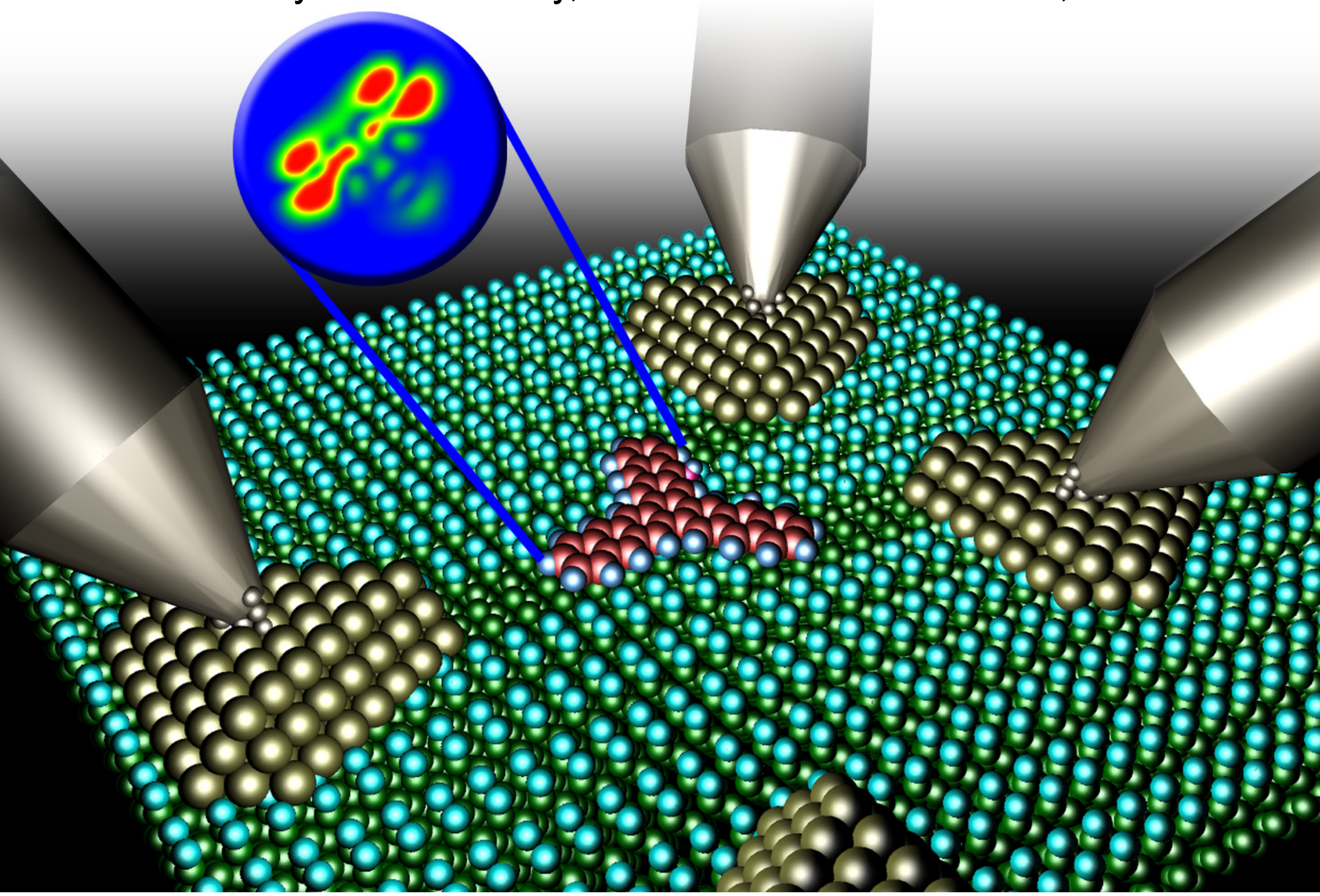

# AtMol International Workshop on Atomic Scale Interconnection Machine

Tuesday & Wednesday, 28 & 29 June 2011 • IMRE, SR1



Agency for Science, Technology and Research
SINGAPORE

AtMol

# CONTENT

## SCOPE OF THE WORKSHOP

Multiple access mechanical and/or electrical interconnects with atomic scale precision are promising technologies that can open the door to the design and measurement of realistic nano-scale machineries like interconnected molecule motors, nanoscale wiring, molecule logic gates, surface atomic scale circuits and memory. A new generation of UHV equipment resulting from the combination of far field microscopy (optical, electronic, ionic) and of a miniaturised set of near field microscopes (UHV-STM, NC-AFM) is now emerging in research and industry. This workshop will bring together groups from all around the world who have designed and started to utilise these new instruments.

## ENQUIRY

For technical enquiries, please contact:
**Cedric Troadec** (cedric-t@imre.a-star.edu.sg)

For registration enquiries, please contact:
**Alice Lee** (alice-lee@imre.a-star.edu.sg)

## ORGANISING COMMITTEE

**C. Joachim** (AtMol-Toulouse)

**J. Goh** (AtMol-Singapore)

**M. Maier** (Omicron)

**C. Troadec** (AtMol-Singapore)

**A. Correia** (AtMol-Madrid)

# PROGRAMME

## DAY 1 (Tuesday, 28 June 2011)

| Time | Programme |
|---|---|
| 0830 | **Registration** |
| 0900 | **Introduction** *by*<br>**Low Hong Yee,** *Director (Research & Innovation), Capability Group Head (Patterning & Fabrication), Senior Scientist II (IMRE, A*STAR. Singapore)*<br>**Christophe Forax,** *EU representant in Singapore*<br>**Christian Joachim,** *AtMol Coordinator (EU), Director of Research (CEMES, CNRS, France) and A*STAR VIP "Atom Tech" (IMRE, A*STAR, Singapore)* |
| 0930 | **Challenges and Advances in Instrumentation of UHV LT Multi-Probe System**<br>*by* **Wang Zhouhang** *(RHK Technology, Inc, USA)* |
| 1010 | **Ultra Compact Multi-tip Scanning Probe Microscope with an Outer Diameter of 50 mm**<br>*by* **Bert Voigtländer** *(Forschungszentrum Jülich, Peter Grünberg Institut, Germany)* |
| 1040 | ***Break*** |
| 1110 | **KolibriSensor™: On the Road to Multi-probed Non-contact AFM**<br>*by* **Tobias Vančura** *(SPECS Surface Nano Analysis GmbH, Germany)* |
| 1150 | **The DUF Project: a UHV Factory for Multi-interconnection of a Molecule Logic Gates on Insulating Substrate**<br>*by* **David Martrou** *(CEMES, CNRS, France)* |
| 1230 | ***Lunch*** |
| 1400 | **High Precision Local Electrical Probing: A New Low Temperature 4-Tip STM with Gemini UHV-SEM Navigation**<br>*by* **Markus Maier** *(Omicron NanoTechnology GmbH, Germany)* |
| 1440 | **A Complete UHV Atomic Scale Interconnection Machine**<br>*by* **Olga Alexandrovna Neucheva** *(IMRE, A*STAR, Singapore)* |
| 1520 | **Atomically Precise Manufacturing via Patterned Si Atomic Layer Epitaxy**<br>*by* **John Randall** *(Zyvex Labs, USA)* |
| 1600 | **Break** |
| 1630 | **Multi-probe Characterization of 1D and 2D Nanostructures Assembled on Clean and Hydrogen Passivated Surfaces of Ge(001)**<br>*by* **Marek Szymonski** *(NANOSAM, Jagiellonian University, Poland)* |
| 1710 | **Nano-gears Manipulation**<br>*by* **Cedric Troadec** *(IMRE, A*STAR, Singapore)* |

Dinner for participants will be at:

**Riverwalk Tandoor @ Upper Circular Road**
20 Upper Circular Road
The Riverwalk #B1-38
Singapore 058416
www.riverwalktandoor.com.sg

Transport will be provided from IMRE to the restaurant.

