Project no.: **505457**

Project acronym: **ULTRA-1D**

Project title: **Experimental and theoretical investigation of electron transport in ultra-narrow 1-dimensional nanostructures**

Instrument: **STREP**

Thematic Priority: **Priority 3 – Nano-technologies and nano-sciences, knowledge-based multifunctional materials, and new production processes and devices – 'NMP'**

Deliverable: D27

Executive summary

Due date of deliverable: 15.10.2007
Actual submission date: 22.11.2007

Start date of project: 01.03.2004 Duration: 42 months

Organisation name of lead contractor for this deliverable:
CR1 - Univeresity of Jyväskylä, Finland

Revision 1

Project co-funded by the European Commission within the Sixth Framework Programme		
Dissemination Level		
PU	Public	✔
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

1. Summary

The main objective of the Ultra-1D Project has been to study the fundamental size limits, when the electron transport in one-dimensional (1D) systems can be considered qualitatively similar to macroscopic regime, and to explore qualitatively new phenomena appearing below the certain scale. Project has been focused on fabrication, theoretical and experimental study of electron transport in the state-of-the-art narrow 1D objects: normal metals, superconductors, semiconducting heterojunctions and carbon nanotubes.

Principal technological objective of the Project has been to elaborate old and develop new methods of microfabrication, pushing the reproducible limit of 1D object fabrication down to ~ 10 nm scale. Three independent, but complimentary methods have been used for fabrication of metallic systems: high-resolution e-beam lithography, electrochemical growth of ultra thin nanowires, and progressive reduction of the effective diameter of pre-fabricated 1D objects by plasma etching. Principal technological objective related to activity with 1D semiconductors has been the fabrication of high-quality systems enabling application of external potential with period < 50 nm. Main technological objective related to electron properties of carbon nanotubes has been the fabrication of structures, formed of a single-wall carbon nanotube positioned (suspended) on top of terraced crystal plane or a cleaved edge of a superlattice.

Research activity with normal electron transport has been concentrated at three main topics: metal-insulator transition in ultra-thin wires, electron decoherence in 1D limit, peculiarities of electron transport in 1D systems with controlled external periodic potential. Study of superconductors has been be focused on the problem of quantum phase slips, which can be experimentally observed in ultra-thin 1D systems (wires and rings).

Experimental part of the scientific activity included state-of-the-art low noise electron transport and magnetic measurements at ultra-low temperatures. Theoretical investigation utilized modern methods of quantum solid state physics.

2. The partners

No.	Participant name	Short name	Country
1	University of Jyväskylä, Department of Physics	JyU	FINLAND
2	Forschungszentrum Karlsruhe, Institute for Nanotechnology	FZK	GERMANY
3	University of California, Irvine, Department of Chemistry	UCI	USA
4	Lund Institute of Technology, Department of Mathematical Physics	LTH	SWEDEN
5	University of Copenhagen, Nano-Science Centre	COP	DENMARK
6	Centre de Recherches sur les Très Basses Températures, Grenoble Laboratoire de Photonique et Nanostructures, Marcoussis	CNRS,CRTBT & LPN	FRANCE
7	Ruhr-University Bochum, Institute of Experimental Physics	RUB	GERMANY

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3. Main R&D achievements.

The project consists of four R&D work packages (WPs).

WP#1. Metal-insulator transition in 1-dimensional normal metals

Objective:

- **to observe experimentally size-dependent metal-insulator transition effect in ultra-narrow wires**

Quantum solid-state theory predicts that normal electron transport is blocked in 1D systems with the effective transverse dimension smaller than the electron de Broglie wavelength. Estimations suggest that at temperatures below few K one might reach the required regime for semimetals (Bi or Sb) with effective diameter ~ 10 nm. Similar effect has been observed in thin films. However, despite numerous attempts over the last decades, for 1D systems experimental confirmation of the phenomenon has been demonstrated only recently by the members of the Jyväskylä team [1.1] (Fig. 1.1).

