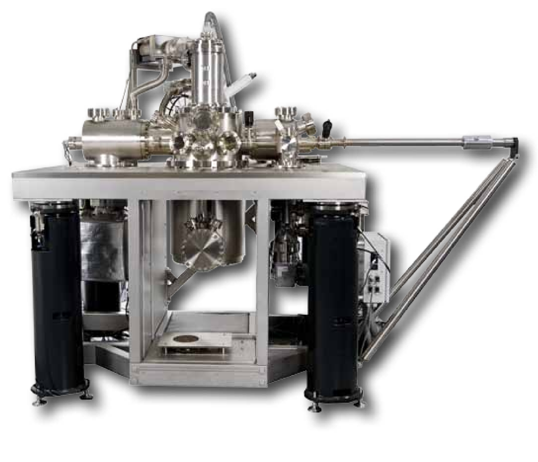
New Experiments and Applications Made Possible by a Low Temperature 4-Tip STM with UHV SEM Navigation

A. Bettac, B. Günther, J. Köble, J. Chrost, J. Hilton, F. Henn, A. Feltz - Email: a.bettac@omicron.oxinst.com -- Omicron NanoTechnology, Germany

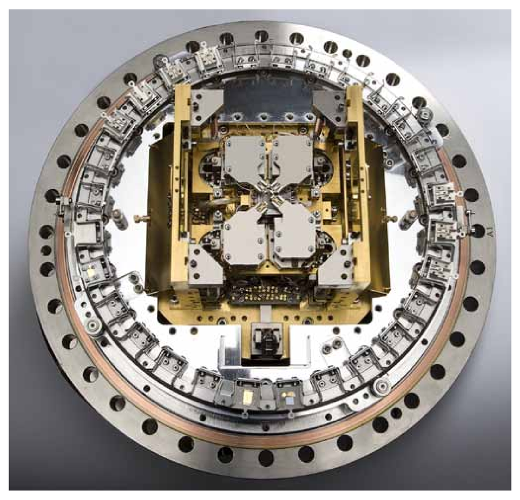
Introduction

A major challenge in the development of novel devices in nano- and molecular electronics is their interconnection with larger scale electrical circuits that are 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.
Recently we developed a new microscope stage that merges the requirements of a SEM navigated 4-probe STM and at the same time satisfies the needs for high performance SPM at low temperatures.

The Microscope Stage



Low Temperature UHV system. LHe/LN2 bath cryostats at the bottom, SEM column at the top.



4-tip SPM (LT NANOPROBE*) stage: 4 individual probe stations and a sample acceptor stage in the centre.

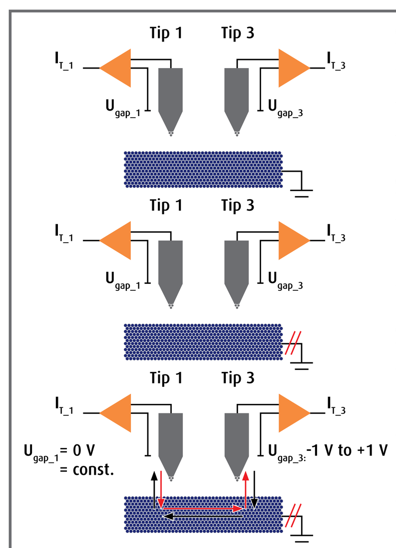
Major Technical Requirements:

Major technical requirements of the instrumentation include:

- Rapid and simultaneous SEM navigation of four local STM probes on small structures in the temperature range of 5 K to 300 K.
- Localization of nanostructures by high resolution SEM (UHV Gemini).
- Individual probe fine positioning by atomic scale STM and NC-AFM imaging.
- STM based probe approach for „soft-landing“ of sharp and fragile probes and controlled electrical contact for transport measurements.
- Suitable low noise signal re-routing for transport measurements with third party electronics.
- Thermal equilibrium of sample and probes for (i) extremely low thermal drift and electrode positioning accuracy in time and (ii) defined temperature of the local electrical contact.
- Performance and stability level of each individual STM probe suitable for STM spectroscopy and atom manipulation.
- Preparation techniques for sharp and clean SPM tips.