# PROGRAMME

## DAY 2 (Wednesday, 29 June 2011)

| Time | Programme |
|---|---|
| 0900 | **Electrical Properties Investigation of Low-dimensional Nanostructures with a Four-Probe Scanning Tunneling Microscope**<br>*by* **Hongjun Gao** *(Institute of Physics, Chinese Academy of Sciences, China)* |
| 0940 | **Location Specific Electron Transport Study of 2D Carbon Using Nanoprobes**<br>*by* **Wu Yihong** *(Department of Electrical and Computer Engineering, NUS, Singapore)* |
| 1030 | **Combined STM and Four-Probe Resistivity Measurements on Single InAs Nanowires**<br>*by* **Maxime Berthe** *(IEMN, France)* |
| 1100 | **Break** |
| 1130 | **Correlating Electron Transport to Local Structures at the Nanoscale**<br>*by* **Li An Ping** *(Center for Nanophase Materials Sciences, Oak Ridge National Laboratory, USA)* |
| 1210 | **Electronic and Spin Transport at Surfaces and Nanostructures Measured by Four-Tip STM**<br>*by* **Shuji Hasegawa** *(Department of Physics, University of Tokyo, Japan)* |
| 1250 | **Lunch** |
| 1400 | **Spin Read-out of Precision Placed Single P Atoms in Silicon**<br>*by* **Michelle Simmons** *(CQC2T, University of New South Wales, Australia)* |
| 1440 | **Silicon Atomic Quantum Dots, Qubits, Artificial Molecules and Surface State Conductors, New Theory and Experimental Results**<br>*by* **Robert A. Wolkow** *(Department of Chemistry, Department of Physics, University of Alberta, Canada)* |
| 1520 | **Break** |
| 1550 | **UHV Nano-probe Surface Conductance Measurements on MOS2**<br>*by* **Ramesh Mohan Thamankar** *(IMRE, A*STAR, Singapore)* |
| 1630 | **Electronic Transport on the Nanoscale**<br>*by* **Rolf Möller** *(Faculty of Physics, University of Duisburg-Essen, Germany)* |

## ABSTRACT AND SPEAKERS' INFORMATION

# Challenges and Advances in Instrumentation of UHV LT Multi-Probe System

**Wang Zhouhang**
RHK Technology, Inc., 1050 East Maple Road, Troy MI 48083, USA
Wang@RHK-Tech. Com

The progress of nanoscience and nanotechnology can be realized only through continued advances and utilization of instruments and techniques for characterizing material properties and manipulating materials and devices at the nanoscale. The UHV LT Multi-Probe SPM system with high resolution SEM has been developed to meet such challenges. This integrated

instrument bridges dimensions from the mm scale to atomic scale, and provides an unprecedented platform for local, non-destructive transportation measurements and for building, manipulating and function-testing complex nanoelectronics and nanoscale machineries. It also enables combining many different techniques for characterizing sample conductance, topography, chemical, optical or magnetic properties with complementary information at the same position or on the same nano-device.

RHK Technology, together with Center for Nanophase Materials Sciences, Oak Ridge National Laboratory, USA, developed the first UHV LT 4-Probe STM/SEM/SAM System at CNMS ORNL. This system consists of 4 independently operational STM, each capable of atomic resolution at below 10 K, and high resolution SEM and high resolution Scanning Auger Microscope (SAM). Subsequently, RHK also developed the first UHV LT Multi-Probe

STM/SEM/CL System, in cooperation with Micro-Nano Research Center of Xiamen University in China. This system utilizes an optical fiber as one of the probe module for light collection with CL (Cathode Luminescence) spectra and mapping modes, or for light illumination. The fiber is mounted on a XYZ probe stage with precisely controlled motion for optimum positioning to yield the best signal collection or optimized illumination.

Design and development of such complex systems pose many issues and challenges. This presentation will discuss some of the issues faced, solutions reached, and advances made. Examples include:

1. Disturbance by magnetic material and magnetic field of SEM imaging and coordination of SEM/SPM position, and their influence on and disturbance of SAM spectra and mapping. The design and use of non-magnetic motors for multi-probe modules will be discussed.

2. Tip holder and sample holder design for better cooling contact and easier handling, and the versatility of the sample holder with multiple contacts.

3. Use of optical fiber as one of the probe modules, and positioning of the fiber. CL spectra and mapping results will be presented.

### About the Speaker

Zhouhang Wang is the leading instrument designer and CTO of RHK Technology, Inc. in Troy MI USA. Mr Wang's deep, first-hand experiences spans over 28 years of research, instrument development, product commercialization, and project and team management. He has established a proven record of research, innovation and creative problem solving for UHV SPM system designs, and of productive collaborations with universities, government labs and businesses.

# Ultra Compact Multi-Tip Scanning Probe Microscope with an Outer Diameter of 50 mm

**Bert Voigtländer**
Forschungszentrum Jülich, Peter Grünberg Institut, 52425 Jülich, Germany
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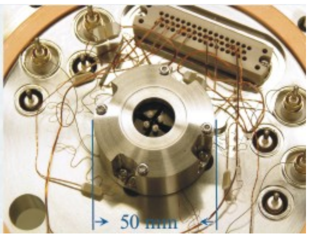
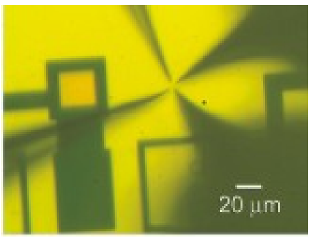
We constructed a multi tip STM where four independent STM units are integrated on a diameter of 50 mm. The lowest resonance frequencies are 2.5 kHz (xy) and 5.5 kHz (z). The coarse positioning of the tips is done under the control of an optical microscope or an SEM in vacuum. Fine positioning is done using STM scanning. The modular and compact design allows building a four tip STM as small as a single tip STM. We present examples of the performance of the multi tip STM designed using the Koala-drive.

It was possible to construct the multi-tip STM this small due to a new kind of nanopositioner, the Koala drive, which has diameter less than 2.5 mm and length smaller than 10 mm and serves as an STM coarse positioning device in our multi-tip STMs. Alternating movements of springs move a tube which holds the STM tip or AFM sensor. This new operating principle provides a smooth travel and avoids shaking which is intrinsically present for nanopositioners based on inertial motion with saw tooth driving signals. Inserting the Koala drive in a piezo tube for xyz scanning integrates a complete STM inside a 4 mm outer diameter piezo tube of < 10 mm length. The use of the Koala-drive makes the scanning probe microscopy design ultra compact and leads accordingly to a high mechanical stability. The drive is UHV, low temperature, and magnetic field compatible.

