Project no. FP6-003673

CANEL

Carbon-based nanoelectromechanical devices

Instrument: STREP

Thematic Priority: IST

Final activity report

Period covered: From 1 June 2004 to May 31 2007

Date of preparation: 10 July 2007

Start date of project. 1 June 2004

Duration: 36 months

Project coordinator name: Mats Jonson
Project coordinator organisation name: Chalmers

Revision: 1

1 Project Execution

Objectives

The overall objective of the CANEL project was to fabricate, analyse and optimise carbon-based nanoelectromechanical (NEMS) devices and to integrate them with silicon technology. With respect to applications the focus has been on information technology devices such as nanoelectromechanical switches and memory elements.

Several types of carbon-based structures – containing carbon nanotubes (CNTs), fullerenes, or peapods – where the mechanical degrees of freedom are connected to electrical functionality of the device have been studied. Since all the proposed devices are fundamentally new, they posed both experimental and theoretical challenges. Our objective was to develop theoretical models for nanoelectromechanical devices, and to use these models to optimise device geometries and to analyse device behaviour. We studied the interplay of physical processes in individual devices, (*e.g.*, single electron charging effects in mechanically soft structures), device sensitivity to external perturbations, (*e.g.*, switching characteristics), and novel applications.

An important feature of our project was the integration of silicon and carbon technologies. Silicon is the material of choice for most electronics, and any new technology that is suggested as an extension to silicon devices must be compatible with silicon both in terms of circuit design and fabrication process. Here our objective was to develop up-scalable growth techniques that are compatible with silicon device processes.

Organisation

The project has been organised in four scientific (WP1-WP4) and one administrative (WP5) workpackage and involves four partners, Partners 1-4: Chalmers University of Technology (Chalmers, coordinator), Göteborg University, TU Delft and Copenhagen University. Professor Mats Jonson (mats.jonson@chalmers.se) has been the coordinator, while professor Jari Kinaret (jari.kinaret@chalmers.se) has been the assistant coordinator.

The goal of WP1 has been to fabricate and characterize carbon nanotube-based nanorelays and nanoelectromechanical single-electron transistors (NEM-SETs) and to study their behavior theoretically. WP2 has dealt with the fabrication and modelling of fullerene-based nanoelectromechanical devices. Its objective was to fabricate and analyse two- and three-terminal geometries on the prototype level, and to develop approaches that allow for the integration of fullerene-based NEMS into silicon technology. The objective of WP3 was to investigate and exploit the NEMS prospects for peapod based devices – peapods are nanotubes filled with fullerene molecules such as C_{60} – where the fullerenes constitutes the mechanically active element. The objective of WP4 was to develop techniques for integrating carbon-based NEMS devices with silicon device technology.

Work performed and results

Experiments towards carbon nanorelays

During the first year Partner 2 (E. Campbell et al.) succeeded in fabricating prototype nanorelay structures using plasma-enhanced CVD grown nanotubes [S.W. Lee et al., Nano Lett. **4**, 2027-2030 (2004)] and by controlled deposition of carbon nanotubes by ac-dielectrophoresis. All tested suspended nanotubes showed a source-drain current dependence on gate voltage that can be interpreted in terms of the expected relay behaviour. Some nanotubes too short to make physical contact with the drain were made. These devices were operated with a higher source-drain voltage in order to have field emission of electrons at the tip. An example is shown in Fig. 1.

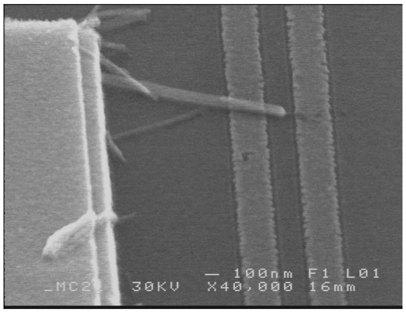


FIG. 1: ”Non-contact” mode operation of a prototype nanorelay.

During the second year Partner 2 (Eleanor Campbell *et al.*) focussed on designing substrates that would allow the high frequency operation of the relay to be tested. The most suitable geometry was identified and the first test structures produced. The status of the dc characterisation of the prototype relay structures was detailed in the deliverable D2 and also in the publication by Axelsson *et al*., New J. Physics **7**, 245 (2005). Work on the high frequency characterization of the nanarelay started but will not be completed before this project ends.

Work also progressed in developing up-scalable methods for growing carbon nanotube NEMS structures on a chip. The CVD growth of SWNT using either gas flow or electric field alignment is now routine. The emphasis has therefore moved to developing techniques by which single and multiwalled nanotubes can be grown on silicon chips at temperatures that will not destroy CMOS components. A novel technique has been developed by which only local heating at the catalyst takes place, leaving the rest of the chip at a temperature significantly below 100 ^{o}C. A report has since been published in Dittmer *et al*. Appl. Phys. A **84**, 243-246 (2006).

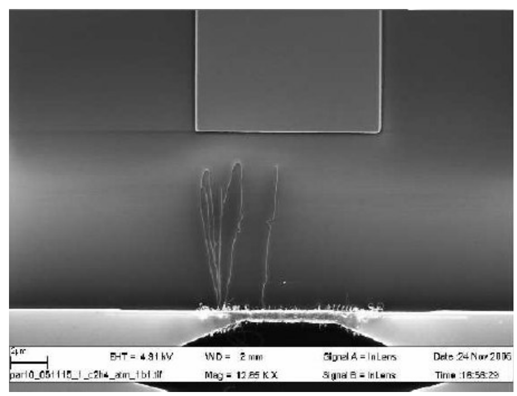


FIG. 2: ”SWNT grown at low ambient temperature in the presence of an aligning electric field. Electrode designs for low temperature nanotube growth was used.