A New Type of Experiment: Multi-Barrier Tunneling Spectroscopy

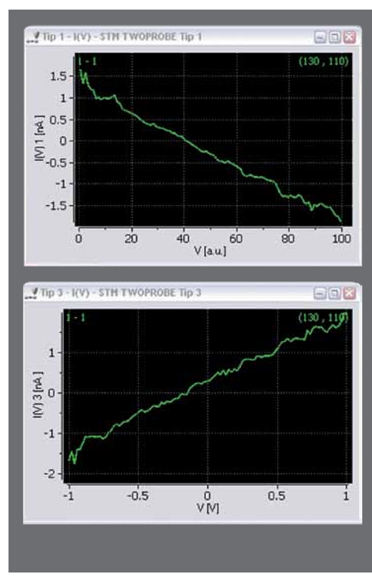
In this experiment up to 4 tips can be placed at different positions above the nanostructure to perform tunneling spectroscopy from one tip to up to 3 other tips via a floating sample (without mechanical contact of tip and nanostructure).
Thus we can gain additional information about preferred current paths in a large molecule/nanostructure. This type of measurement requires a vertical stability in the pm range and very low lateral and vertical drifts between the tips and sample.



Step 1:
- approach of both (all) tips in STM feedback
- tips at gap voltage
- sample grounded

Step 2:
- switch the feedback off (tips are still in tunneling distance)
- disconnect the sample from ground potential

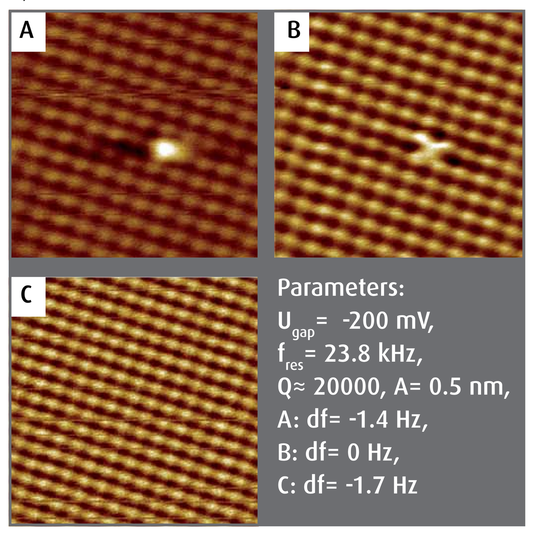
Step 3:
- keep the gap voltage of tip 1 constant at U_{gap_1}=0 V
- ramp the voltage of tip 3 from U_{gap_3}=-1 V to U_{gap_3}=+1 V
- synchronous measurement of tunneling current at both tips while ramping the voltage U_{gap_3}



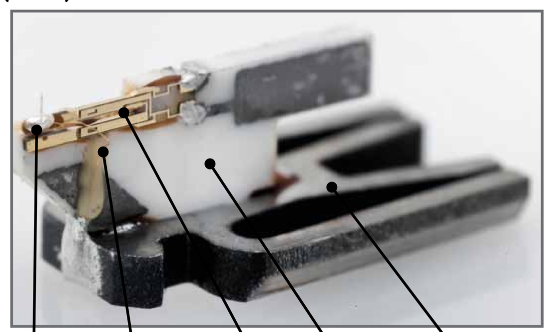
Simultaneously measured I-V curves: Ugap of tip 1 was kept constant while U_{gap} of tip 3 was ramped from -1 V to 1 V.

First NC-AFM QPlus Results with LT NANOPROBE

QPlus NC-AFM Measurements on NaCl(001) at 4.4 K



Parameters:
U_{gap}= -200 mV,
f_{res}= 23.8 kHz,
Q≈ 20000, A= 0.5 nm,
A: df= -1.4 Hz,
B: df= 0 Hz,
C: df= -1.7 Hz



If nanostructures are deposited on an insulating substrate (for better electrical decoupling of the nanowire), an AFM is needed for imaging and tip fine positioning.
For this purpose, a QPlus NC-AFM detection mode was implemented.