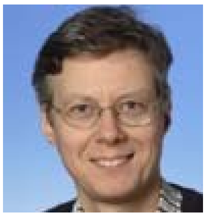
The design of a UHV low temperature (4K) multi-tip STM operating in magnetic fields of 8 Tesla and capable of charge and magneto transport measurements is presented. Four individual beetle-type STM units are stacked into each other in order to make the design as compact as possible. For the coarse approach of the tip towards the sample the Koala drive is used. This multi tip STM is located inside the UHV part of a liquid Helium cryostat, which additionally hosts an 8 T superconducting magnet. In order to navigate the four tips, a SEM is installed. The scanning areas on the sample overlap sufficiently in order to contact nanostructures with all four tips at the same time and execute transport measurements.






*Ultra compact multi tip STM with 50 mm outer diameter. Four tips brought together within 5 µm.*

## About the Speaker



Prof Bert Voigtländer obtained a PhD in Physics at RWTH Aachen University in 1989. After a post doctorate at IBM, he became Principal Investigator at Forschungszentrum Jülich. His research is mainly oriented towards the growth of semiconductor nanostructures, the development of multiprobe STM techniques, and the charge transport through nanostructures and molecules.

# KolibriSensor™: On the Road to Multi-probed Non-contact AFM

*Tobias Vančura, Stefan Schmitt, Vincenz Friedli, Oliver Schaff, Stefan Torbrügge*

**Tobias Vančura**
SPECS Surface Nano Analysis GmbH, Voltastrasse 5, 13355 Berlin, Germany
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The possibility of probing a sub-micrometer small area of a sample with multiple probes simultaneously has become a very promising field of research in the past years. The main challenges in building a multi-probe microscope lie in the following fields:

- Scan Head: the size constraints that have to be met in order to get multiple tips into close proximity of each other are substantial, especially if atomic resolution should be achieved with each tip
- Probe: the first instruments using multiple tips relied on the tunneling current. In order to do more involved experiments new sensors capable of doing non-contact AFM will be required to open the road to new experiments
- Control System: once the difficulties of the mechanics have been overcome the control system should be aware of the multiple probes, rather than working as multiple copies of single probe system.

Piezoelectric force sensors are very promising in the field of multiprobe microscopy since the fully electrical control of these sensors omits any complicated optical beam/detector alignment. This enables the design of very compact multiprobe systems with STM and NC-AFM functionality. SPECS' new Curlew™ scan head is an extendable platform for building up a multi probe microscope with up to four tips working on the same sample. The head fully supports piezoelectric force sensors like the Akiyama™ sensor as well as the KolibriSensor™ for combined STM and NC-AFM operation. We have recently achieved resolution of atomic steps in air and UHV with Akiyama™ sensors by frequency-modulation AFM (FM-AFM).

The KolibriSensor™ has been used to achieve atomic resolution FM-AFM imaging on various samples. Beyond this particularly the measurement of surface potentials via Kelvin Probe force microscopy is of interest in multiprobe systems. To take full advantage of the imaging modes feasible with the KolibriSensor™ the heterogeneous sample system was chosen: graphene grown on Ru(0001) [1]. To further elucidate the properties of this fascinating material, complementary studies of the electronic and geometrical structure of single layer graphene on Ru(0001) (g/Ru) using STM, noncontact atomic force microscopy (NC-AFM) (see Fig. 1), and frequency-modulation Kelvin probe force microscopy (FM-KPFM) (see Fig. 2) were applied. These experiments were carried out with a commercial SPM 150 Aarhus equipped with the piezoelectric KolibriSensor [2] in ultra-high vacuum.

Finally, the Nanonis control system can be expanded from a single probe controller to a multi-probe control system where each probe can be controlled individually. Still, one instance can take over control over all the others to coordinate measurements, run complex sequences of experiments or coordinate transport measurements in the device under investigation.

**References**

[1] S. Günther, S. Dänhardt, B. Wang, M.-L. Bocquet, S. Schmitt, J. Wintterlin, Nano Lett. **ASAP** (2011)

[2] S. Torbrügge, O. Schaff, J. Rychen, J. Vac. Sci. Technol. B **28**, C4E12 (2010)

[3] T. Brugger, S.Günther, B.Wang, J. H. Dil, M.-L. Bocquet, J. Osterwalder, J. Wintterlin, T. Greber, Phys. Rev. B **79**, 045407 (2009)

[4] P. Sutter, M. S. Hybertsen, J. T. Sadowski and E. Sutter, Nano Lett. **9**, 2654 (2009)

## Figures

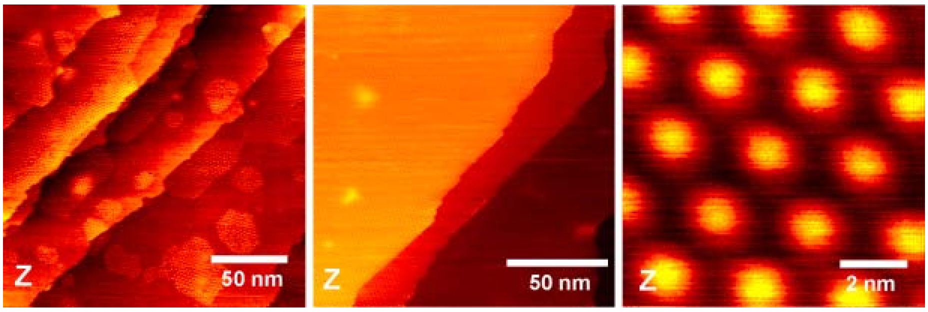


***Figure 1:*** *Topographic (Z) NC-AFM images of single layer graphene on Ru(0001) at room temperature. The graphene monolayer shows the characteristic buckling resulting in a hexagonal reconstruction as shown in detail in the right image. By varying the growth conditions the total coverage and shape of the graphene islands can be tuned ranging from partial coverage (left) to full monolayer coverage (center)*

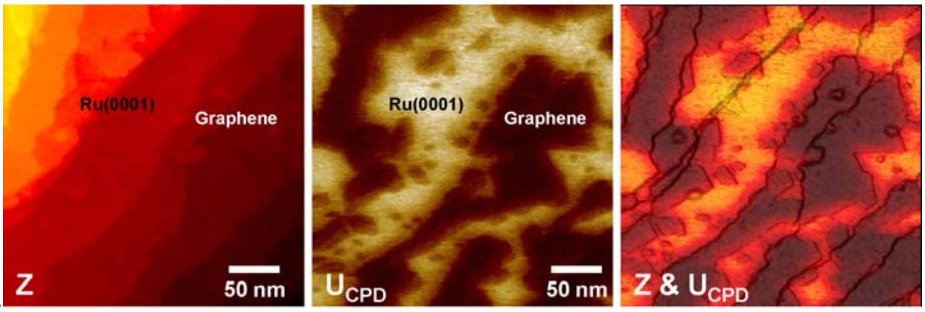


***Figure 2:*** *FM-KPFM image of graphene islands on Ru(0001). Left: topographic image (Z), Center: simultaneously recorded image of contact potential difference ($U_{CPD}$). Right: Superposition of topography and contact potential difference. Bright areas in the contact potential map $U_{CPD}$ correspond to the metal substrate.*

## About the Speaker

Tobias Vančura received his PhD from ETH Zurich in 2002. His research focused on local spectroscopy of semiconductor heterostructures at low temperatures. Today he works for the sales department at SPECS Surface Nano Analysis.