The third and final year Partner 2 continued work on their local heating technique, which allows the growth of good quality single- and multiwalled carbon nanotubes while keeping the overall chip temperature below 100 ^{o}C. This is the preferred direct growth technique for fabricating multiple horizontal geometry NEMS devices on chip. The method is based on resistively heating a small metallic bridge on top of which CNT growth catalyst is patterned.

Using ethylene feedstock it is possible to grow SWNT. These are predominantly semiconducting in nature as determined by Raman spectroscopy. This is a suitable technique to grow multiple CNT-SET devices on chip. For practical NEMS devices it may be necessary to work with arrays of nanotubes. An example of an array grown between two electrodes, using the local heating technique is shown in Fig. 3(a). Fig. 3(b) shows a similar array, but with a larger spacing between the individual nanotubes grown across a trench with a gate structure. The NEMS behaviour of such arrays has still to be determined.

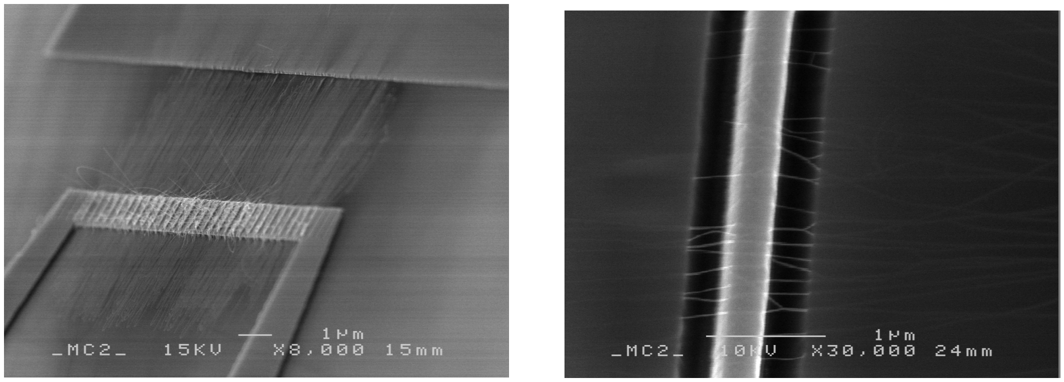


FIG. 3: (a) array of SWNT grown with the local heating technique between two metal electro-des; (b) a similar array of SWNT grown across a trench with a gate structure.

Theory of nanorelays

The theoretical analysis of carbon-nanotube-based structures at Partner 1 (J. Kinaret et al.) focused on the AC behavior of nanorelays during the first year. Clear electromechanical resonances were found. The resonances are tunable by a DC gate bias, and the resonance frequencies can typically be varied over several GHz by changing the gate bias by one volt [L.M. Jonsson et al., Nanotechnology **15**, 1497 (2005)]. We have investigated the potential for applications, and to this end contacted several industrial partners. The response has been quite positive.

During the second year the theoretical analysis by Partner 1 (Jari Kinaret *et al.*) revealed that treating a non-contact-mode nanorelay as a field emission device is not very informative. Instead one has to apply a more complete description of the tunneling between tube tip and drain electrode [S. Axelsson *et al*., New J. Phys. 7, 245 (2005)]. In another piece of work the performance of ordinary stationary electronic switches was found to be enhanced by incorporating mechanical motion, in particular the subthreshold slope – a measure of how rapidly the leakage current decreases as the switch is turned to the nominally OFF position [K.E. Engström and J.M. Kinaret, IEEE Electron Device Letters **27**, 988-991 (2006)].

Possibilities for detecting quantum aspects of the mechanical motion of nanorelays and NEM-SETs was also considered. Below a few mK coherent Rabi oscillations between two mechanical configurations of the nanorelay were predicted. The NEM-SET structure considered is a doubly clamped double-walled nanotube where the central part of the outer tube is pealed off. The exposed inner tube can the rotate freely inside the stubs of the outer wall, it should be possible to detect the quantization of its rotational.

No resources were devoted to the theoretical studies of nanorelays during the third reporting period. The theoretical studies on both the nanorelay and NEM-SET structures during the entire project are summarised in the deliverable D3.

Experiments towards NEM-SET devices

NEM-SET devices are routinely made by Partner 3 (H.S.J. van der Zant et al.), with free hanging SWNTs of lengths between 100 and 1200 nm. At low temperatures the suspended nanotubes form one-dimensional quantum dots of high quality. Experimental results from the first year permit the complete identification of the electron quantum states. At low energies, additional harmonic excitations occur due vibration-assisted tunneling. The energy scale and the length dependence are consistent with that of longitudinal modes in the nanotube. The current-voltage characteristics show multiple steps whose step heights are in agreement with the predictions of Franck-Condon physics (see Fig. 4). The exact mechanism behind the rather strong coupling is still unclear.

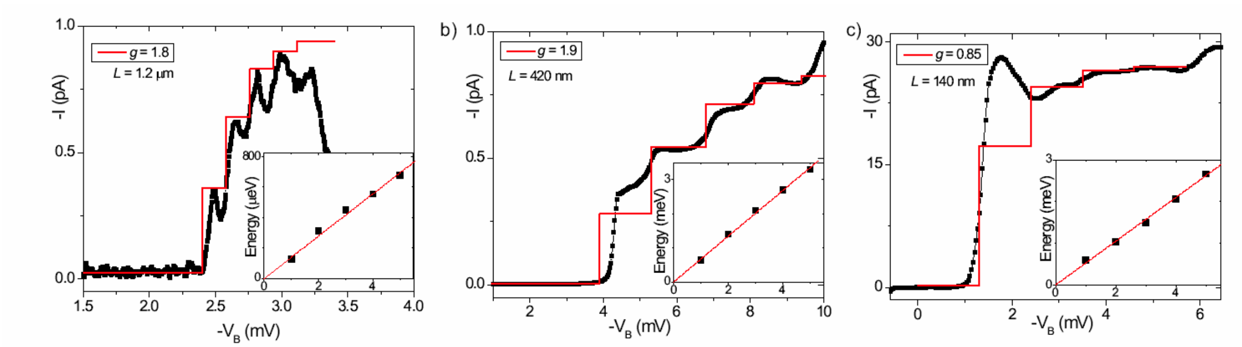


FIG 4: Current-voltage characteristics showing steps due to vibration assisted tunneling. The red lines are fits to the Franck-Condon theory.