The effect has a universal validity setting fundamental size limitations for miniaturization of nanoelectronic components. The elaborated methodology of the Jyväskylä team [1.2-1.4] is an important breakthrough in nanofabrication: for the first time single-crystalline semi-metal nanostructure has been fabricated.

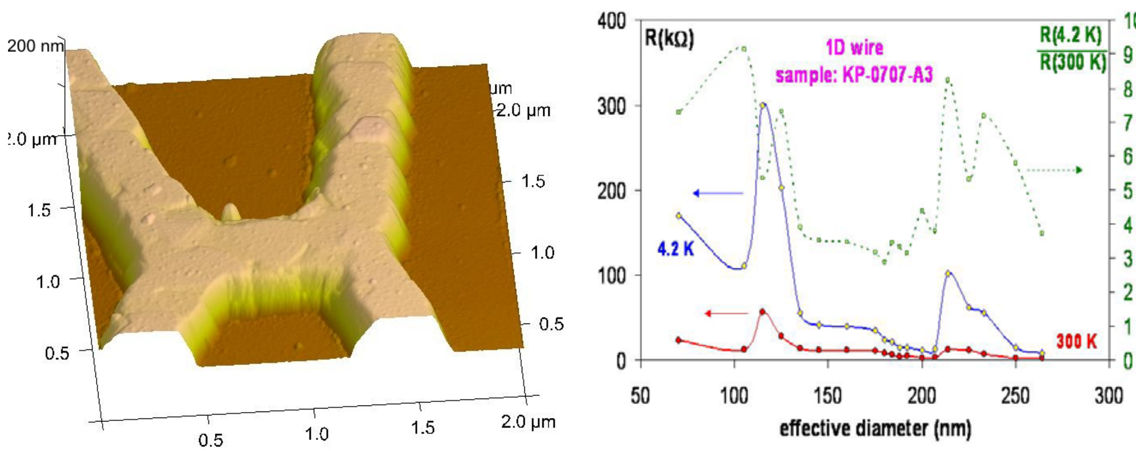

Fig. 1.1. (Left) SPM image of Bi nanostructure on mica substrate. One can clearly see individual hexagonal-shaped single crystals forming the contacts of the central nanostructure, which looks as a mono-domain crystal. (Right) Resistance vs thickness of Bi nanowire measured at room temperature (red) and at 4.2 K (blue). Right axis (green) shows the ratio of the both resistances. Note the non-monotonous variation of the resistance as a function of the effective diameter manifesting the quantum size effect under investigation

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WP#2 Electron dephasing in 1D limit

Objective:

- **to deduce the temperature dependence of the electron decoherence time in 1D systems with and without magnetic impurities;**
- **to develop a general microscopic theory of electron transport and quantum noise in quasi-1D disordered conductors with electron-electron interactions.**

CNRS-RUB teams have studied the phase coherence time of various metallic quantum wires containing different concentration of implanted ions. The idea has been to check the electron dephasing mechanism provided by implantation of magnetic and non-magnetic impurities. The experiments clearly indicate that the implantation process does not lead to any additional dephasing compared with non-implanted samples (Fig. 2.1, left), while the presence of magnetic scattering dramatically reduces coherence time at sufficiently low temperatures (Fig. 2.1, middle). The observation supports the model of the FZK team that saturation of the electron coherence time observed in numerous experiments cannot be accounted for presence of small (= uncontrolled) amounts of residual impurities.

FZK team has developed a novel unified approach enabling to non-perturbatively investigate weak localization effects in arrays of quantum dots and arbitrary diffusive conductors in the presence of electron-electron interactions. A new general formula has been derived for zero-temperature electron decoherence rate which universally applies to (i) weakly disordered conductors, (ii) strongly disordered conductors and (iii) metallic quantum dots, i.e. embraces essentially all types of disordered conductors. The theory quantitatively explains the results of all available decoherence experiments (including the experiments of the CNRS-RUB team) which show a non-trivial dependence of the electron decoherence time on the diffusion coefficient (see Fig. 2.1, right).