# The DUF Project: A UHV Factory for Multi-interconnection of a Molecule Logic Gates on Insulating Substrate

*D. Martrou, R. Laloo, L. Guiraud, P. Abeilhou and S. Gauthier*

**David Martrou**
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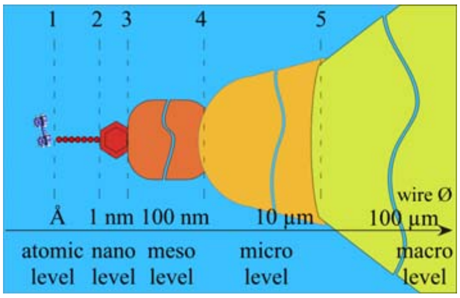
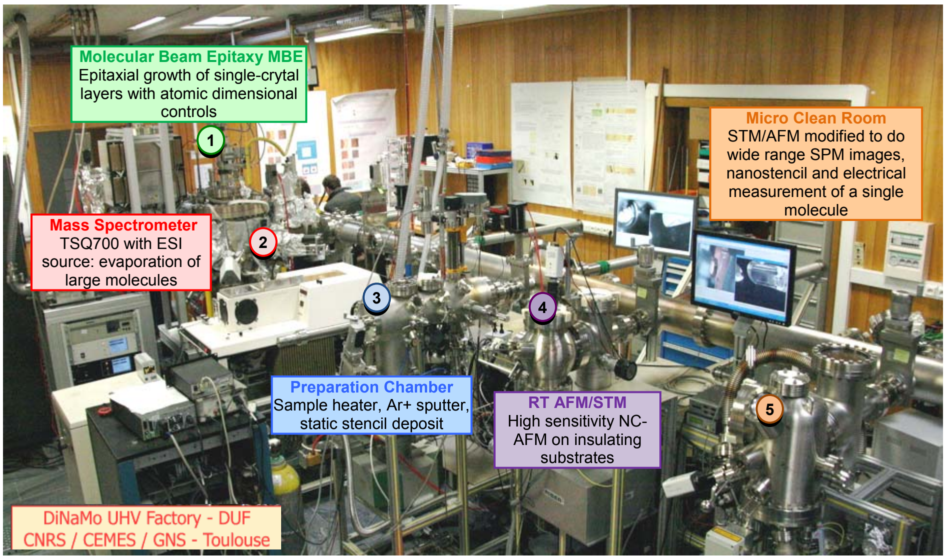
To measure the electronic properties of a single molecule one needs to contact electrically a single molecule with more than one electrode with an atomic precision around the molecule. Each connection should be a succession of wiring with increasing width starting from the atomic level to reach the macroscopic level. The figure 1 gives an illustration of one electrical contact on an ideal insulating substrate.




These 5 interconnects can be separated in two groups : one with the first and the second interconnect levels, which are more relevant to surface science, and the second group with the three last, which can be treated as technological interconnects.

*Figure 1–The five interconnect levels allowing an electrical contact on a single molecule*

The solution we have developed at Toulouse is to realize the 5 levels of interconnect under ultra high vacuum (UHV) with the conception and the fabrication of a dedicated UHV experiment called DUF (for “DiNaMo” UHV Factory). This equipment allows to transfer samples under UHV between five different UHV chambers : (1) MBE growth dedicated to nitride semiconductors (AlN, GaN) and stencil evaporation for microelectrodes growth (2) Room Temperature AFM/STM for surface characterization by STM and NC AFM (3) MicrocleanRoom see the MicroClean Room page (4) preparation chamber to clean substrate, STM tip and AFM cantilever (5) Mass spectrometer transformed in molecular ions source.




For more technical details, visit the DUF website : http://www.duf.cemes.fr

## About the Speaker

David Martrou works for the CEMES, CNRS in Toulouse, France. He is in charge of the development of the UHV factory. He studied in the Engineer School of Chemistry in Paris (ENSCP) and did his PhD thesis in CEA-Grenoble on STM studies of II-VI semiconductors (001) surfaces grown by MBE and obtained his diploma in 2002.

# High Precision Local Electrical Probing: A New Low Temperature 4-Tip STM with Gemini UHV-SEM Navigation

*B. Guenther, A. Bettac, Markus Maier, Joerg Lenz, F. Matthes (Forschungszentrum Jülich, Germany), C.M. Schneider(Forschungszentrum Jülich, Germany), A. Feltz.*

**Markus Maier**
Omicron NanoTechnology GmbH, Germany
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A major challenge in the development of novel devices in nano- and molecular electronics is their interconnection with larger scale electrical circuits required to control and characterize their functional properties. Local electrical probing by multiple probes with STM precision can significantly improve efficiency in analyzing individual nano-electronic devices without the need of a full electrical integration. Among a very few commercial approaches, the Omicron *UHV NANOPROBE* has been established as a suitable instrument for local electrical probing in UHV on nano-structures down to structure sizes in the 10 nm range. The mayor technical requirements for such sophisticated instrumentation are:

- Rapid and simultaneous SEM navigation of four local STM probes on small structures
- Localization of nanostructures by high resolution SEM (UHV Gemini)
- Individual probe fine positioning by atomic scale STM imaging
- STM based probe approach for "soft-landing" of sharp and fragile probes and controlled electrical contact for transport measurements
- Preparation techniques towards sharp and clean and STM tips
- Suitable low noise signal re-routing for transport measurements with third party electronics

Although the *UHV NANOPROBE* has been successfully used for various applications, today´s scientific requirements motivated the development of the next generation probing system. We will present the newly developed *LT NANOPROBE* which takes experimental capabilities one step further and opens up new research opportunities in nano-electronics, spintronics, and molecular electronics. Besides SEM/STM probe fine navigation and imaging, the excellent STM performance level of the LT NANOPROBE expands applications to tunneling spectroscopy and even the creation or modification of nano-structures by an ultimately precise STM probe. The R&D project has been driven by the following major milestones:

- Operation at temperatures of T<5 K for STM imaging and STM based probing
- SEM navigation at base temperature T<5 K
- Simultaneous operation of STM and SEM at base temperature
- Thermal equilibrium of sample and probes for (i) extremely low thermal drift and electrode positioning accuracy in time and (ii) efined temperature of the local electrical contact and
- Performance and stability level of each individual STM Probe suitable for STM spectroscopy and atom manipulation

First evaluation measurements with the system installed at the Forschungszentrum Jülich will be presented: STM on Au(111) with pm stability, STS revealing the supeconducting gap of a Nb tip with approx. 3meV gap size, and transport measurements on nanowiresires at T<5K.

### About the Speaker

Dr Markus Maier is Vice-President Sales, Marketing and Product Management of Omicron NanoTechnology GmbH in Germany. With more than 1000 UHV systems delivered worldwide, Omicron is established as the global leader in UHV surface science. Beyond major activities in conventional SPM, electron spectroscopy and thin film techniques, the class of highly integrated "multi-technique" instruments represents an important R&D line that will play an important role for future AtomTechnology.

M. Maier graduated from the Technical University of Darmstadt in 1996, working on low temperature SPM. He received his PhD in Physics from the University in Mainz in 2000 on superconductivity and magnetism. In 2000, he joined Omicron NanoTechnology and started as Product manager for low temperature UHV SPM and UHV Nanoprobing. In 2007, he was promoted to Omicron´s management board and is now responsible for the worldwide sales and marketing activities and strategic product development.

# A Complete UHV Atomic Scale Interconnection Machine

*Olga A. Neucheva, Ramesh M. Thamankar, Cedric Troadec, Jie Deng, Francisco Ample, and Christian Joachim*

**Olga Alexandrovna Neucheva**
Institute of Materials Research and Engineering (IMRE), Agency for Science, Technology and Research (A*STAR),
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Building of a single molecular device is a complicated process which involves different steps: surface preparation, UHV transfer printing, atomic and cluster manipulation (device assembly), multi-tip spectroscopy and packaging. This talk will focus on the surface preparation and positioning all necessary components of the device: electrodes, atomic wires and molecules.

