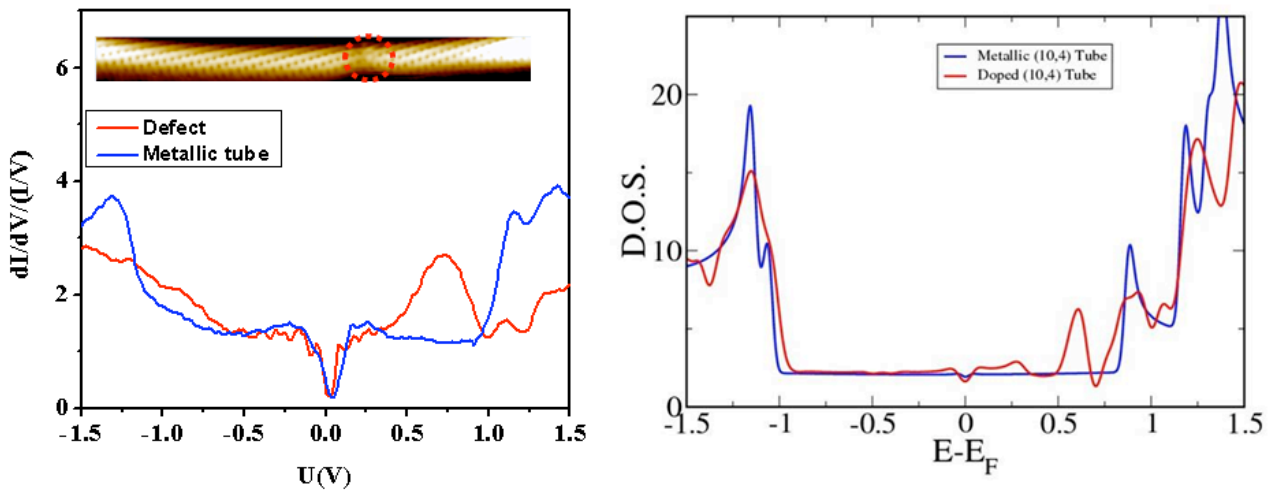


Fig. 5: (a) Local spectra measured by STS on a defective metallic tube. The blue spectrum measured far from the defect displays the well-known characteristics of a metallic tube (Van Hove singularities around $\pm 1V$ and a pseudo-gap around $0V$). The red spectrum measured on the defect shows a specific peak around $0.7V$. (b) Simulated Density of State of a (10,4) tube with a substitutional N atom.

1.3 Modelling

In the modelling work package, the aim was to develop both atomic and reactor level descriptions of nanotube formation mechanisms and investigation of heteroatomic nanotube properties based on detailed atomistic modelling using *ab initio*, molecular dynamics and Monte Carlo simulations. In practice, we concentrated on the most accurate *ab initio* models for studying the growth mechanism, electronic properties, and electronic transport of doped nanotubes.

During the first project year, mechanistic studies regarding BN-SWNT formation mechanisms during the laser evaporation synthesis were performed at CNRS. AALTO modelled catalyst particle growth via collisions during the floating catalyst synthesis by the moment method. Results showed that catalyst particle growth rate and their size at the time the nanotubes are nucleated depend on catalyst particle concentration. In addition, UOULU modelled the carbon diffusion processes during nanotube growth, as well as carried out studies concerning the bonding and chemistry of CO (important carbon precursor for CNT synthesis) and its fragments on a catalyst cluster Fe_{55} .

During the second project year UOULU focused on the chemical kinetics of surface reactions leading to carbon atoms forming the tube (Figure 6) and continued to model the carbon diffusion processes during nanotube growth. AALTO also employed atomistic computational simulations to study the possibility for a moderate temperature (e.g. 200-800 C) route for the synthesis of BN and B-N-C nanotubes by studying the boron and nitrogen containing precursor decomposition in both vacuum and on a catalytic metal surface.

In the third period of the project, UOULU finished calculating the reaction barriers for the key reactions of both N and C precursors and reactants. Remarkably good agreement was obtained with reaction barriers that AALTO determined experimentally. Additionally, AALTO finished modelling several reaction and diffusion barriers of B and N on Fe and Mg (Figure 7) surfaces, relevant for BN nanotube synthesis. Finally, FUNDP performed modelling of the quantum transport properties of doped heteroatomic nanotubes (Figure 8). The simplest doping configurations were studied by *ab initio* techniques. From these, parameters can be deduced to perform semi-empirical calculations on larger and more complex systems.

