Precision Local Electrical Probing: Potential for the Analysis of Nanocontacts and Nanointerconnects

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Introduction

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 ultimate scanning tunneling microscopy (STM) precision can significantly improve efficiency in analyzing individual nano-electronic devices without the need for full electrical integration.

Measurment Systems

Among the few commercial approaches, the Omicron UHV NANOPROBE has been established as a suitable instrument for local electrical probing on nanostructures down to structure sizes in the 10 nm range. The major technical requirements of such sophisticated instrumentation are:

- Rapid and simultaneous scanning electron microscopy (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
- Temperature variation from 50 K to 500 K
- Suitable low noise signal re-routing for transport measurements with third-party electronics
- Preparation techniques for sharp and clean STM tips

Although the UHV NANOPROBE has been successfully used for various applications, today's scientific requirements motivated the development of the next-generation probing system. The new LT NANOPROBE (Figure 1) has been specifically designed for local and non-destructive scanning probe microscopy (SPM)-based 4-point measurements at low temperatures. It opens up new research opportunities in nanoelectronics, spintronics, and molecular electronics. Besides SPM probe fine navigation and imaging, the improved SPM performance of the LT NANOPROBE expands applications to tunneling spectroscopy and even the creation or modification of nanostructures by a precise SPM probe.

The development project was driven by the following major milestones:

- Operation at temperatures of $T < 5\,\mathrm{K}$ for SPM imaging and STM based probing.
- SEM navigation at a base temperature of $T < 5\,\mathrm{K}$.
- 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.
- Option to operate each SPM probe module in NC-AFM mode for experiments on insulating surfaces.
- Each SPM probe module capable to achieve atomic resolution in STM mode on metals and semiconductors and in NC-AFM mode on insulators.
- Picometer stability of each STM probe for STM spectroscopy and atom manipulation.

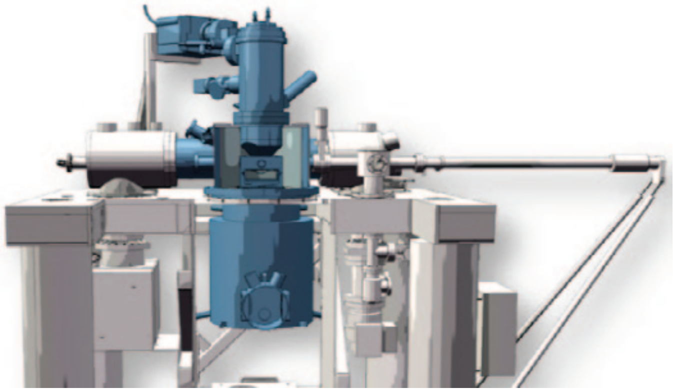


Figure 1: Schematic showing the LT NANOPROBE concept. LHe/LN2 bath cryostat at the bottom and SEM column at the top.

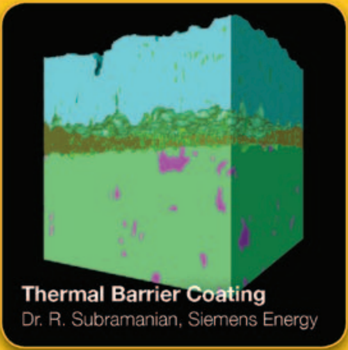
SEM Imaging and Tip Navigation

For the navigation of four independent STM probes, simultaneous SEM imaging is necessary to bridge dimensions from the mm scale down to the nm scale. The SEM enables a large field of view for coarse probe positioning as well as fine positioning and rapid localization of small structures with its high-resolution capabilities (Figure 2). As a suitable tool for that purpose, the UHV Gemini column offers unsurpassed resolution under true UHV conditions. In combination with the Low Temperature UHV NANOPROBE, the in-lens secondary electron detector (SED) represents a key advantage. Only one small access port in the thermal shield compartment of the microscope stage (at $T < 5\,\mathrm{K}$) is needed, thus minimizing thermal impact, while still offering a suitable signal for high-resolution imaging.