Hydrogen passivated Si(100) is used as a substrate. The device consisting of metal electrodes, atomic wire contacts and functional molecule is going to be assembled in situ with a help of Omicron Multiprobe System located at Institute of Materials Research and Engineering, Singapore. With a lateral size of a few tens of nm, the Au contact planar nano-electrodes are UHV transfer printed using $MoS_2$ surface stamps on an Si(100) and Si(100)H surface to be STM manipulated on those surfaces. The surface dangling bond atomic wires from the electrodes to the functional molecule will be formed via extracting hydrogen atoms from the Si(100)H passivated substrate. These wires must be relatively long in order to be able to land the 4 UHV STM probes onto the 4 Au nano-electrodes. The preliminary results will be demonstrated.

### About the Speaker

Olga obtained a diploma of Engineer from the Baltic State Technical University of St Petersbourg in Russia, for her work on "Investigation of the optical properties of nanowhiskers". She then did a PhD thesis in RWTH Aachen in Germany on "Investigation of a metal-organic interface - realization and understanding of a molecular switch". She obtained her PhD in 2010. She is now working in IMRE A*STAR in Singapore.

# Atomically Precise Manufacturing via Patterned Si Atomic Layer Epitaxy

**John Randall**
Zyvex Labs, Richardson, Texas USA
jrandall@zyvexlabs.com

Over two decades ago, Don Eigler demonstrated the technological capability of placing atoms within the capture range of chemical bonds. Since that time, this capability has been used across the globe in a wide variety of scientific experiments. Zyvex Labs believes that the there is an opportunity to apply the extremely high precision instrumentation that has evolved since 1990 to nanomanufacturing. Manufacturing has always benefited from improved precision which leads to products with higher performance, better reliability, improved efficiency, and in the long run lower manufacturing costs. Beyond simply improving precision, which is already in the small number of nanometers, there is an opportunity to make precision absolute. A computer controlled process with the ability to make three dimensional designed structures that are not only close to the same size but are constructed with the same number and arrangements of atoms, would be transformative. This talk will present efforts to improve the tools and processes that we expect to make Atomically Precise Manufacturing (APM) possible. We will also present some of the near term products and applications that we expect to produce with APM.

### About the Speaker

John Randall has over 30 years of experience in Micro- and Nano- Fabrication. He joined Zyvex in March of 2001 after 15 years at Texas Instruments where he worked in high resolution processing for integrated circuits, MEMS, and quantum effect devices. Prior to working at TI, John worked at MIT's Lincoln Laboratory on ion beam and x-ray lithography. He has 91 scientific articles published, 25 issued US Patents and loves his wife of 29 years, Patrice, and his two children Ashley and Ian.

# Multi-probe Characterisation of 1D and 2D Nanostructures Assembled on Clean and Hydrogen Passivated Surfaces of Ge(001)

*M. Kolmer, M. Wojtaszek, J. Budzioch, F. Krok, and M. Szymonski*

**Marek Szymonski**

Research Center for Nanometer-Scale Science and Advanced Materials, NANOSAM, Faculty of Physics, Astronomy, and Applied Computer Science, Jagiellonian University, Krakow, Poland, ufszymon@cyf-kr.edu.pl

The demand to discover new, alternative solutions in future electronics has currently focused the attention on the possible use of single atomic wires and conductive mesa pads as components in electronic circuits. For such applications, we need a good knowledge of structural and electronic properties of such 1D and 2D nanostructures fabricated on large and/or moderate band gap semiconductor surfaces. The lecture is reporting on case studies invoking preparation of well organized atomic wires and 2D conductive pads by STM tip aided nanolithography of gold on clean reconstructed Ge(001) surface, as well as dangling bond wires and nanopads obtained by STM tip-induced atom-by-atom hydrogen desorption from hydrogen passivated Ge(001). Structural characterization of the fabricated nanostructures is performed with atomic resolution LT scanning tunneling microscope of the Omicron Nanotechnology multi-probe UHV system. Furthermore, it is demonstrated that I/V STS characteristics could be measured successfully for individual atomic Au and dangling bond wires. Using the far field, high resolution SEM microscope the pre-prepared nanostructures are identified after UHV transfer into a 4-probe station of the system, and their surface conductance could be measured with 2-STM probes for nanowires laying alone and/or in side contact with the 2D conducting pads.

## About the Speaker

Prof M. Szymonski was awarded his PhD from Jagiellonian University, Krakow, in 1978. He joined the Physics Department of the Jagiellonian University in 1973, he was awarded a higher doctoral degree (sa called “habilitation”) in 1982, and he was appointed to the full professor position at this University in 1991. His scientific interest is focused on surface science research with particular emphasis on physics of nanostructures assembled on semiconductor and insulator surfaces and scanning probe methods of nanostructure characterization. Currently he is heading the Department of Physics of Nanostructures and Nanotechnology of the Institute of Physics, Jagiellonian University and he is Director of the Research Centre for Nanometer-Scale Science and Advanced Materials, NANOSAM, at the Jagiellonian University.

# Nano-gears Manipulation

**Cedric Troadec**
Institute of Materials Research and Engineering (IMRE), Agency for Science, Technology and Research (A*STAR), 3 Research Link, Singapore 117602. Singapore
cedric-t@imre.a-star.edu.sg

Top down approach of solid state gears have been demonstrated down to 0.5 µm [1]. In a bottom up approach, 1.2 nm gear molecule [2] have been demonstrated to rotate step by step in a controlled way. Here, we will present the fabrication process of sub 500nm gears, down to 60 nm in outer diameter. The gears can be manipulated one by one, using an atomic force microscope (AFM) tip, to construct a train of gears where mechanical motion can be transmitted from one gear to another by mastering the surface friction. The use of a multiprobe UHV STM with integrated SEM is of great advantage to study the motion and interconnection of these nano mechanical systems from the nanoscale and preliminary results using such integrated machine will be presented.

**References**

[1] Yun Y J, Ah C S, Kim S, Yun W S, Park B C and Ha D H, Nanotechnology, **18** 505304 (2007).

[2] Manzano C, Soe W-H, Wong H S, Ample F, Gourdon A, Chandrasekhar N and Joachim C, Nat. Mater. **8** 576 (2009)

[3] J Deng, C Troadec, F Ample and C Joachim, Nanotechnology **22** 275307 (2011)

## About the Speaker

**Cedric TROADEC** completed his PhD in Physics at the Royal Holloway College, University of London in 2001. His thesis was on hybrid superconductor / ferromagnetic metallic nanostructures: fabrication and study of the proximity effect. After working for ThermoVG Semicon designing gas cells for molecular beam epitaxy, he joined the Institute of Materials Research and Engineering (Singapore) in 2003, where he presently works. His current research interests are in the development of ballistic electron emission microscopy for the characterisation of metal/organic interfaces and in device interconnections from atomic to macroscopic scale.