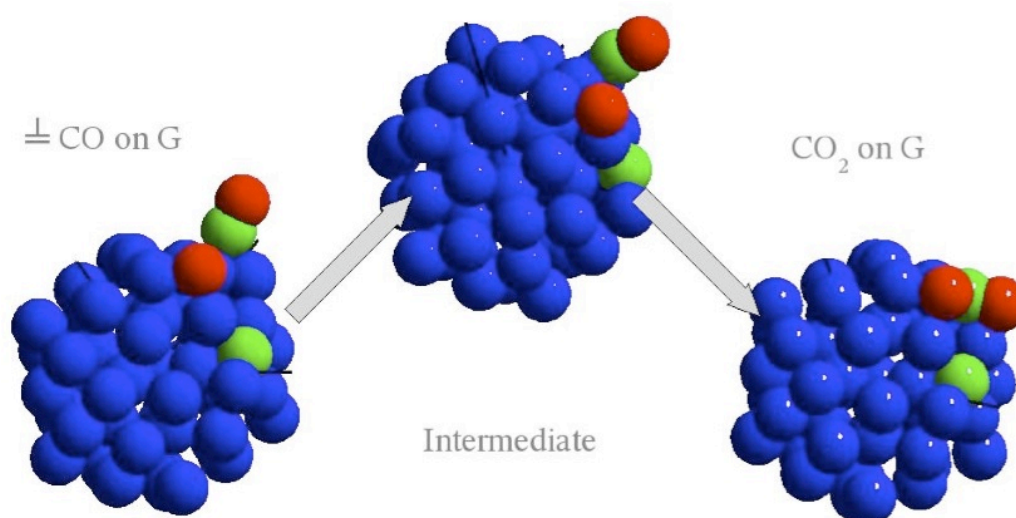


Fig. 6: Formation of C and CO_2 during the CO surface reaction on an iron catalyst cluster.

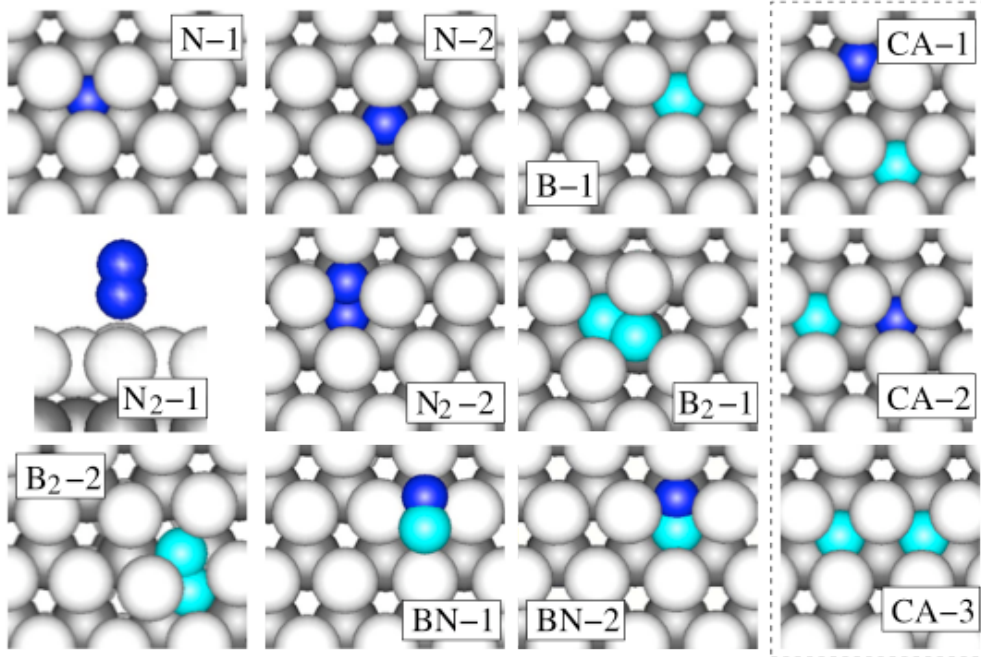


Fig. 7: Some of the most stable geometries for B_2 , BN , and N_2 molecules and the B and N atoms on the $Mg(0001)$ surface. In the case of BN , magenta (blue) corresponds to boron (nitrogen). Coadsorption geometries, where atoms are adsorbed into the same unit cell are labeled CA .