During the second year Partner 3 (Herre van der Zant) finished a study on phonon-assisted tunneling by longitudinal stretching modes in suspended nanotubes publishing two papers on the subject. Partner 3 also devoted a lot of effort to building up new experimental set-ups. Their dilution refrigerator became operational was tested at 18 mK; low temperatures are needed for a further characterization of NEM-SETs. RF lines in the cryostat were set up, unfortunately delayed by long delivery times. The low-temperature probe station was modified so that high-frequency measurements could be performed. The measurements are demanding and quite a few months were spent to optimize the set-up. Nevertheless, the bending mode in three different devices, could be measured, including their gate dependence. A model was developed to describe the response of suspended nanotubes as a function of gate voltage (which induces tension) and the amplitude of the ac signal. Analysis of the data and comparison with this model got underway.

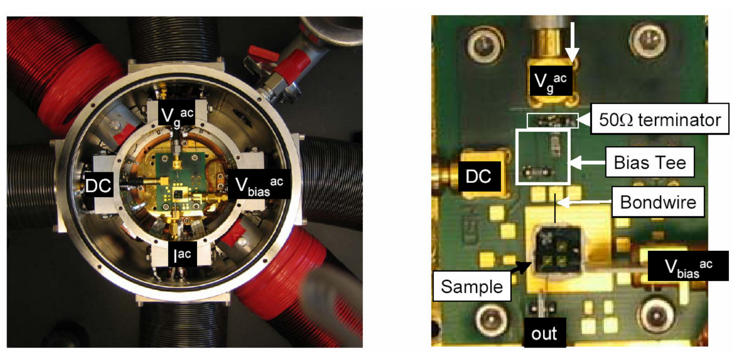


FIG. 5: Left panel: Overview of the sample space in the low-temperature probe station set-up. Right panel: zoom in of the circuit board containing a sample with several suspended nanotubes. The circuit board is used to minimize reflections of the applied RF signals.

During the third year Partner 3 (Herre van der Zant and collaborators) concentrated on characterising the bending-mode vibration in suspended nanotubes, following three different approaches (A-C).

A. Suspended double quantum dot (DQD) devices. The idea here is to enhance the energy resolution for spectroscopy of the vibronic modes. DQD characteristics have clearly been observed in transport measurements at low temperature including possibly the presence of vibrational modes. However, demanding fabrication has hindered this part of the research. Even so, many issues have been resolved and new samples are ready to be measured.

B. Short suspended nanotube quantum dot devices. By using a dilution refrigerator, phonon-assisted tunneling should allow for the observation of the bending modes if L <70 nm. Several devices with a suspension length of about 100 nm have been measured before and after suspension. A common feature in five single-dot devices is that the free hanging nanotube devices show non-closing diamond structures at the lowest temperatures (see Fig. ES-2); for the same devices before suspending them, the diamonds do close indicating that this feature is associated with mechanical motion of the free hanging nanotubes. The suppression of current for any gate voltage is a sign of strong electron-phonon coupling resulting in an effect that is called phonon blockade. (This effect has intensively been studied theoretically but only Kotthaus group in Munich has reported on it in their suspended semiconducting quantum dot structures; for nanotubes this effect has not been reported previously). Our data gives a phonon gap of about 0.2 meV, which indicates a normalised electron-phonon coupling strength (g) of 3-5.

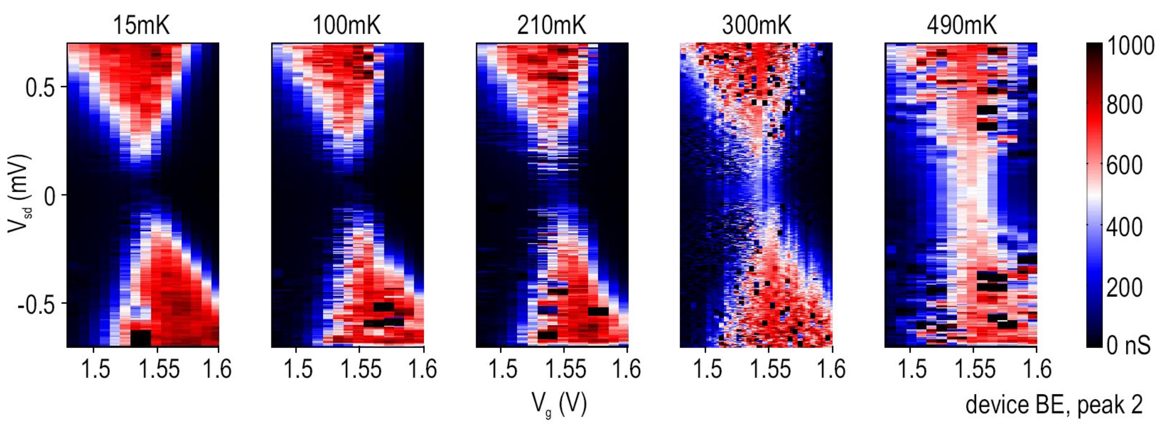


FIG. 6: Five conductance maps of a suspended carbon nanotube quantum dots (100 nm long). The data at the lowest temperatures (left hand side) show a suppression of the current around zero-bias indicative of a phonon blockade and a strong electron-phonon coupling. A temperature of about 400 mK lifts the blockade and induces switch events in the current-voltage characteristics.