# Electrical Properties Investigation of Low-dimensional Nanostructures with a Four-Probe Scanning Tunneling Microscope

*H. M. Guo, H. J. Gao*

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In nanoelectronics and molecular electronics, there have been great efforts being concentrated on the electrical characterization on a nanoscale or molecular system. However, the contact effect or impurities between the nanosystems and the electrodes made it difficult to study the intrinsic I-V properties. Scanning tunneling microscopy (STM) is an essential and important tool to investigate local electrical properties and conductivities from contact to tunnel regimes with extreme accuracy, and thus four probe systems associated with SPM have been developed to approach this aim. In this talk, we will present our combined system which contains a four-probe scanning tunneling microscopy and molecular beam epitaxy (FSTM-MBE) for preparation, manipulation, electrical and optical property measurements of nanosystems. As its applications, the experimental works on some typical low-dimensional nanostructures, such as 1D nanowires or nanotubes, thin films and epitaxial graphene/metal substrate hetrostructures will also be discussed. Our results have shown that such combined system is a powerful tool in investigation of electronic transport properties of nanostructures.

*In collaboration with C. D. Zhang, H. L. Lu, M. Gao, J.M. Cai, X. B. He, X. Lin, Y. Pan, and H. Hu, et al.

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## About the Speaker

Prof Hongjun Gao earned his PhD (1994) in the field of physics, Peking University, Beijing, China. He worked at Beijing Laboratory of Vacuum Physics, Chinese Academy of Sciences as an associate professor and then full professor from 1995 to 1997. He was a visiting professor at Oak Ridge National Laboratory from 1997 to 1999. Since 2000, he is a full professor in the Institute of Physics, Chinese Academy of Sciences (CAS) and becomes the deputy-director of this institute. He is the chair of Nanosciences division at the International Union for Vacuum Science, Technique and Applications (IUV-STA), associated editor of Applied Physics Letters and member of Editorial board of New Journal of Physics, deputy council chairman of Chinese Vacuum Society.

# Location Specific Electron Transport Study of 2D Carbon Using Nanoprobes

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Graphene/metal contacts are intensively studied because of their importance in determining the electron transport properties of graphene-based devices. Various aspects such as nature of chemical bonding at the interface, metal-induced doping of graphene, effects of process induced defects, etc., have been investigated both theoretically1 and experimentally.2-4 Like in the cases of other types of semiconductor devices, most of the works reported so far are focused on surface contact. Considering the large anisotropy of graphene in electronic properties between the in-plane and out-of-plane directions, it would of great interest to study how an edge contact would differ from its surface counterpart in terms of electrical transport properties. Due to the ultra-small thickness, however, formation of a pure edge contact using lithographic techniques poses a great challenge. In order to overcome this difficulty, in this work, we have used nanoprobes with high precision position accuracy to form both surface and edge contact with graphene in an ultrahigh vacuum environment (UHV) and studied their electrical transport properties through measuring the differential conductance (dI/dV) as a function of probe-sample bias voltage (V). Measurements have been performed for both graphene sheets grown vertically on a substrate (or carbon nanowalls5) and those exfoliated from highly ordered pyrolytic graphite (HOPG). For the former case, for comparison purpose, we have also performed the measurements on samples coated by a thin Fe layer which was deposited in-situ by using the UHV system.

Figs. 1(a) and 1(b) illustrate the two different measurement configurations that have been employed in this work, including physical configuration, Fermi surface of the probe (using free-electron approximation) and Dirac cone of graphene. The electrical transport measurements were performed at room temperature using an Omicron UHV system equipped with a Gemini SEM and four independently controllable nanoprobes with auto-approaching capability. Before the dI/dV measurements, both the electrochemically etched tungsten (W) tip and carbon samples were thermally annealing at 300oC for 3-4 hours in a separate chamber and then transferred to the measurement chamber without exposing them to air. All the electrical measurements were performed using a standard lock-in technique with an AC current of 10-20 □A and frequency of 1 kHz. During the measurement, one of the probes was used to form a low resistance contact by pressing it strongly against the sample and the other for an adjustable contact resistance. The automatic approaching function of both tips helps to make reliable and reproducible contact without damaging the sample and the probe, unless the substrate is an insulator in which case the first tip has to be sacrificed by being pressed manually on the sample. Figs. 2(a)-(c) show the typical dI/dV curves for the three different types of contacts: (a) surface contact, (b) edge contact, and (c) edge contact with Fe-coated sample. Distinctive dI/dV-V curves have been obtained for three different types of contacts with good reproducibility: a linear curve (dI/dV~V) for the edge-contact, a dI/dV~V3/2 dependence for the surface contact and a parabolic shape (dI/dV~V2) for the Fe-coated samples. Detailed calculations have been carried out to simulate these curves by taking into account the peculiar band structure of graphene. Good agreement has been obtained between experimental and theoretical results.

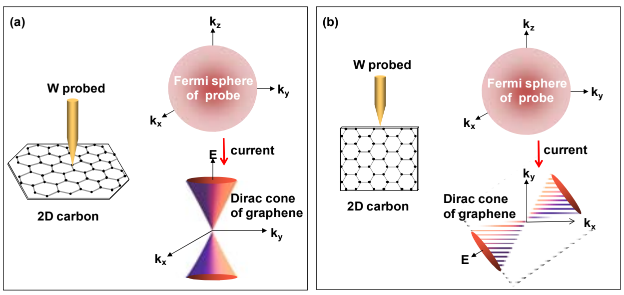


*Fig.1: Schematics of (a) surface and (b) edge contact between graphene and W tip. Also shown are the Fermi sphere of the probe based on the free-electron model and energy dispersion surface of graphene.*

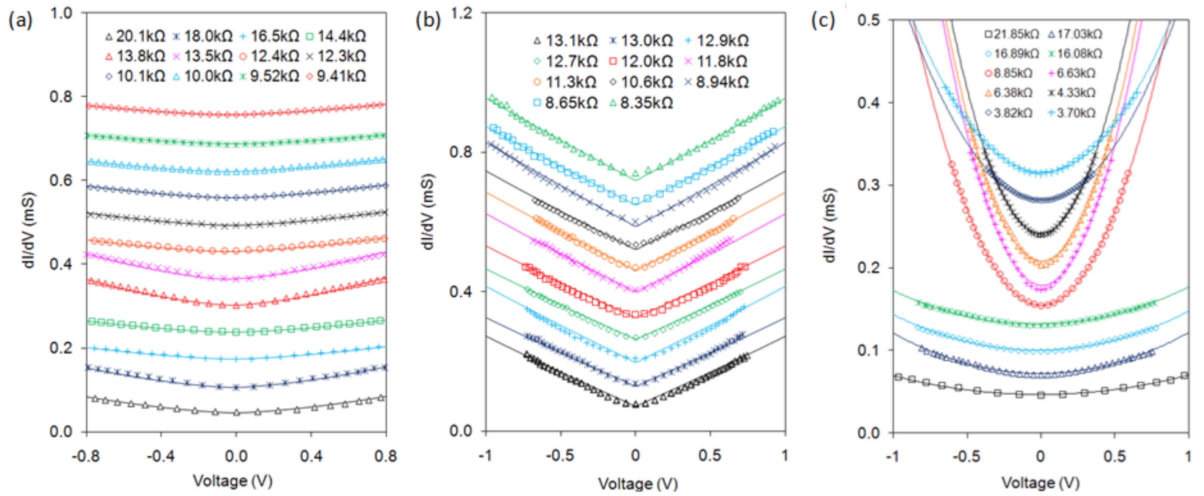


*Fig.2 Typical dI/dV curves for the three different types of contacts taken at different zero-bias resistance values: (a) surface contact, (b) edge-contact, and (c) edge-contact with Fe-coated sample. Symbols are experimental data and solid lines are fitted curves according to relations (a) dI/dV = aV3/2+b, (b) dI/dV = aV+b and (c) dI/dV = aV2+b.*


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## About the Speaker

Dr Wu Yihong received his PhD from Kyoto University in 1991 for his work on low-dimensional wide-bandgap semiconductors and their applications in blue-green lasers. From 1991 to 1996, he had worked at various positions at Center for Optoelectronics, National University of Singapore, Panasonic Singapore Laboratories, and Tohoku University, Sendai, Japan. He re-joined NUS in 1996 and is currently a Professor at Department of Electrical and Computer Engineering, NUS. Dr Wu has been involved in researches in several different areas including optoelectronics, optical data storage, magnetic data storage, spintronics and carbon nanomaterials. His current research interests are in nanoscale spintronics for data storage and logic applications and 2D carbon nanostructures. He has published over 170 journal papers and more than 110 conference papers. He holds 7 US patents.