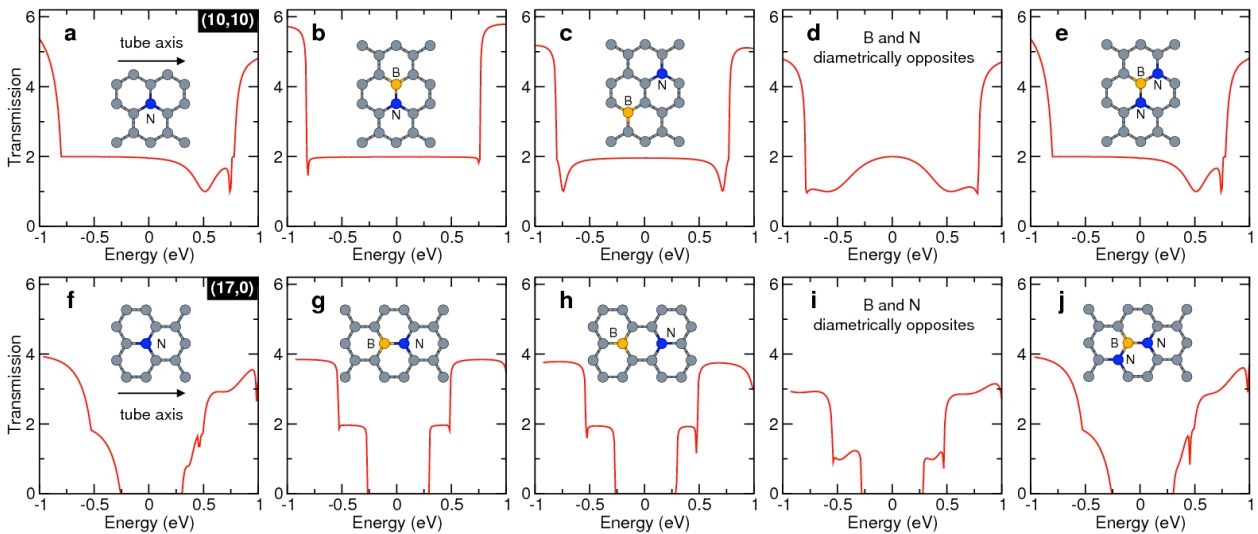


Fig. 8: Calculated conductance of metallic (upper frames) and semiconducting (lower frames) nanotubes containing B and N co-doping. The simple nitrogen substitution (a,f) induces a damping of the conductance created by the quasi-bound state located at $E = 0.50$ eV, whereas a pair of adjacent B and N atoms (b,g) is mainly transparent for conducting electrons close to E_F , and only two narrow dips in the transmission are predicted, close to the VHS. When B and N dopants are separated, like in a $BCCN$ case (c,h) the two dips become broader and move closer to E_F . At last, when B and N atoms are far from each other (d,i) effect of back scattering is intense, and is reminiscent of both the N and the B substitutions. The doping by the more complex NBN group of atoms, shown in (e,j), exhibit a transmission curve very similar to the single N substitution [3].

1.4 Applications

One main objective of this project was to develop methods for fabricating transparent yet conductive enough as well as flexible nanotube network thin films on polymeric substrates. The ultimate goal was to develop nanotube mats with performance similar to that of non-flexible, conductive metal oxides, like ITO. It became clear in the course of the project, that direct dry deposition of nanotube mat would offer the best properties with very little effort. Thus this is the method that was selected for mat deposition.

During the first project year, NSC GPI focused on developing methods to purify nanotubes and disperse them into a solvent by separating tubes with surfactant via ultrasonic treatment. They developed stable solutions of SWCNTs using several surfactants (Figure 9), and demonstrated the efficient dispersion via UV-VIS analyses. AALTO deposited nanotube mats via filtering from the gas phase, and studied their conductivity as well as transparency.

During the second project year, AALTO successfully deposited nanotube mats via filtering from the gas phase, and studied their conductivity as well as transparency. The results up to now showed that nanotube bundle length as well as the bundle diameter are the most important parameters to be controlled for depositing highly conductive, yet transparent networks on the flexible polymer substrates, regardless of the semiconducting/metallic nature of the nanotubes themselves due to the domination of the electrical performance by bundle-bundle contacts.

In the third period of the project, AALTO studied the optical and electrical performance of nitrogen-doped single-walled carbon nanotube films, measured in terms of optical transmittance and sheet resistance. The analysis shows the nitrogen-doped films have a significantly increased sheet resistance (Figure 10), and that this effect is likely due to an increase in the intrabundle resistances. A possible cause is the increased backscattering of charge carriers by defect sites in the nanotubes. Thus it seems nitrogen doping does not offer the anticipated enhancement of optoelectronic performance for transparent, conducting nanotube mats. However, undoped dry-deposited CNT mats do outperform the traditional i.e. ITO films on polymer in terms of their flexibility, and are on par in terms of their conductivity vs. transmittance properties (Figure 11). Thus the original project goal was achieved.

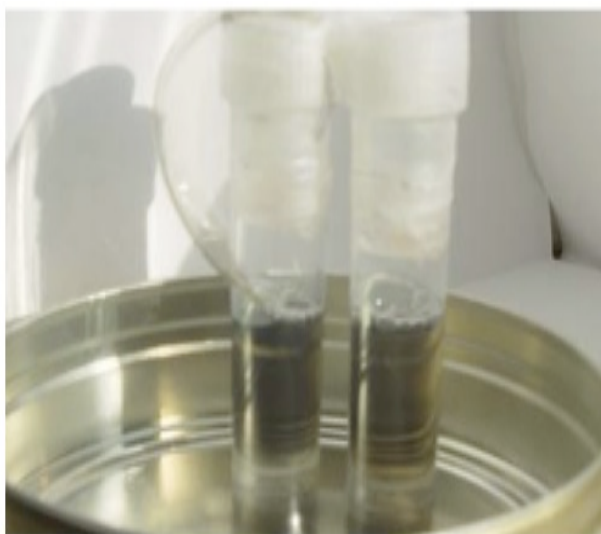


Fig. 9: Solutions of individual single-wall carbon nanotubes separated from the upper fraction of suspensions after ultrasonication and ultracentrifugation.