Atom Manipulation

The atom manipulation experiment takes place in 4 steps:

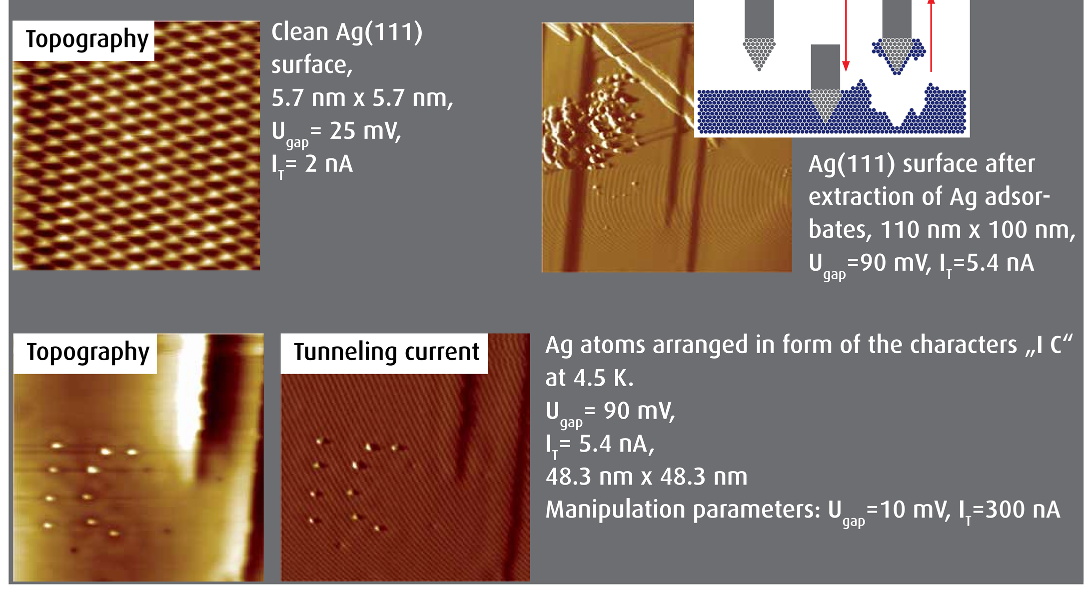
Step 1: Imaging the surface with a certain set of measurement parameters (imaging parameters) in order to find the current position of the adsorbate to be moved.

Step 2: Definition of a parameter set for manipulation (tunneling voltage, tunneling current, move speed, etc).

Step 3: Definition of a position for picking up and laying down the adsorbate (vector can be easily defined by mouse control in the image that was recorded in step 1).

Step 4: The scanning process is interrupted and the tip moves automatically to the pick-up position. After reaching this position, the parameters are changed from imaging parameters to manipulation parameters and the tip is moved along the manipulation path (as defined in step 3). After reaching the lay-down position, the parameters are switched back and imaging is continued.

STM atom manipulation on Ag(111) at T<5K

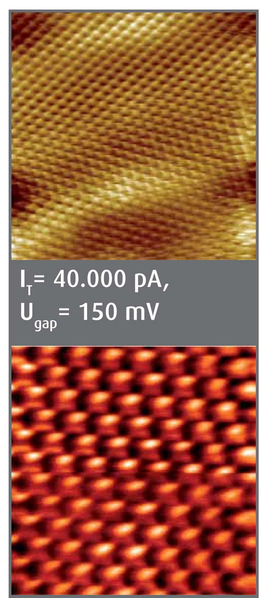


Clean Ag(111) surface, 5.7 nm x 5.7 nm, U_{gap}= 25 mV, I_T= 2 nA

Ag(111) surface after extraction of Ag adsorbates, 110 nm x 100 nm, U_{gap}=90 mV, I_T=5.4 nA