C. High-frequency resonators of nanotube strings. Here Partner 3 has used a suspended carbon nanotube as a frequency mixer to detect its own mechanical motion. A continuum model is used to fit the gate-dependence of the resonance frequency, from which values for the ground-frequency and for both the gate-induced and residual tension in the nanotube are otained. This analysis shows that by applying a gate voltage, the nanotube can be tuned from a regime without strain to a regime where it behaves as a vibrating string under tension.

Theory of NEM-SET devices

Partner 3 started by investigating the influence of mechanical motion of suspended carbon nanotubes on their transport properties in the single-electron tunneling (SET) regime for weak coupling between electrons and vibrations of the nanotube [Ya. M. Blanter, Phys. Rev. Lett. **93**, 136802 (2004); **94**, 049904(E) (2005)]. For this purpose, the nanotube is modeled as a single-electron tunneling device weakly coupled to a single-mode harmonic oscillator. In the underdamped regime, the oscillator can develop large-amplitude oscillations due to a feedback mechanism provided by the position dependence of the energy differences required for electron tunneling.

During the second year Partner 3 (Yaroslav Blanter *et al.*) finished an investigation of current and noise in a single-electron transistor (SET) coupled to a linear single-mode oscillator. Analytical estimates as well as numerical results are obtained. Calculations indicate a strong enhancement of the current noise even in the regime where strong mechanical feedback is absent.

Partner 2 (Robert Shekhter) and Partner 1 (Mats Jonson, Leonid Gorelik) proposed an alternative method to sense ultrasmall quantum vibrations of a suspended carbon nanotube by means of measuring its magnetoresistance which has now been published [R.I. Shekhter *et al.*: *Electronic Aharanov-Bohm effect induced by quantum vibrations*, Phys. Rev. Lett. **97**, 156801 (2006)].

Partner 3 (Yarorslav Blanter *et al.*) was during the third year able to demonstrate the feasibility of a strong feedback regime for a single-electron tunneling device weakly coupled to an underdamped single-mode oscillator. In this regime, mechanical oscillations are generated and the current is strongly modified, whereas the current noise is parametrically large with respect to the Poisson value. [O. Usmani *et al.*, Phys. Rev. B **75**, 195312 (2007)].

Partner 2 (Robert Shekhter) and Partner 1 (Mats Jonson, Leonid Gorelik) has modelled nanoelectromechanical vibrations in extended SET structures, in particular a CNT-based NEM-SET. Various bending modes of the suspended carbon nanotube may be unstable with respect to small displacements of the tube caused by electrically probing its suspended part by an STM-tip. If several modes become unstable quasi-random mechanical vibrations are first generated. But as the many-mode shuttle instability develops into a stationary regime of mechanical vibrations, it turns out that the quasi-random oscillations self-organise into periodic oscillations with a frequency that corresponds to only one of the unstable modes.

Experiments towards fullerene-based devices

Partner 1 (S. Kubatkin et al.) during the first year of the project refined its methods for nanogap fabrication and demonstrated controllable variation of nanogap widths of order 1nm. Six devices with fullerenes (C_{60}-molecules) trapped between metallic (gold) nanogaps were studied. The main observations are the following (see Fig. 7). *(i)* None of the six devices showed any effects of Coulomb blockade of tunneling at low bias voltages. *(ii)* Features spaced 5-6 mV apart appear in the differential conductance. These are similar to those that have previously been attributed to fullerene motion manifested in the form of inelastic electron tunneling. *(iii)* The dynamical resistance of the devices changes at some characteristic voltage V_c. Most of the devices had a negative differential resistance in this region. *(iv)* The critical voltage V_c increases with increasing temperature; this temperature dependence is of a universal character as illustrated in Fig. ES-3. *(v)* At low temperatures the devices show hysteresis. This indicates a nanomechanical origin of the observed effects.

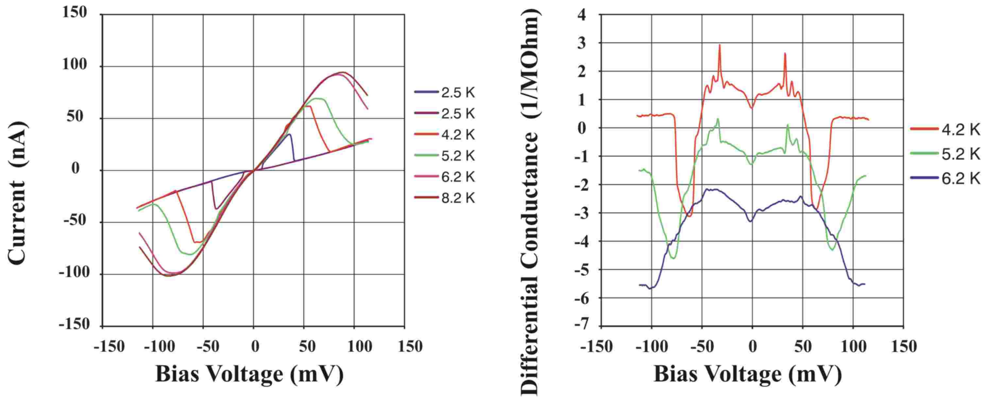


FIG. 7: Temperature dependence of the current (left) and the differential conductance (right) of one sample containing a C_{60}–molecule trapped in a nanogap.