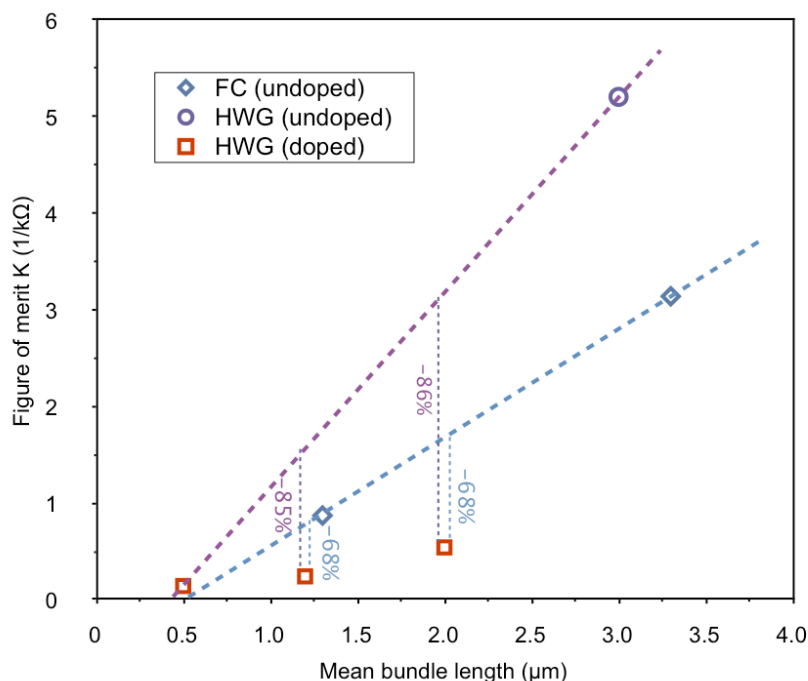
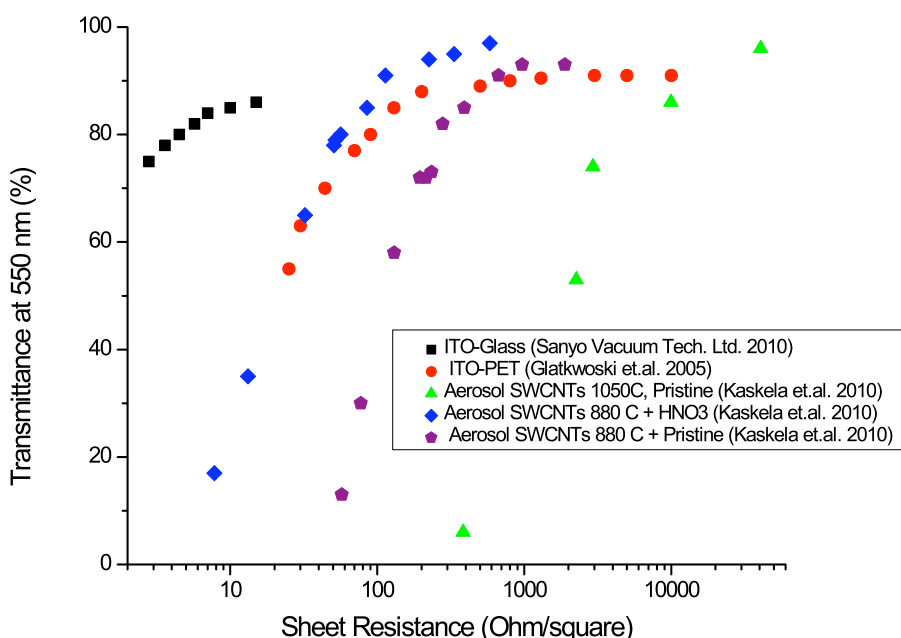


Fig. 10: Optoelectronic performance figure of merit K versus average bundle length for undoped films from the ferrocene² (blue diamonds) and HWG⁷ (purple circle) reactors and nitrogen-doped films from the HWG (red squares). The purple thick dotted line is a linear fit to the undoped and 300 ppm NH_3 doped HWG sample, while the blue thick dotted line is a linear fit to the undoped ferrocene samples. The vertical dotted lines represent the deficits of the figures of merit of the doped films compared to the ferrocene data (blue) and the undoped HWG data (purple).



1.5. Summary

During the project we produced and characterised all B-, N- and BN- doped, single- and multi-walled carbon nanotube samples described in Table 3.

The sample purity, nanotube structure, defect density and dopant concentration were characterised using state of the art characterisation methods including transmission electron microscopy, scanning electron microscopy, Raman spectroscopy, electron energy loss spectroscopy, X-ray photoelectron spectroscopy, optical absorption spectroscopy, combined STM–Raman studies, *in-situ* TEM/STM conductivity measurements and field emission measurements.

We optimised the nanotube production, investigated the synthesis parameters - nanotube properties relationship and demonstrated control over the nanotube properties. We were able to tune the dopant concentration, structure, diameter, chirality, length, defect concentration, oxidation resistance, optical absorption and electric conductivity of the nanotubes.

This work opens the way to produce nanotubes with well-defined properties at large scale. These results also highlight the advantages and disadvantages of different synthesis methods, the possibilities and limitations of the doping.

2. Dissemination and use

The dissemination plan of this project uses three different routes for promoting the project mission as well as the divulgation of the results obtained. These routes are grouped as follows:

- Electronic Dissemination
- Networked Dissemination
- Non-Electronic Dissemination

Electronic Dissemination

A dedicated project website has been located online under the following site:

<http://tfy.tkk.fi/nanomat/bnctubes>

This website describes in detail the BNC Tubes project as European Specific Targeted Research Project. In order to promote attentiveness from a general interested audience, the public missions and goals have been described extensively.

The information of the coordinator and the consortium members has been displayed as follows:

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The name of the corresponding entities, as well as the e-mail addresses of the responsible partners have been automatically linked to their respective websites. This allows to openly show the general audience the individual expertise of the worldwide known leading experts on the field.

Networked Dissemination

This is permanently being done via international, national and regional networks of partners within the consortium.

For instance, University of UOXF.DJ has been working on the characterization of their N-doped samples within the collaboration of the project partners but also with external collaborations to widen the understanding of the synthesized materials. With this a link between two STREPS has been established, with the project dedicated to Nano2Hybrids. The results have been for profitable benefit of both projects having successfully detected gases with N-CNTs.

The BNC Tubes project has a half of female representativeness. In this context, Women In Nano activities were carried out linking in this way EU wide dissemination of the aims and goals of the project reported here.

There was a good balance of academia and industry interest on the outcome of this project. For instance, some data have been presented in the TEKES Finnish meeting dedicated to industrial researchers having attracted a significant attention of a broad audience.