Microscope Stage Design

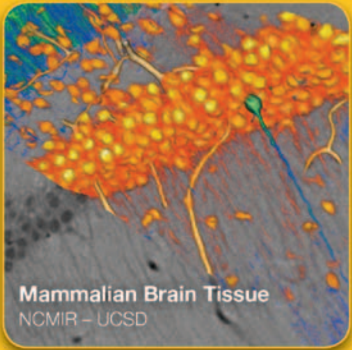
Cooling the whole microscope to LHe temperatures requires the stage to be extremely compact, only $100 \times 100\,\mathrm{mm}^2$ in size. This is a real challenge if four independent STMs need to be fully functional.

An efficient thermal shield compartment allows for temperatures well below 5 K, low thermal drift, and thermal equilibrium of sample and probes. In addition, the integration



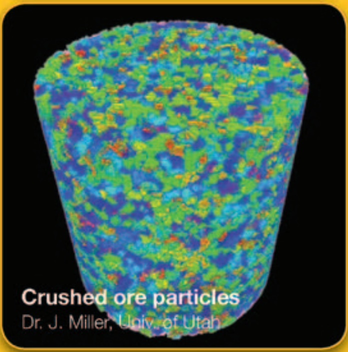
Thermal Barrier Coating
Dr. R. Subramanian, Siemens Energy

Mite on Spider Fossil
Prof. P. J. Withers, Univ. of Manchester

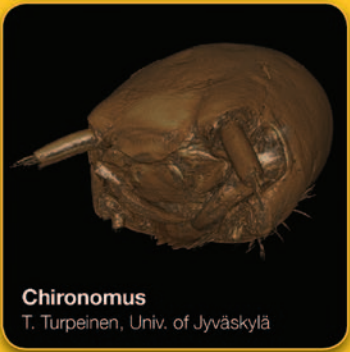


Mammalian Brain Tissue
NCMIR – UCSD

Mouse Knee Vasculature
M. Riccio, Cornell University

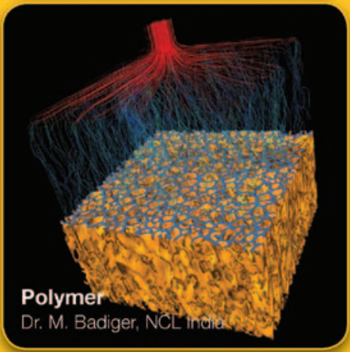


Crushed ore particles
Dr. J. Miller, Univ. of Utah

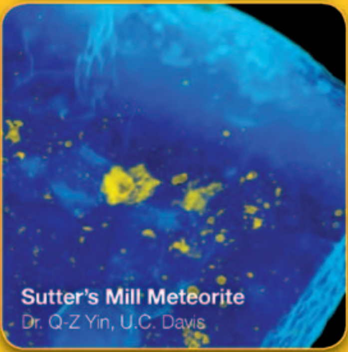


Chironomus
T. Turpeinen, Univ. of Jyväskylä

Bump Short
ST Crolles



Polymer
Dr. M. Badiger, NCL India



Sutter's Mill Meteorite
Dr. Q-Z Yin, U.C. Davis

Amia Teeth
Prof. B. Metscher, Univ. of Vienna

Defective TSV
ST Crolles

Liver Corrosion Cast
T. Gregor, Univ. of W. Bohemia

https://doi.org/10.1017/S1551929513000084

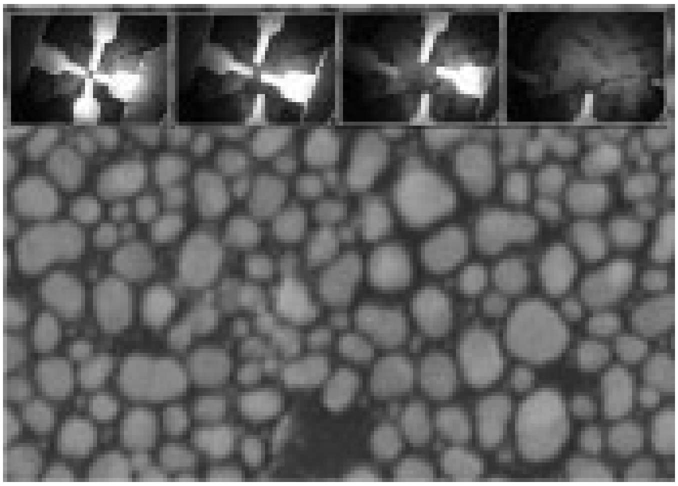


Figure 2: Sequence of SEM images taken at $T < 5$ K. Inserts: Coarse positioning of the four STM probes under SEM navigation. Main image: High-resolution SEM imaging on Au islands on carbon with a typical island size of smaller than 100 nm.