# Combined STM and Four-probe Resistivity Measurements on Single InAs Nanowires

*C. Durand, M. Berthe, T. Xu, J.P. Nys, P. Caroff, B. Grandidier*

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InAs is a semiconductor well-known for its high electron mobility and the accumulation of electrons at the surface [1], providing ohmic contacts. Such properties are highly compatible with high-speed devices, especially nanowire-based opto-electronics. Such devices are still in need of appropriate test setups in order to improve the control of their fabrication and properties.

In this study, Low Temperature Scanning Tunneling Microscopy (LT-STM) and nanoscale 4-probe transport measurements are combined in order to characterize single InAs nanowires (Fig.1). These nanowires were grown at IEMN and protected before transfer into the microscope. Once unprotected in the preparation chamber, LT-STM showed the atomic reconstruction on the nanowires, proving the cleanliness and control of the growth method. For the transport measurements, the Omicron Nanoprobe turned out to be the tool of choice for connecting single, free-standing, nanowires and measuring their resistivity as a function of probe separation. Resistivity measurements were performed on various single nanowires by the in-line 4-probe method (Fig 1.). These measurements show a constant resistivity of 9.72kΩ/µm across the population of nanowires.

The combination of high resolution LT-STM, SEM and 4-probe measurements for the characterisation of a population of InAs Nanowires gives a good understanding of the transport mechanisms of such structures, it is a preliminary result that demonstrates the interest of such a platform for nano-device testing, even in a complex 3D configuration, before encapsulation.

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**Figures**

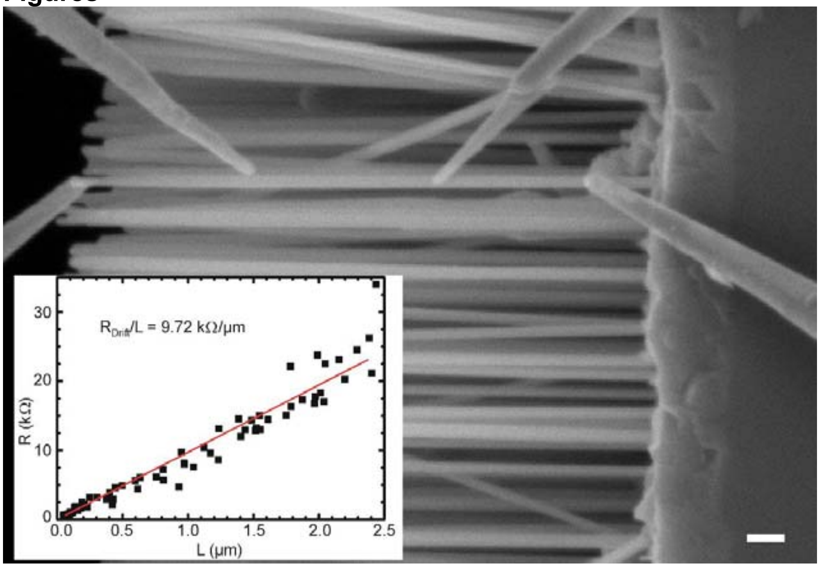
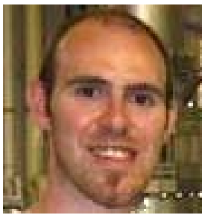



*Figure 1: SEM image (scalebar 200nm) of a single NW contacted with 4 tips. Inset : four-point probe resistivity measured on a population of InAs nanowires as a function of the inner probe separation. The diameter of the nanowires was 70nm, the length 3µm.*

## About the Speaker



After an Engineering diploma from the *Institut Supérieur d'électronique et du numérique (**ISEN**)* of Lille, Maxime Berthe obtained a PhD of Material sciences in 2007. This PhD thesis on electronic transport in confined quantum system by STM and STS was partly done in Japan, ***Shigekawa Lab.*** In Tsukuba (Japon). He is now doing a Post-doc in instrumental development in the field of Scanning Probe Microscopy in the physics group of IEMN.

# Correlating Electron Transport to Local Structures at the Nanoscale

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ORNL Four-probe STM is a "nano" version of a conventional four-probe station; it combines STM local imaging and spectroscopy functions with four-point contact electrical transport capability in a well-controlled sample environment at temperatures down to 8 K [1]. In this talk, I will give a brief overview on this unique facility, and then present a few examples to demonstrate how we are using this platform to study the electron transport properties and the structure/function relationships over multiple length scales, from individual atoms, molecules, to nanowires and mesoscopic systems[2-5]. My focus will be on the measurements of individual grain boundary resistance in copper interconnect nanowires [2] and the manipulations of electronic phases near the Mott metal-insulator transition in a ruthenate surface[4]. The goal of this research is to establish the relationship between transport functionalities and local structural and electronic properties down to atomic scale. This research was sponsored by the Office of Basic Energy Sciences, U.S. Department of Energy.

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## About the Speaker

An-Ping Li is a staff physicist in Oak Ridge National Laboratory with an Adjunct Professor appointment in The University of Tennessee. Before joining ORNL in 2002, he held a Senior R&D Scientist position in Galian Photonics Inc. He obtained his PhD degree in physics from Peking University in 1997 and worked on nano-porous alumina as a Max-Planck-Society Fellow in Max Planck Institute of Microstructure Physics from 1997 to 1999. He has published 50 papers that have been cited more than 2,000 times. His current research interest is electrical transport and novel functionalities in nanostructured materials.

# Electronic and Spin Transport at Surfaces and Nanostructures Measured by Four-Tip STM

*Shuji Hasegawa* and Toru Hirahara*

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Conductivity measurements in sub-micron or nano-meter scale with/without spin resolution are of great interest in nanoscience and nanotechnology. For example, nano-electronics such as semiconductor devices requires low and stable electrical resistance of interconnects to maintain device performance. Spin transport is restricted in nanometer scale in many cases because of a short spin-relaxation length. Several kinds of methods to measure the conductivity at nano scales have been developed including fixed electrodes made by microlithography techniques. A method which adopts tips of scanning tunneling microscope (STM) as electrodes, however, has great advantages in positioning of the probes in arbitrary configurations as well as in high spatial resolution of measurements. We have developed a four-tip scanning tunneling microscope (STM) and metal-coated carbon-nanotube (CNT) tips for it, and demonstrated the ability to measure transport properties at nanometer scale. Resistance of self-assembled silicide nanowires on Si(110) surface [1] and damascene Cu nanowires used in LSI industry [2]. The resistance is now measured at 20 nm scale, and individual scattering events are directly seen as discrete change in resistance. By using CNT tips coated with magnetic metal layer, we can measure spin flow as an additional voltage drop by inverse spin-Hall effect. At a surface of strong-spin-orbit coupling materials, we can expect spin-polarized current due to spin-split surface-state bands [3]. By using ultra-thin films of pure Bi, BiSb, BiSe, and BiTe, I will show that the surface-state bands are really spin-split and the Dirac-cone conductivity is directly measured by microscopic four-point probe method. An on-going project to detect the spin-polarization of surface current by using magnetic tips in a four-tip STM will be also introduced.