Arkema has developed a novel fluidized bed CVD synthesis method for N-doped multiwalled CNTs in this project. They are in position to use this technology within their future CNT-based products. Beneq Oy is developing thin coating reactors for e.g. coating of glass, semiconductors and polymers. They are in good position to consider CNT coatings in their future coating business line development.

Academic partners in this project have several industrial collaborators, which can benefit directly from this project results via other projects with the current project partners. E.g. Aalto University is extensively collaborating with Nokia Oy, Toyota and Fortum Oy as well as with Aalto spin-off company Canatu Oy. All of these companies will benefit from the results of this project via doped CNT know-how generated in this project within Aalto University.

The latest outcoming results have been presented – among many others – at the Ninth, Tenth and Eleventh International Conferences on the Science and Application of Nanotubes (NT08, NT09, NT10) with a very significant participation from members of this project. The very comprehensive summaries of the results attracted major attention of the participating audience. This is an outstanding result taking into account that this conference series is the major annual gathering of scientists working in the field. The BNC Tubes project members participated with invited talks as well as poster contributions in all events.

Non-electronic dissemination

The BNC Tubes project is based on a multidisciplinary cooperation. It provides a cost effective way to improve the production of novel heteronanotubes made of BN as well as B or N-doped carbon nanotubes. The non-electronic dissemination is permanently being done through publications in journals, research papers, monographs and presentation in conferences. This targets experts and professionals in the field that so far have given a very encouraging feedback. This has lead to interesting interacting peer review. Proof of this is given in the following up to date lists of activity (first summarized in an overview Table 4).

The results of the project have been published in respected journals, including JACS, Journal of Nanoscience and Nanotechnology, Fullerenes, Nanotubes and Carbon Nanostructures, Nanotubes and Carbon Nanostructures and Physica Status Solidi. See Table 5 for statistics.

The results of the project have been published in peer-reviewed journals. The different partners have been extremely active in international meetings such as including the Nanotube conference series, the MRS Fall Meeting, NanoTeC, IWEPNM, ScanDem, EMC, NTNE, RusNanoTech, ChemOnTubes, and IMM. In total 35 talks and 60 posters have been presented (Table 5).

Table 4: Overview table of activities.

Planned / actual dates	Type	Type of audience	Countries addressed	Partner responsible / involved
PDT*	Conference Talks	Research	Worldwide	All partners
PDT*	Proceedings/ Posters	Research	Worldwide	All partners
PDT*	Publicity in gender conferneces	Research	Worldwide	All partners
PDT*	Exhibitions	Industry	Worldwide	All partners
PDT*	Publications	Research & Industry (semiconductors)	Worldwide	All partners
2007**	Project web-site	General Audience	Worldwide	All partners
PDT*	Books and Review Articles	Research	Worldwide	All partners
From 2008	Direct e-mailing and Networking	Research & Industry	Worldwide	All partners

* PDT: Permanently delivered data during project duration.

** Website is permanently updated upon changes.

Table 5: Dissemination for the entire duration of the project (1.2.2007 – 31.7.2010).

Type	Amount	Co-authored with 2 partners	Co-authored with 3 partners
Publications	47	8	1
Conference Talks (invited)	57 (31)	7 (1)	1
Proceedings / Posters	76	11	1
Books and Review Articles	5		
PhD and MSc theses	4		

Publications in Peer reviewed Journals

Published or accepted

1. Susi, T.; Zhu, Z.; Ruiz-Soria, G.; Arenal, R.; Ayala, P.; Nasibulin, A. G.; Lin, H.; Jiang, H.; Stephan, O.; Pichler, T.; Loiseau, A.; Kauppinen, E. I., "Nitrogen-doped SWCNTs synthesized using ammonia and carbon monoxide". *Phys. Status Solidi B* 247 (2010), DOI: 10.1002/pssb.201000312.
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45. Susi, T.; Zhu, Z.; Tian, Y.; Nasibulin, A. G.; Jiang, H.; Kauppinen, E. I. "TEM verification of optical diameter distribution analysis for nitrogen-doped SWCNT films". *Submitted to Journal of Nanoelectronics and Optoelectronics* (2010).
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47. R. Arenal, M.S.Wang, Z. Xu, A. Loiseau, D. Golberg, "Young Modulus, Mechanical and Electrical Properties of Isolated Individual and Bundled Single-Wall Boron Nitride Nanotubes". *ACS Nano, in press* (2010).