Because of the strong coupling between C_{60} and Au, Partner 1 (Sergey Kubatkin *et al.)* did not find not it possible to fabricate a single-electron transistor (SET) based on a C_{60} molecule trapped in a nanogap between Au electrodes, although they achieved mechanical switching. The experimental data could be explained by assuming that C_{60} on gold has two conformations with different conductance. Although this phenomenological approach works well, the microscopic origin of the two conformations is not yet clear.

Partner 1, during the second year, also studied electron transport through single-molecular devices where the active C_{60} center was substituted by conjugated molecules provided by Partner 4 (Thomas Bjørnholm). The wide choice of end groups that can be used to terminate these molecules allowed the coupling strength between the molecule and the metallic leads to be controlled. For the weak coupling provided by the presence of a CH_2 group in the molecular structure SET behavior was found. On the other hand single-electron effects were suppressed in strongly coupled devices, resembling the behavior found in C_{60} on gold (manuscript in preparation).

A search for bistable behavior in devices based on strongly coupled conjugated molecules revealed two types of distinct switching behaviour, one of them could be shown to have a nanomechanical origin, see Fig. 8.

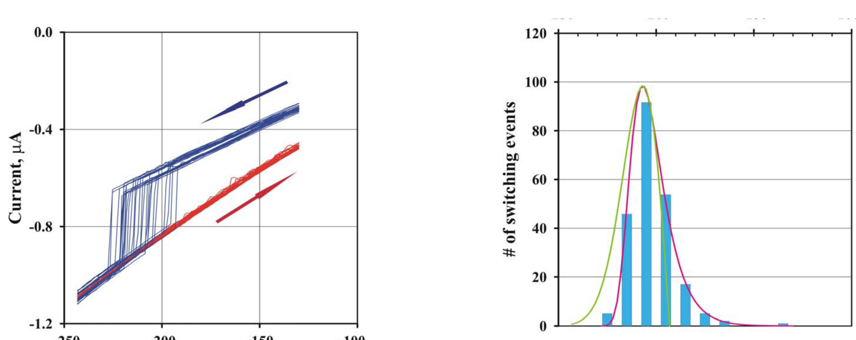
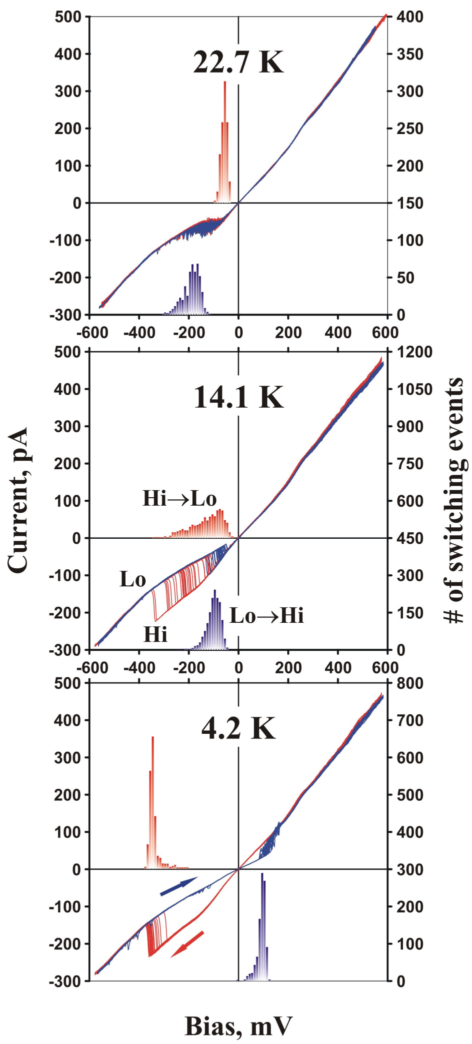


FIG 8: Current switching of nanomechanical origin (left panel). A statistical analysis of the switching events (right panel) was performed. A statistical analysis (right panel) different switching mechanisms to be ruled out: the green curve calculated for an alternative model of switching obviously fails to reproduce the switching histogram.

As mentioned, the first devices of Partner 1 (Sergey Kubatkin and collaborators) containing a C_{60} molecule placed between two gold electrodes demonstrated bi-stable behavior involving two states with clearly different conductances. However, switching was only observed at low temperatures. Similar devices with the C_{60} molecule placed between silver rather than gold electrodes was therefore prepared during the third year in order to enhance the molecule-metal interactions and, hopefully, increase the operation temperatures of the bi-stable devices. This strategy worked, and the device works as a prototype molecular device with a nanoelectromechanical bistability (Deliverable 7). Figure 9 summarises the switching behavior for C_{60} in a silver nanogap. The data shown demonstrate that C_{60} in a clean nanogap switches between two different conformations with different conductance.



The analysis shows that OFF-switching is mediated by excitation of two vibrational modes - 35 meV at high temperatures and 160 meV at low temperatures. The increased temperature promotes switching - both modes are getting more active at high temperatures. A preliminary analysis shows that switching ON-switching is mediated by excitation of a low-energy vibration mode (around 5 meV). The switching is current-assisted – the energy supplied by tunneling electrons increases the average oscillator energy and promotes the switching.

FIG. 9: Switching data for a device with a C_{60} molecule trapped between two silver electrodes. At 4 K the switching between the two conductance states is hysteretic. At 14 K the hysteretic area shrinks, and the histograms for the ON (blue) and OFF (red) transitions start to overlap and C_{60} trembles between two states. At still higher temperatures the switching happens so fast that individual switching events can not be resolved, which results in a smooth I-V curve with negative differential resistance.