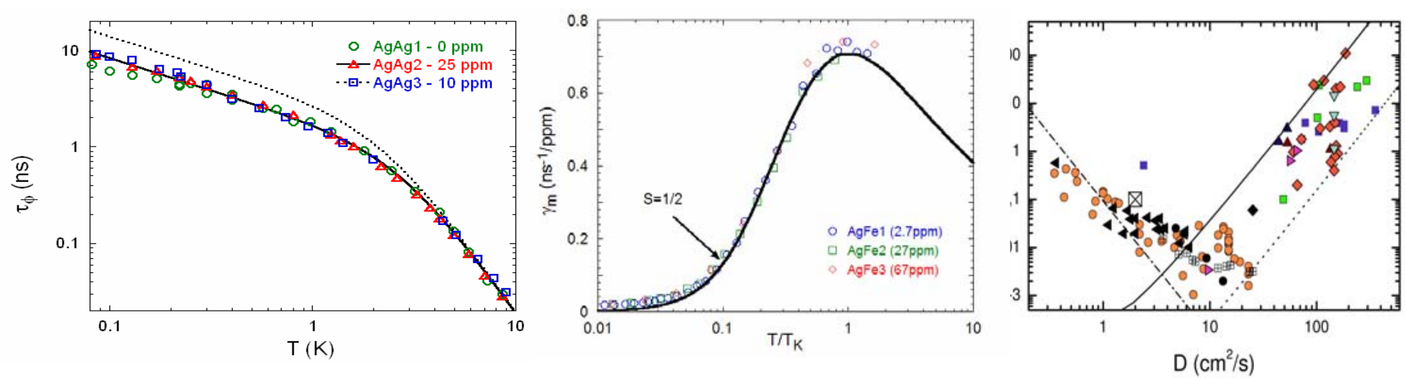

Fig 2.1: (Left) Phase coherence time as a function of temperature for Ag quantum wires implanted with different concentration of implanted Ag ions. The solid line corresponds to the theoretical prediction for dephasing taking into account electron-electron interactions as well as electron-phonon interaction with experimentally determined prefactors. The dotted line is the purely theoretical prediction. (Middle) Magnetic dephasing rate for Ag quantum wires containing magnetic Fe impurities of different concentration. The solid line corresponds to the NRG theory for the s=1/2, single channel model. (Right) The low temperature dephasing times observed in metallic conductors with different values of diffusion coefficient D changing by over 3 decades. The data points were taken from over 30 different experiments of different groups on more than 130 metallic samples (one data point corresponds to one sample). Our theoretical predictions are indicated by straight lines.

The phenomenon of electron decoherence at low temperatures has a fundamental validity for our knowledge about quantum properties of matter. Elaborated experimental and theoretical material is unique and represents leading-edge knowledge in the field.

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[2.8] Scaling of the low temperature dephasing rate of Kondo systems, F. Mallet, J. Ericsson, D. Mailly, S. Ünlübayir, D. Reuter, A. Melnikov, A.D. Wieck, T. Micklitz, A. Rosch, T.A. Costi, L. Saminadayar, and C. Bäuerle, Phys. Rev. Lett. 97, 226804 (2006)

WP#3 Electron interactions in external potential in 1D limit.

Objective:

- **to investigate electron spectra in 1D systems in external periodic potential;**
- **to elaborate theoretical methods enabling calculations of the eigenstates of 1D finite-size systems containing small number of electrons**

Various 1-D systems have been fabricated and studied by the COP team. An example of a structure based on a single wall carbon nanotube is shown in Fig. 3.1. A system similar to a transistor where the source and drain contacts are superconducting or are in Kondo regime have been studied. The superconducting contacts give rise to Josephson effect as well as characteristic Andreev scatterings. Another type of 1-D systems has been investigated: InAs nanowires grown by molecular beam epitaxy (MBE). Contacted with superconducting aluminium and measuring at 0.3 K these 0.3 µm long nanowires exhibit Josephson supercurrent, excess current and subharmonic energy gap structure.