Talks

1. Kauppinen, E. I. (invited). *The Villa Conference on "Interaction Among Nanostructures" (VC-IAN)*, Orlando, FL, USA, 3–7 February 2008.
2. Kauppinen, E. I. (invited). *Particles 2008: Particle Synthesis, Characterization, and Particle-Based Advanced Materials*, Orlando, FL, USA, 10–13 May 2008.
3. Kauppinen, E. I. (invited). *MIICS 2008: Mikkeli International Industrial Coating Symposium*, Mikkeli, Finland, 26–28 March 2008.
4. Kauppinen, E. I. (invited). *LPHYS2008: 17th International Laser Physics Workshop*, Trondheim, Norway, 30 June – 4 July 2008.
5. Kauppinen, E. I. (invited). *NanoteC08: International Conference on carbon nanoscience and nanotechnology*, University of Sussex, Brighton, UK, 27–30 August 2008.
6. Kauppinen, E. I. (invited). *Nanotech Northern Europe (NTNE) 2008*, Copenhagen, Denmark, 23–25 September 2008.
7. Kauppinen, E. I. (invited). *Nanotechnology International Forum*, Moscow, Russia, 3–5 December 2008.
8. Kauppinen, E. I. (invited). *International Powder Technology Forum 2009*, Frankfurt, Germany, 12–13 May 2009.
9. Kauppinen, E. I. (invited). *NT09: Tenth International Conference on the Science and Applications of Nanotubes*, Beijing, China, 21–26 June 2009.
10. Kauppinen, E. I. (invited). *SPIE Optics + Photonics Conference 7399: Carbon Nanotubes, Graphene and Associated Devices II*, San Diego, CA, USA, 2–6 August 2009.
11. Kauppinen, E. I. (invited). *ESF Research Conference: Nanocarbons - From Physicochemical and Biological Properties to Biomedical and Environmental Effects*, Acquafredda di Maratea, Italy, 8–13 September 2009.
12. Kauppinen, E. I. (invited). *Second International Nanotechnology Forum*, Moscow, Russia, 6–8 October 2009.
13. Kauppinen, E. I. (invited). *MIICS 2010. Mikkeli International Industrial Coating Symposium*. Mikkeli, Finland, 17-18 March 2010.
14. Kauppinen, E. I. (invited). *The Second International Workshop on Nanocarbon Photonics and Optoelectronics*, Koli, Finland, 1–6 August 2010.
15. Kauppinen, E. I. (invited). *International Conference on Nanotechnology: Fundamentals and Applications*, Ottawa, Canada, 4–6 August 2010.
16. Kauppinen, E. I. (invited). *2010 International Conference on Solid State Devices and Materials (SSDM 2010)*, The University of Tokyo, Tokyo, Japan, 22–24 September 2010.
17. Kauppinen, E. I. (invited). *A3 Symposium on Emerging Materials 2010: Nanocarbons and Nanowires for Energy*, Chonju, Korea, 7–11 November 2010.
18. Susi, T.; Lanzani, G.; Ayala, P.; Arenal, R.; Kaskela, A.; Tian, Y.; Zhu, Z.; Mali, J.; Nasibulin, A.; Jiang, H.; Jiang, T.; Bligaard, T.; Pichler, T.; Loiseau, A.; Laasonen, K.; Kauppinen, E.I., "Gas phase floating catalyst synthesis, formation mechanism and characterization of nitrogen-doped SWCNT films" (contributed). *International Workshop Nanotube Photonics and Optoelectronics 2010*, Koli, Finland, 2–6 August 2010.
19. S. Riikonen et al., "Computational study of BNNT catalytic synthesis" (contributed). *Workshop on Inorganic Nanotubes*, San Sebastián, Spain, 2–4 September 2009.
20. S. Riikonen, A.S. Foster, A. V. Krashennnikov, and R.M. Nieminen, "Role of nanoparticle facets in carbon nanotube synthesis" (contributed). *First Japanese-Finnish workshop on carbon and boron-nitride nanostructures 2010*, Helsinki, Finland and Stockholm, Sweden 18–20 May 2010.
21. Annick Loiseau, Michèle Cau, Marie-Faith Fiawoo, Nelly Dorval, Jean-Lou Cochon, Anne-Marie Bonnot, Brigitte Attal-Tretout, "Understanding the formation of C-SWNTs via in situ and ex situ diagnostics in laser vaporization and CVD techniques" (invited). *IWEPNM 2008*, Kirchberg, Austria, 1–8 March 2008.
22. R.Arenal. *MRS 07: Mat. Res. Soc., II symposium*, Boston, USA, 25–30 November 2007.