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## About the Speaker

Shuji Hasegawa graduated from Master Course of Univ. Tokyo, Dept. Physics in 1985. He then worked for Hitachi Ltd. as a researcher and for the Department of physics of the University of Tokyo, as a research associate and as an associate professor. He is now Professor in this Department of Physics and works experimentally on condensed matter physics.

# Spin Read-out of Precision Placed Single P Atoms in Silicon

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We report low temperature transport measurements of few-to single P donor quantum dots in silicon. Dots with a high donor number (approx. 7) show a surprisingly dense spectrum of excited states with an average energy spacing of 100 micro μeV. The energy spacing of these features is much too low to be accounted for by the nm-scale lateral confinement of either the dot or the leads and can be explained by lifting of valley degeneracy of the dot orbital states [1]. The use of all epitaxial in plane P:Si gates allow us to tune both the electron number in the dot and modulate the transparency of the tunnel barriers [2]. We also present transport through a deterministic single donor device, where we observe both the signature of a single donor directly through STM imaging and demonstrate that the charging energy and excited state spectrum is consistent with the orbital states of a single P-donor. Finally we present our latest results of spin read-out of the single electron spin associated with the precision placed single P atom.

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### About the Speaker

Scientia Professor Michelle Y. Simmons is the Director of the Australian Research Council Centre of Excellence for Quantum Computation and Communication Technology and a Federation Fellow at the University of New South Wales in Sydney, Australia. She has a double degree in physics and chemistry, and after 6 years as a Research Fellow at the Cavendish Laboratory in Cambridge, UK went to Australia in 1999 as a QEII Research Fellow. In 2003 she was awarded a prestigious Australian Government Federation Fellowship for work in quantum electronics. In 2005 she was awarded the Pawsey Medal and in 2006 became the youngest elected Fellow of the Australian Academy of Science. Her research interests are to build devices at the atomic-scale – with the ultimate goal of addressing the issues that industry faces at this scale and investigating the possibility of a silicon-based quantum computer.

# Silicon Atomic Quantum Dots, Qubits, Artificial Molecules and Surface State Conductors, New Theory and Experimental Results

**Robert A. Wolkow**
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A new and rather complex model, including numerous competitive and simultaneous processes will be described to account for the appearance of single dangling bonds on a silicon surface. Previous descriptions were incomplete.

Tunnel coupled dangling bonds will be considered as a charge qubit. While substantial problems prevent deployment of such entities today, such qubits have several attractive attributes, leading among those, the entities are made on and of silicon, and also, the silicon charge qubits have enormously high tunnel rates, larger than expected decoherence rates by many orders of magnitude.

Larger ensembles of silicon dangling bonds can be viewed as quantum dot collectives, or artificial molecules. Numerous provocative structures can be explored. A model system of current interest is the quantum dot cellular automata, due to Craig Lent and Greg Snider and many others. This extraordinarily beautiful and adaptable construct has long been viewed as a kind of ideal that is unfortunately beyond practical realization because of various problems – fabrication and low temperature requirements being foremost among those. We intend to make a functioning, room temperature, atomic silicon-based quantum dot cellular automata device. Demonstrations in this presentation will be limited to the basic building block – the 4 dot cell – and the biasing of that cell. We will as well describe some finer details of our developing characterization of such entities.

A home made multi-probe scanning tunneling microscope will be introduced.

Preliminary results include demonstration of an insulating to highly conducting transition as adsorbates are driven off by heat to free up silicon state states, and, the direct visualization of the potential drop at a single atomic step between terraces on the silicon surface. A coordinated ab initio model result, by student Manuel Smeu, co-supervised by Prof Hong Guo at McGill University, will hopefully be ready for presentation also.

### About the Speaker

Dr Robert Wolkow was born in Canada in 1958. He obtained a PhD from the University of Toronto in 1987 under the supervision of Professor Martin Moskovits. Then, he studied first atom-resolved surface chemistry as a postdoc at IBM, Yorktown Heights and received a T.J. Watson IBM Outstanding Achievement Award in 1989. As a staff scientist at Bell Laboratories, he developed first cryogenic variable temperature STM, solved the Si (100) structure and observed new adsorption phenomena. From 1992 he progressed in the National Research Council of Canada, working the Scanning Tunneling Microscopy group and then led the molecular interfaces group. He is now professor of physics in the University of Alberta, and also Molecular Scale devices group leader and principal research officer at NINT/NRC in Edmonton Alberta.

# UHV Nano-probe Surface Conductance Measurements on $MOS_2$

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To realize the ultimate scaling down of electronic logic devices, variety in instruments and processing procedures need to be involved. In this regard, the Interconnection Machine established in Institute of Materials Research and engineering (IMRE) is a giant leap towards building atomic scale logic devices. In this talk, I will focus more on the Multi-probe part of the IMRE interconnection machine including the Scanning Electron Microscope (SEM). The Au(111) and $MoS_2$ surface were selected as model surfaces to perform preliminary measurements with the UHV-Nanoprobe. To identify the position of the tips and separation on the surface, we used high resolution UHV SEM, a part of the IMRE interconnection machine. First results of the surface conductance measurements on $MoS_2$ surface at room temperature and Liquid Helium temperature will be presented.

### About the Speaker

Ramesh M.Thamankar studied a MSc in Mangalore University, India and a Masters in technology (M.Tech) in the National Institute of Technology, Karnataka, India. He obtained his PhD in 2004 at the Freie Universität in Berlin, Germany. He then worked for the Physics Department of the University of California, Riverside and for the Max-Planck Institute for Microstructure Physics in Halle (Germany). Since 2010, he works for IMRE in Singapore and his research is focused on single molecular electronics, scanning tunneling microscopy and on magnetism in low dimensions.

# Electronic Transport on the Nanoscale

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A scanning tunneling microscope with several tips is ideally suited to analyze the electronic transport through objects on the nanoscale. Two different configurations will be discussed. The lateral transport of electrons may be studied by using two tips to drive a current parallel to the surface. A third tip enables to map the corresponding electrochemical potential. Measurements for a 2D conducting layer will be discussed. To analyze the transport perpendicular to the surface, a thin metallic layer is placed on a semi conducting surface. At the interface a Schottky barrier is formed, which can only be overcome by electrons of sufficient energy. This may be used to split the tunneling current coming from the tip of the microscope, into the ballistic electrons and the electrons which underwent inelastic scattering processes. This technique has been applied to study the ballistic transport of electrons through individual molecules. On the other hand inelastic processes may be revealed by analyzing the fluctuations in the tunneling current observed at different positions of the tunneling tip above an adsorbed molecule.

## About the Speaker

Rolf Möller has been professor at the University of Duisburg-Essen since 1994. He is interested in electronic transport on the nanoscale, elementary processes of friction and in geometric and electronic structure of organic molecules adsorbed on inorganic surfaces. He studied Physics in Freiburg and in Grenoble and experienced research as a visiting scientist at the Stanford Research Institute (USA). He obtained his PhD with honors in 1986 from the University of Freiburg and worked then as a post doctorate fellow at IBM Rüschlikon Laboratory (Switzerland).

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