Ag atoms arranged in form of the characters „I C“ at 4.5 K.
U_{gap}= 90 mV,
I_T= 5.4 nA,
48.3 nm x 48.3 nm
Manipulation parameters: U_{gap}=10 mV, I_T=300 nA

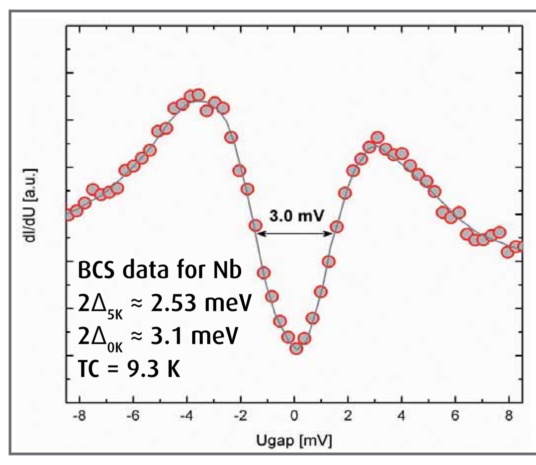
STM Measurements on Au(111) at T = 4.5 K



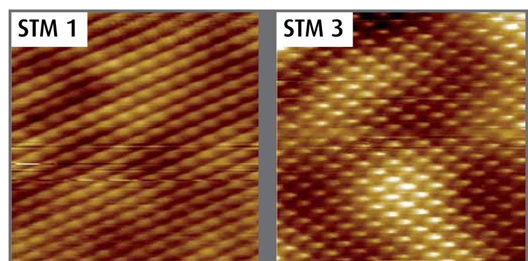
I_T= 40.000 pA, U_{gap}= 150 mV

I_T= 10 pA, U_{gap}= 7 mV

STM measurements with atomic resolution on Au(111) measured with high and low tunneling current.



Scanning tunneling spectroscopy measurement at temperatures below 5 K, spectrum shows the superconducting energy gap of the Nb tip on a Au(111) sample.
U_{GAP}=80 mV,
I_{SET}=40 nA,
f_{MOD}=540 Hz,
U_{MOD}=140 µV



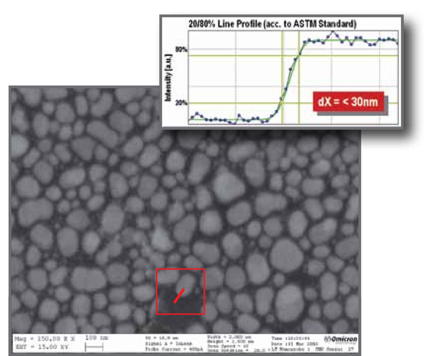
STM 1: 5 nm x 5 nm, U_{gap}= 200 mV, I_T= 9 nA

STM 3: 5 nm x 5 nm, U_{gap}= 190 mV, I_T= 12 nA

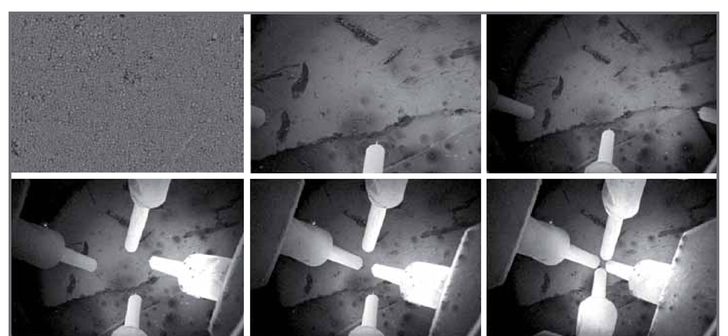
Simultaneous and independent imaging with 2 of the 4 STM modules.

STM mode ensures extremely accurate probe positioning and STM-based safe tip approach of fragile probe tips with diameters in the range of a few ten´s of nanometres or less. STM imaging is required for final precise positioning of the probe tip when it shadows nm-sized structures in the SEM field of view or if the structures are even smaller than accessible by SEM.
Each STM module is designed to achieve atomic resolution on metal surfaces with pm stability.