23. R. Arenal. *Diamond 08, 19th European Conference on Diamond*, Sitges, Spain, 7–11 September 2008.
24. A. Loiseau, P. Jaffrennou, J. Barjon, J.-S. Lauret, B. Attal-Trétout, F. Ducastelle, “Optical properties of individual boron nitride nanotubes” (invited). *TNT09 New trends in Nanotechnology*, Barcelona, Spain, 7–11 September 2009.
25. A. Loiseau, R. Fleurier, “Transmission Electron Microscopy : a tool for the direct determination of carbon nanotube structure” (invited). *ICAM09, 11th International Conference on Advanced Materials*, Rio de Janeiro, Brasil, 20–25 September 2009.
26. J. Lagoute, H. Lin, V. Repain, C. Chacon, Y. Girard, F. Ducastelle, A. Loiseau and S. Rousset, “Wavefunctions and many-body effects in CNTs measured by STM” (invited). *MRS Fall meeting, symposium K*, Boston, USA, 29 November – 4 December 2009.
27. F. Ducastelle, H. Lin, J. Lagoute, P. Jaffrennou, S. Maine, B. Attal-Trétout and A. Loiseau, “Band gaps in Carbon and Boron Nitride Nanotubes” (invited). *MRS Fall meeting, symposium K*, Boston, USA, 29 November – 4 December 2009.
28. R. Arenal, H. Lin, J. Lagoute, O. Stephan, S. Rousset, A. Loiseau, “EELS and STM/STS measurements on nitrogen doped single-walled nanotubes: towards knowledge of nitrogen atomic configuration in the C network” (contributed). *MRS 09 Spring meeting*, San Francisco, USA, 13–17 April 2009.
29. R. Arenal; H. Lin; J. Lagoute; T. Susi; O. Stephan; S. Rousset; P. Ayala; E. Kauppinen; A. Loiseau, “Studies of nitrogen atomic configuration on nitrogen doped single-walled nanotubes via EELS and STM/STS measurements” (contributed). *Carbon 09, Annual World conference on carbon*, Biarritz, France, 14–19 June 2009.
30. R. Arenal, H. Lin, O. Stephan, A. Loiseau, “Etude de la configuration atomique de l’azote dans les nanotubes monoparoi dopés (CN_x-SWNTs) via ELNES” (contributed). *SFMu ‘09*, Paris, France, 22–26 June 2009.
31. H. Lin, J. Lagoute, C. Chacon, R. Arenal, O. Stéphan, V. Repain, S. Enouz, S. Rousset and A. Loiseau, “Combined STM/STS and TEM/EELS investigation of CN_x –SWNTs” (contributed). *NT09*, Beijing, China, 19–26 June 2009.
32. H. Lin, J. Lagoute, C. Chacon, R. Arenal, O. Stéphan, V. Repain, S. Enouz, S. Rousset and A. Loiseau, “STM/STS investigation of C-SWNT and CN_x –SWNTs” (contributed). *GNT09, Annual meeting of the GDRI GNT*, Coma-Ruga, Spain, 19–23 October 2009.
33. R. Fleurier, J.-S. Lauret, E. Flahaut, A. Loiseau, “Electron Microscopy study of sorted carbon nanotubes” (contributed). *GNT09*, Coma-Ruga, Spain, 19–23 October 2009.
34. J. Lagoute, H. Lin, V. Repain, C. Chacon, Y. Girard, F. Ducastelle, A. Loiseau and S. Rousset, “Scanning tunneling microscopy and spectroscopy of single wall carbon nanotubes” (invited). *APS march meeting 2010*, Portland, USA, 15–19 March 2010.
35. V. Repain, H. Lin, J. Lagoute, C. Chacon, Y. Girard, F. Ducastelle, A. Loiseau and S. Rousset, “Spectroscopie tunnel des nanotubes de carbone : gap électronique et fonctions d’onde” (contributed). *Forum 2010 microscopies à sondes locales*, Mittelwihr, France, 15–19 March 2010.
36. R. Arenal, “Single-walled boron nitride nanotubes: synthesis, structure and properties” (invited). *JSO ONERA 2010: a nanoworld of tubes*, Chatillon, France, 8–9 April 2010.
37. R. Arenal, “Transmission electron microscopy: a key technique in nanoscience” (invited). *Ist international nanotechnology congress*, Quito, Equator, 7–11 June 2010.
38. Hong Lin, Jérôme Lagoute, Raul Arenal, Vincent Repain, Toma Susi, Esko Kauppinen, Sylvie Rousset, A. Loiseau, “N-doped C single wall nanotubes : a combined STM-TEM investigation” (contributed). *NT10*, Montréal, Canada, 25 June – 2 July 2010.
39. H. Lin, J. Lagoute, V. Repain, F. Ducastelle, H. Amara, L. Henrard, J.S. Lauret, S. Rousset, A. Loiseau, “Wave functions imaging and many-body effects in single-walled carbon nanotubes measured by STS” (invited). *E-MRS*, Strasbourg (France), 1–8 June 2010.
40. Hong Lin, Jérôme Lagoute, Raul Arenal, Vincent Repain, Toma Susi, Esko Kauppinen, Sylvie Rousset, A. Loiseau, “Electronic properties in C and CN_x single wall nanotubes : a combined STM-TEM approach” (invited). *NPO2010*, Koli, Finland, 1–6 August 2010.
41. S. Rousset, H. Lin, J. Lagoute, V. Repain, C. Chacon, Y. Girard, J.-S. Lauret, F. Ducastelle, H. Amara, A. Loiseau, L. Henrard, S. Rousset, “Wave functions imaging and many-body effects in single-walled

carbon nanotubes measured by STS” (invited). *International Conference on Nanoscience and Nanotechnology*, Beijing, China, 23–27 August 2010.