Synthesis of alternative organic molecules for NEMS devices

As an alternative to fullerene-based NEMS devices Partner 4 (T. Bjørnholm et al.) has synthesising larger, linear chain molecules – molecular wires – for inclusion in a device. Progress has been made both with respect to the synthesis of isolated π-islands and switchable molecular wires. This work was concentrated to the first half of the project.

Theoretical modeling of fullerene-based devices

Nanoelectromechanical effects due to spin-polarized electrons were investigated by Partner 1 (M. Jonson et al.) and Partner 2 (R. Shekhter) during the first year [D. Fedorets et al., Phys. Rev. Lett. **95**, 057203 (2005)]. They considered the limit of weak mechanical dissipation where a condensate of coherent phonons can form. Partner 4 (K. Flensberg et al.) studied the influence of many-body effects on molecular transistors of the NEM-SET type in the opposite limit of strong or medium dissipation of the molecular motion, in particular the interplay between many-body effects (the Kondo effect) and vibron states [J. Paaske and K. Flensberg, Phys. Rev. Lett. **94**, 176801 (2005)].

Partner 2 (Robert Shekhter) and Partner 1 (Mats Jonson, Leonid Gorelik) studied the shot noise in the electrical current due to mechanically assisted spin-dependent transport of electrons during the second year [L.Y. Gorelik *et al.*, Appl. Phys. Lett. **90**, 192105 (2007).]. The shot noise in a spin-polarized magnetic NEM-SET was found to carry information about electronic spin-flip processes and to be a useful spectroscopic tool.

Partner 1 (Jari Kinaret *et al.*) has developed a multiscale model of shuttling that incorporates atomistic information of the shuttling molecule and the electrodes [C. Huldt and J.M. Kinaret, New J. Phys. **9**, 51 (2007)]. Recent results for metal clusters (Cu_{13}) and larger molecules (C_{20}). suggest that regular shuttling is limited to a voltage range between a lower threshold voltage needed to initiate shuttling, and an upper threshold voltage at which the tunneling rate between the shuttling particles and the electrode is no longer fast compared to the mechanical motion.

Experiments towards peapod based devices

Partners 2 (E. Campbell et al.) and 4 (J. Nygård et al.) obtained material from three different sources (types A-C). The materials have been assessed by a suite of complimentary techniques;

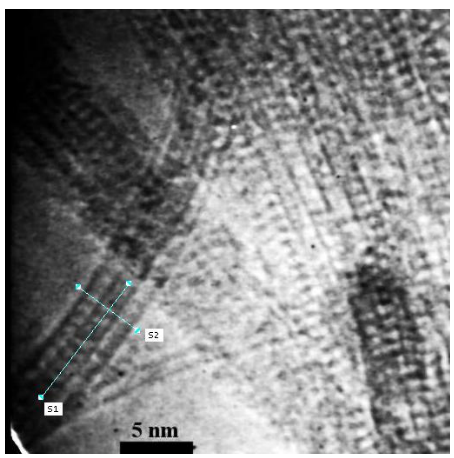


FIG. 10: TEM of nanotube bundles from material type A. Fullerenes can be seeen inside the nanotubes

Transmission Electron Microscopy (TEM), Atomic Force Microscopy (AFM), Raman spectroscopy, and electrical transport measurements. Type A is based on single-wall nanotubes grown by arc discharge with a diameter distribution which is appropriate for the following filling with fullerenes, carried out at CEMES, Montpellier. All results during the first year indicated that type A peapod material (Fig. 10) is suitable for further device fabrication.

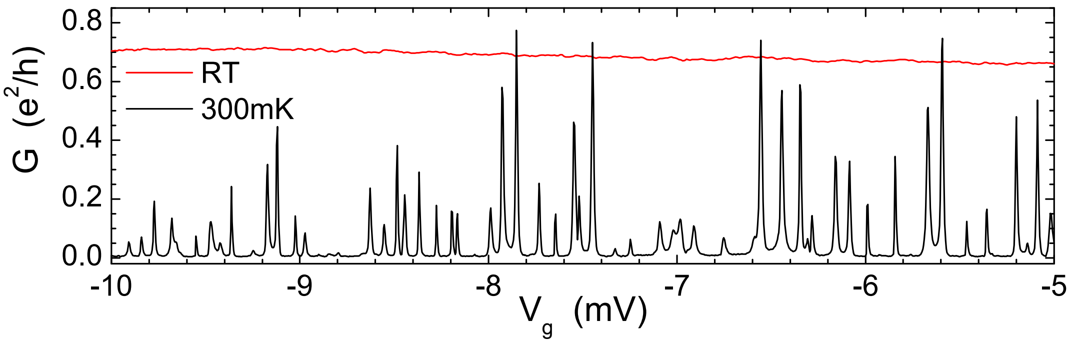


FIG. 11: Linear conductance G of type A peapod vs gate voltage V_g at T = 300K (red) and T = 300 mK (black).

Electrical transport measurements were during the second year performed down to 300mK. Figure 11 shows the differential conductance as a function of backgate voltage for one device. Single electron charging dominates the electric transport through the tube. Features revealed in such bias spectroscopy experiments at sub-kelvin temperatures further confirm a high structural quality of type A material. The fairly regular structure of Coulomb blockade diamonds indicates that the tube behaves as a single quantum dot, at least within a certain range of gate voltages. These results are the first experimental report on electrical properties of C_{60} peapod material at sub-kelvin temperatures.

Further electrical measurements by Partner 4 during the third year showed that devices based on C_{60}-filled nanotubes can behave as highly regular individual quantum dots, with signatures of Kondo physics at sub-kelvin temperatures [P. Utko *et al.*, Appl. Phys. Lett. **89**, 233118 (2006)]. Further electrical transport measurements on fullerene nanopeapods have been triggered by theoretical work carried out by Partner 2. Figure 12 shows a temperature dependence of the conductance peak heights, measured for one of our peapod devices. The low-temperature data (T<10 K) differs from a G_{max}~1/T dependence, which is generic for quantum dots in a thermally-broadened quantum Coulomb blockade regime and approaches rather G_{max}~1/√T, in a good agreement with the suggested model that involves polaronic effects on the resonant tunneling transport caused by the encapsulated fullerenes.