SEM Imaging and SEM Controlled Navigation at Low Temperatures



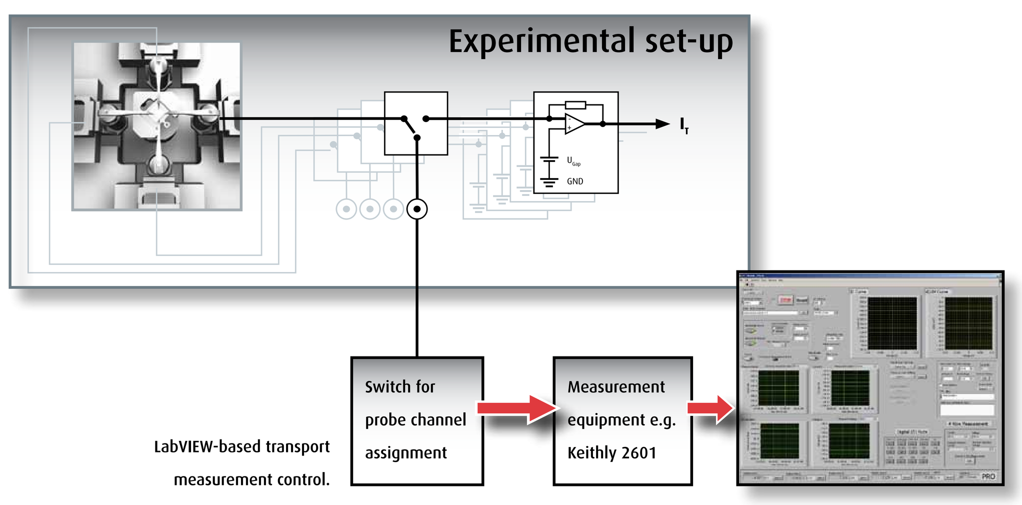
SEM imaging at <5K
The specified resolution was determined by using a Au island on a carbon surface.

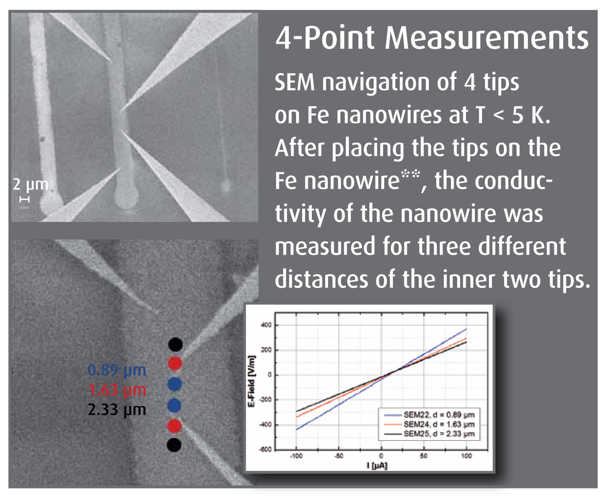


Sequence of SEM images taken at T < 5 K shows the coarse positioning of the four STM probes under SEM navigation.

For the navigation of four independent STM probes, simultaneous SEM imaging is indispensable to bridge dimensions from the mm-scale down to the nm-scale. The SEM enables a large field of view for probe coarse positioning as well as high resolution for fine positioning and rapid localization of small structures.

SEM and 4-Point Contact Measurements





4-Point Measurements

SEM navigation of 4 tips on Fe nanowires at T < 5 K. After placing the tips on the Fe nanowire**, the conductivity of the nanowire was measured for three different distances of the inner two tips.

*The LT NANOPROBE has been developed in collaboration with the 'Inst. f. Festkörperforschung' (IFF, Prof. C. M. Schneider) at the 'Forschungszentrum Jülich', Germany.
**Sample courtesy of H. Marbach, University of Erlangen, Germany.