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43. Antal Koós, Michael Dowling and Nicole Grobert*, “Nitrogen-doped Carbon Nanotubes: From synthesis to applications” (invited). *NT08*, Montpellier, France, June 29 – July 4, 2008.
44. Nicole Grobert, “Nitrogen-doped Carbon Nanotubes: A Case Study” (invited). *INM Mittwochs-Kolloquium*, Leibniz Institute for New Materials, Saarbrücken, Germany, 07 May 2008.
45. Nicole Grobert, “Carbon Nanotubes: Controlling structure properties relationships through N-doping” (invited). *IFW Seminar*, Leibniz Institute for Solid State Research, Dresden, Germany, 17 July 2008.
46. Antal A. Koós, Alison Crossley, Ekaterina A. Obraztsova, Mhairi Gass, Michael Dowling, Nicole Grobert, “Effect of the experimental parameters on the structure properties relationship of nitrogen- and boron-doped carbon nanotubes” (contributed). *NanoteC08*, University of Sussex, Brighton, U.K. 27–30 August 2008.
47. Nicole Grobert, “Production of pure and doped CNTs at Oxford Materials” (invited). *Bayer Technologies*, Leverkusen, Germany, 8 June 2009.
48. Zabeada Aslam, Rebecca Nicholls, Valeria Nicolosi and Nicole Grobert, “Electronic property investigations of graphene flakes” (contributed). *NanoteC09*, Brussels, Belgium, 26–29 August 2009.
49. Geoffrey Otieno, Antal Koos, Frank Dillon, Claire Dancer, Gareth Hughes, Nicole Grobert, Richard I. Todd, “Dense aligned multi-walled carbon nanotube/aluminoborosilicate glass composite by solgel processing and hot pressing” (contributed). *NanoteC10*, Oxford, UK, 1–4 September 2010
50. Nicole Grobert, Antal Koos, Irene Suarez-Martinez, Frank Dillon, Zabeada Aslam, Geoffrey Otieno, Andrew Searle, Jingyu Sun, Adrian Murdock, Fatma Dinc, Madhuri Dutta, Sarah Downes, Teodor-Matei Cirstea, Christopher P Ewels and Alison Crossley, “Carbon nanomaterials, a show-case for standardised characterization” (invited). *NT10*, Montréal, Canada, 27 June – 2 July, 2010.
51. Antal A. Koós, Frank Dillon, Zabeada Aslam, Alison Crossley, Nicole Grobert “Tuning the structure and properties of carbon nanotubes” (invited). *MRS Fall Meeting*, Boston, USA, 29 November – 3 December 2010.
52. L. Henrard, V. Meunier, S. Latil, A. Debarre, M. Kobylko, A. M. Bonnot, A. Richard, V. N. Popov and M. Kociak, “Few Layer Graphite and interacting carbon nanotubes. Electronic and vibrational properties” (invited). *CCTN08 "Computational Challenges and Tools for nanotubes"*, Montpellier, France, 28 June 2008.
53. L. Henrard, P. Hermet, V. Meunier, S. Latil, “Playing with electronic properties of graphene” (contributed). *11ième journées de la matière condensée (JMC11)*. Strasbourg, France, 25–29 August 2008.
54. P. Hermet, B. Amadon, and F. Jollet, “Modern theory of polarization within the Projected Augmented Wave method” (contributed). *4th International ABINIT Developer Workshop*, Autrans, France 24–27 March 2009.
55. G. Lanzani and K. Laasonen, “NH₃ adsorption and dissociation on a nanosized iron cluster” (contributed), *Fifth International Symposium on Computational Challenges and Tools for Nanotubes (CCTN09)*, Tsinghua University (Beijing, China), 20 June 2009.
56. G. Lanzani, T. Susi, A.G. Nasibulin, T. Jiang, T. Bligaard, K. Laasonen, E.I. Kauppinen, “Mechanism study of aerosol CVD synthesis for N-doped SWCNTs” (contributed). *Towards Reality in Nanoscale Materials 2009*, Levi, Finland, 7–9 December 2009.
57. G. Lanzani and K. Laasonen, “Mechanism study of NH₃ adsorption and dissociation on a nano-sized iron cluster” (invited). *Sky-pro Conference*, Oulu, Finland, 3 June 2010.

Conference participations and proceedings

1. T. Susi, P. Ayala, A.G. Nasibulin, R. Arenal, H. Lin, C. Roquelet, D. Garrot, J.S. Lauret, A. Loiseau, E.I. Kauppinen, "Aerosol CVD synthesis of N-doped SWCNTs". *International Winterschool on Electronic Properties of Novel Materials (IWEPNM 2009)*, Kirchberg, Austria, 07–14 March 2009.
2. T. Susi, P. Ayala, A.G. Nasibulin, V. Valtavirta, R. Arenal, H. Lin, C. Roquelet, D. Garrot, J.S. Lauret, A. Loiseau, E.I. Kauppinen, "N-doped SWCNT film synthesis using vertical flow aerosol reactor". *10th International Conference on the Science and Application of Nanotubes (NT'09)*, Beijing, China, 21–28 June 2009.
3. T. Susi, A.G. Nasibulin, P. Ayala, Y. Tian, Z. Zhu, R. Arenal, C. Roquelet, D. Garrot, J.S. Lauret, A. Loiseau, E. I. Kauppinen, "Aerosol CVD synthesis of N-doped SWCNTs". *GDR09 Meeting Nanotube and Graphene: Science and Application*, Coma-Ruga, Spain, 19–23 October 2009.
4. T. Susi, G. Lanzani, P. Ayala, A.G. Nasibulin, H. Maoshuai, K. Laasonen, E. I. Kauppinen, "Synthesis of nitrogen-doped SWCNTs - towards understanding through combined experiments and simulation". *Towards Reality in Nanoscale Materials (TRNM 2009)*, Levi, Finland, 07–09 December 2009.
5. T. Susi, P. Ayala, A.G. Nasibulin, R. Arenal, H. Lin, J. Lagoute, D. Sun, Y. Ohno, M. Zavodchikova, C. Roquelet, J-S. Lauret, A. Loiseau, E.I. Kauppinen, "Synthesis, characterization and applications of N-doped SWCNT films". *International Winterschool on Electronic Properties of Novel Materials (IWEPNM 2010)*, Kirchberg, Austria, 06–13 March 2010.
6. T. Susi, P. Ayala, A.G. Nasibulin, R. Arenal, H. Lin, J. Lagoute, D. Sun, Y. Ohno, M. Zavodchikova, C. Roquelet, J-S. Lauret, A. Loiseau, E.I. Kauppinen, "Gas phase floating catalyst synthesis, characterization and applications of nitrogen-doped SWCNT films". *11th International Conference on the Science and Application of Nanotubes (NT'10)*, Montreal, Canada, 28 June – 7 July 2010.
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