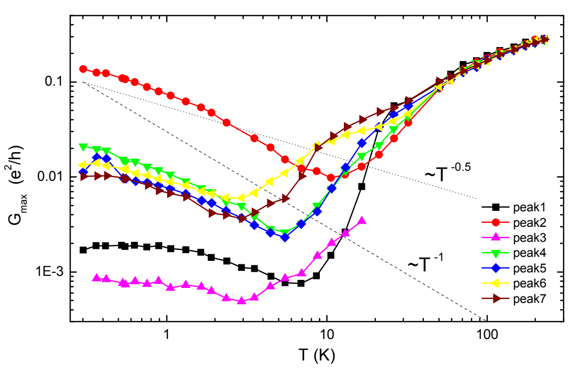


FIG. 12: Temperature dependence of conductance peak heights G_{max} measured for a peapod device.

Theory of peapod devices

The modeling by Partners 1 and 2 duringthe first year focused on the “peashooter” device application and concentrated on understanding the conditions for electroemission of C_{60}

molecules encapsulated by a single-wall carbon nanotube. In the model a voltage V is applied between a semi-infinite metal electrode and a peapod of radius R, whose open end is at a distance L from the electrode. Quantities of interest are the critical voltage V_c, for which the initially neutral fullerene becomes charged by a single electron, and the voltage V_e, for which the fullerene is emitted from the nanotube. The conclusion from the modeling was that a peashooter action is possible [I. V. Krive, R. I. Shekhter and M. Jonson: *Carbon "peapods" – a new tunable nanoscale graphitic structure,* Low Temp. Phys. **32**, 887 (2006)].

During the second and third year Partner 1 (Mats Jonson, Leonid Gorelik) and Partner 2 (Robert Shekhter) explored possible effects of the vibrational degrees of freedom in peapods on their electrical conductance properties. They studied in particular the influence of quantum fullerene vibrations on peapod transport properties in two different cases. In the first [I.V. Krive *et al.*, cond-mat/0702153] a strong coupling between the electronic states on the CNT shell and the localized states on the fullerenes affects the resonant tunneling transport of electrons through the metallic peapod system. This is an observable effect due to the unconventional temperature dependence of the resonant conductance peaks (as mentioned above). In the second case one is in the ballistic transport regime where scattering is weak. The interference of electron waves scattered by quantum fluctuations of the fullerene modifies the electronic properties and promotes the current. This effect manifests itself in a measurable voltage- and temperature-independent excess current at high bias voltage [G. Sonne *et al.*, arXiv:0706.4240].

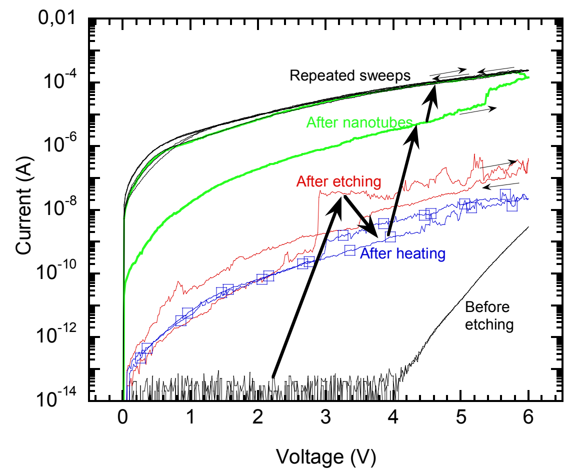
Integrating carbon-based NEMS with silicon device technology

Partner 1 (P. Enoksson/S. Bengtsson et al.) in collaboration with Partner 2 (E. Campbell et al.) has made experiments in order to study the plasma-enhance CVD (PECVD) growth of nickel-catalyzed freestanding carbon nanotubes on six CMOS-compatible metal underlayers (Cr, Ti, Pt, Pd, Mo and W). The most important part of this investigation was to determine the optimum conditions for growing vertically aligned carbon nanotubes (VACNTs) on metal substrates using DC PECVD. Two sets of experiments were carried out to investigate the growth of VACNTs: (i) Ni was deposited directly on metal underlayers and (ii) a thin amorphous layer of Si was deposited before depositing the Ni catalyst of the same thickness (10 nm). The introduction of an amorphous Si layer between the metal electrode and the catalyst was found to produce improved growth activity in most cases.

Partner 1 (P. Enoksson/S. Bengtsson et al.) showed during the second year that it is possible to attach and contact carbon nanotubes to a silicon nanogap structure, although the significance of having a nanometer-size contact as opposed to a separation in the micrometer range has not been clearly demonstrated. In addition the noise and breakdown features of the nanogap devices were characterized.

Since gaps of order 1-2 nm – without excessive parasitic leakage currrents – required for a three terminal fullerene NEMS have not been achieved, the pursuit of a CMOS compatible nanotube growth process looks more promising at present for silicon integration of carbon based NEMS devices. To this end vertical nanonorelay structures have been succesfully grown. Process optimization have been accomplished with respect to (i) growth on a different metal underlayers, (ii) the control over growth, density, diameter and length, (iii) the importance and effects of Si as part of the catalysts system, (iv) oxide deposition on catalyst and post growth.

FIG. 13: Sample device with a 7 nm nanogap displaying a significant change in current-voltage characteristics after CNT deposition.