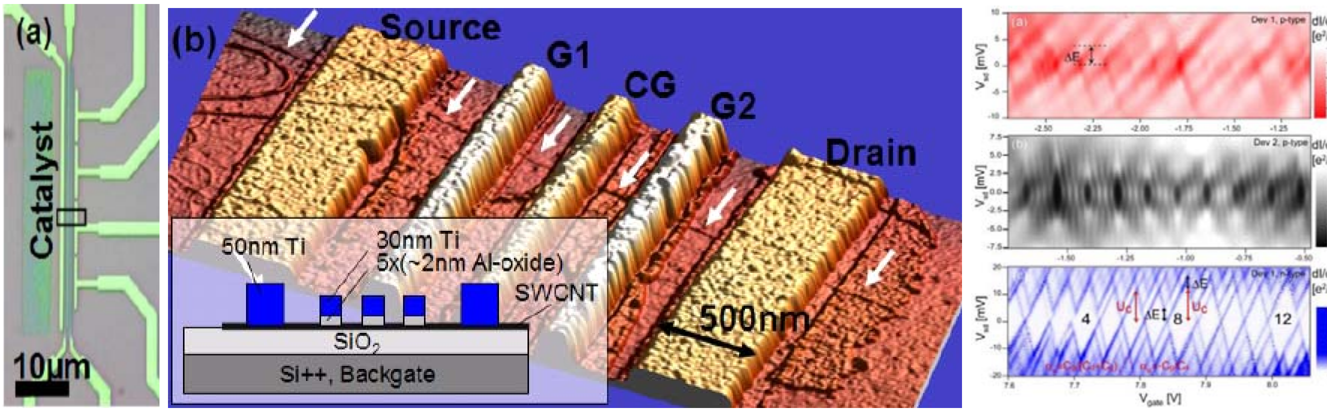

Fig. 3.1. (a) Optical image of 4 potential devices based on SWCN consisting of one common source electrode, three common top-gate electrodes, and four individual drain electrodes. On the left hand side of the source electrode an island of catalyst material is positioned from where the carbon nanotubes grow. (b) Atomic force microscope micrograph of the region indicated by the black rectangle in (a). White arrows shows the position of the nanotube. (Right) Three types of contact regime showing Fabry-Perot interference, Kondo effect andCoulomb blockade (T=4K).

The origin of the large diamagnetic persistent current in quantum rings has been studied using a new model consisting of a ring with a defect connected to an infinite wire which provides the effect of thermal bath. It has beenshown that the magnetic phase diagram of 1D-lattices is not sensitive to the effective interaction between the particles. Qualitatively similar results were obtained for quantum dot lattices with Coulomb interaction and optical lattices where the interaction between the atoms is local. The effect of the spin on the rotational states in quantum dots has been studied. It was observed that the excitation spectrum was rich and showed many properties of infinite quantum Hall liquids. The formation of vortices is suppressed by the spin excitations. The relation of the boson and fermion wave functions in rotating systems was studied using exact numerical solution of the many-particle problem. The results show that in the weak interaction limit the rotational states of bosons and fermions are closely related and can be directly compared by computing the overlaps. Thermal transport in low-dimensional quantum membranes and wires was studied using elastic and inelastic scattering theory of phonons. It was shown that the so-called Lamb modes are important in the heat transport at low temperatures.

The experimental and theoretical material is unique and represents state-of-the-art methodology elaborated by the joint efforts of the COP-JyU-LTH teams.

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WP#4 Quantum fluctuations in 1-dimensional superconductors

Objective:

- **to study the effect of quantum fluctuations in ultra-thin superconducting nanostructures;**
- **to develop theoretical description of the phenomenon.**

Zero resistance is a fundamental attribute of superconductivity. Ability to carry a dissipationless electric current is an extremely attractive solution for future development of ultra-high integrated nanoelectronic components where heat dissipation is an important issue. However, it has been already noticed couple of decades ago, that in sufficiently narrow superconducting channels the onset of superconductivity is never 'abrupt'. There is always a range of temperatures where the effective resistance of a superconductor is smaller than in normal state, but not yet zero. The resistive state of a quasi-1D superconductor is associated with activation of so-called phase slips. It 'orthodox' theory this mechanism is provided by thermal fluctuations. In a macroscopically coherent system there might be an additional mechanism, when phase slips due to quantum tunnelling. There have been a limited number of reports stating experimental evidence of QPS phenomenon. Members of the Jyväskylä team used their recently patented method [4.1-4.4] to progressively reduce the diameter of superconducting nanowires from ~100 nm down to ~ 8 nm. The pioneering approach eliminates artifacts typical in studies using different samples. It has been demonstrated the size dependent cross-over from the thermal to the quantum regimes [4.5-4.8] (Fig. 4.1). The experimental findings are in a perfect agreement with the renormalization model produced by the FZK team [4.9].

Apart from the significant importance for fundamental science, the phenomenon of quantum fluctuations sets fundamental limitations on utilization of superconducting elements in nanoelectronic circuits designed to carry a dissipationless supercurrent. Pioneering technological invention of the JyU experimental team [4.1-4.4] demonstrated reproducible sub-10 nm nanofabrication. The patented method [4.1] clearly represents an approach beyond the existing state-of-the-art enabling progressive reduction of dimensions of pre-fabricated nanostructures and is compatible with industrial clean room/vacuum technologies. Currently the JyU team in collaboration with national industrial partners continues implementation of the invention.

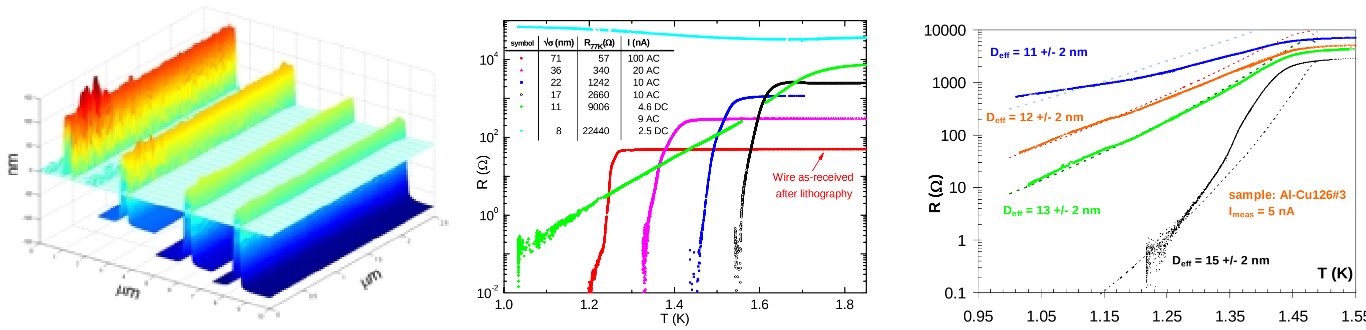

Fig. 4.1. (Left) AFM images showing evolution of the same nanowire after multiple sessions of ion beam sputtering [4.8]. (Middle) Evolution of shape of the resistance vs. temperature R(T) transition measured on a same aluminium nanowire [5]. One can clearly see the qualitative change of the shape of the R(T) dependence between 17 nm (black) and 11 nm (green) curves. (Right) Detailed evolution of the R(T) dependence between 15 nm and 11 nm wires [8]. Note the precision of the sample diameter characterization: +/- 2 nm. Dotted lines are fits to the model [9].

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