During the third year, issues regarding compatibility of CNT and CMOS processing were addressed by Partner 1 (P. Enoksson/S. Bengtsson et al.) in close collaboration with Partner 2 (Campbell) in conjunction with the benchmarking of CNT devices to mature technologies for switching applications (Deliverable D12). In particular CMOS compatibility in terms of insulator deposition and etching has been investigated with success. Carbon nanofibers survive the oxide deposition and etch process steps which enables device definition within a standard CMOS frame of processing. As for compatibility of dc plasma assisted CNT growth on CMOS chips it was apparent that a lower temperature than 500 °C is preferred and avoiding discharge from the plasma is required if there is to be a chance to have functional CMOS circuits after CNT growth. With present knowledge it appears that RF-PCVD may be the most promising approach to achieve the growth of individual vertically aligned carbon nanofibres at temperatures that are low enough to be compatible with CMOS circuitry (below 450 ^{o}C).

Consortium management

General

The CANEL project has been carried out according to the original plans and all deliverables have been achieved. During its three years the project has resulted in 60 scientific publications (as this report is written 51 have been published, 5 are in press, and 4 have been submitted) and more than 150 oral presentations. The consortium has established contacts with several companies that have showed interest in carbon-based nanoelectromechanical devices. A joint project on the high frequency properties of the nanorelay involving Partner 1 (Jari Kinaret), Partner 2 (Eleanor Campbell) and NOKIA, with funding from NOKIA, started during the second reporting period was renewed during the third reporting period and runs till the end of 2007. A startup company, Smoltek, was formed in late 2005 in order to market technology developed with in CANEL.

The CANEL consortium has coordinated by Chalmers University of Technology. Professor Mats Jonson has been the coordinator and professor Jari Kinaret has been assistant coordinator. The coordinators are assisted by a Project Coordination Committee which has been established in accordance with the consortium application, and includes representatives from all Partners. The consortium management functions very well, and no particular problems have been encountered.

The contractors' roles and responsibilities has follow the lines set out in the ***Annex I*** to the contract (with the extension of WP2 decided after the first annual review of CANEL).

Management activities

The consortium has organized seven workshops/project meetings during its three years, a kick-off meeting was organised in Gothenburg in early June 2004, project meetings took place in Delft in January 2005, in Gothenburg in June 2005, in Copenhagen in January 2006, and again in Gothenburg in May 2006; during the final reporting period a project meeting was held in Amsterdam (Schiphol) in December 2006 and a final workshop was organised in Edinburgh in May 2007.

The kick-off meeting in June 2004 was used to introduce the different Partners to each other both socially and scientifically, and to establish management routines and to discuss their implementation. The meeting was attended by all principal investigators, several other senior scientists from the Partners, and numerous graduate students. The meeting was arranged immediately before an international workshop on NEMS that was organized by representatives of Partners 1 (Mats Jonson), 2 (Robert Shekhter), and 3 (Yaroslav Blanter).

The project meetings in Delft in 2005 and Copenhagen 2006 focused on discussing the project's progress towards its goals, and featured mainly scientific presentations both by principal investigators and by junior scientists. The the main objective of the two project meetings in Gothenburg (after the first and second reporting periods, respectively) was to prepare the reports to the EC. However, back-to-back to the 2006 project meeting in Gothenburg a two-day workshop on "Current Problems in Nanoelectromechanical Systems" was held with four invited speakers from outside the CANEL project and with scientific presentations by CANEL PIs, students and postdocs. The December 2006 project meeting in Amsterdam was mainly intended to make sure that the project was on track as it entered its last six months, while the Edinburgh workshop in May 2007 was more ambitious with four external invited speakers in addition to contributions from CANEL Pis, studetns and postdocs.

The management routines introduced in the kick-off meeting and implemented by the project include the establishment of the Project Coordination Committee as stipulated by the consortium agreement. The committee includes one voting representative from each Partner, and an additional non-voting representative from workpackage 4 on silicon integration so that all Partners and all workpackages are represented. The committee has met twice a year in connection with the project meetings.

A startup company called Smoltek started by former CANEL project member Dr. M.S. Kamir (Partner 1) has been formed. Its business idea is to commercialize technology developed within CANEL. CANEL PI:s Stefan Bengtsson (Partner 1), Eleanor Campbell (Partner 2) and Peter Enoksson (Partner 1) form the Scientific Advisory Board of the company.

The following quotes from the Smoltek home page, http://www.smoltek.com/index.html, are relevant:

"Smoltek was founded by M.S. Kabir, David Brud and Swedish top business incubator Chalmers Innovation in the winter of 2005. The company is a spin-off from the Department of Microtechnology and Nanoscience at Chalmers University of Technology and the Atomic Physics Group at Göteborg University, Sweden."

"With research originating from Europe's premier research group investigating carbon nanostructures and their CMOS-compatibility, Smoltek has developed a patent pending technology platform to utilize carbon nanostructures in a CMOS-compatible process."

"Smoltek is devoted to develop, validate and utilize state of the art nanoscale technologies for the semiconductor industry by enhancing performance, enabling new functionalities and prolonging the lifetime of current and future manufacturing techniques. With its patent pending technology platform, Smoltek offers the semiconductor industry a unique solution on how to utilize nanostructures in their products. As primarly application, Smoltek is offering a carbon nanostructure based solution to increase the data transfer rates and to reduce the energy consumption in microprocessors."

2 Dissemination and use

We have chosen not to publish the exploitable results yet, even in those cases when IPR protection has already been applied for, in order to further develop the technology and to await the conclusion of ongoing negotiations on commercialization.

The CANEL consortium maintains a webpage at http://www.fy.chalmers.se/projects/canel that contains a description of the consortium's activities including a publications list.