of high-resolution SEM navigation requires a small SEM working distance. Because the SPM probe tips are located between the SEM column and the sample, a very flat SPM scanner was developed to fit into this small space. This sophisticated, very compact shared-stack scanner ensures highly linear, orthogonal, and stable STM scanning characteristics.

For ultimate STM performance, the microscope stage employs an effective eddy current damped spring suspension. The system provides a locking mechanism to lock the spring suspension for optimal SEM working conditions.

The microscope stage (Figure 3) carries four individual SPM modules with independent and guided 3D coarse positioning of $XYZ = 5 \times 5 \times 3$ mm. The sample can be independently positioned by $XY = 4 \times 4$ mm. Omicron's patented piezo-electric inertia drives provide highly reliable and efficient navigation with step sizes from a few tens of nanometers up to several hundred nanometers. Fine positioning as well as STM and NC-AFM (QPlus) imaging with atomic resolution is achieved by shared-stack scanners with a $XY = 1 \times 1$ μm^2 scan (fine positioning) range at LHe temperatures. The sample acceptor stage is compatible with Omicron's standard flat sample plates with a maximum sample size of 10 mm × 10 mm. A fast and secure tip and sample exchange is crucial for ease of use and high throughput. Individual probe modules are moved to a tip exchange position, and spring-loaded tip carriers can easily be exchanged by wobble-stick. Twenty-eight samples or tips are accessible from the stage-integrated storage carousel (Figure 3). The use of a high-resolution SEM column for tip navigation from above implies an unconventional cryostat concept. A specifically designed bath cryostat with LN2 and LHe reservoirs allows for a measurement time of >36 hours at $T < 5$ K and cools the microscope stage from below. A LN2 and LHe double shielding minimizes thermal impact on the stage and employs doors for tip/sample exchange, operated by wobble-sticks. In addition, the sample stage facilitates a controlled thermal coupling for a defined sample temperature and quick sample cool down.

Electrical Transport Measurements

In this case, the four STM tips will be positioned above the nanostructure under SEM control. The following fine approach of the tips is carried out in STM mode. During the STM approach, the distance control is based on tunneling current feedback and therefore requires a dedicated low noise I/V converter. When the tunneling contact is established, the probe-sample distance is well controlled in the nm range. To establish an electrical contact and to control its resistance, the STM feedback is deactivated, and the probe is manually approached by piezo scanner *z*-offset. Afterwards a pA-STM compatible and TTL trigger controlled switching technology is used to reroute the signals of the four probes to external

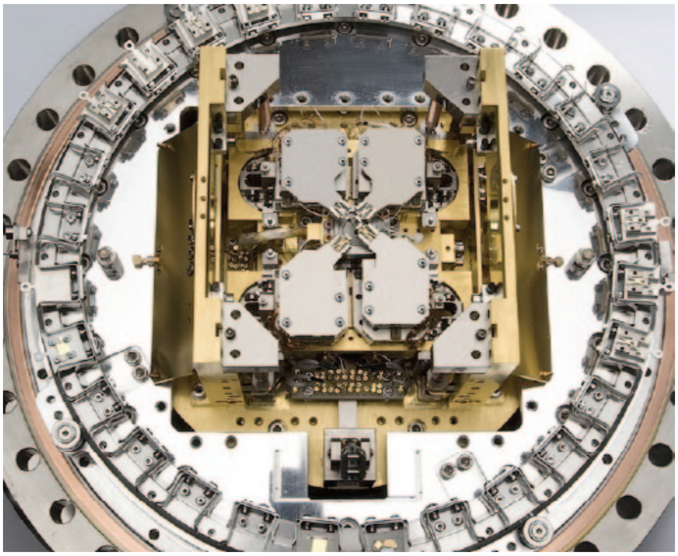


Figure 3: Image of the LT NANOPROBE stage.

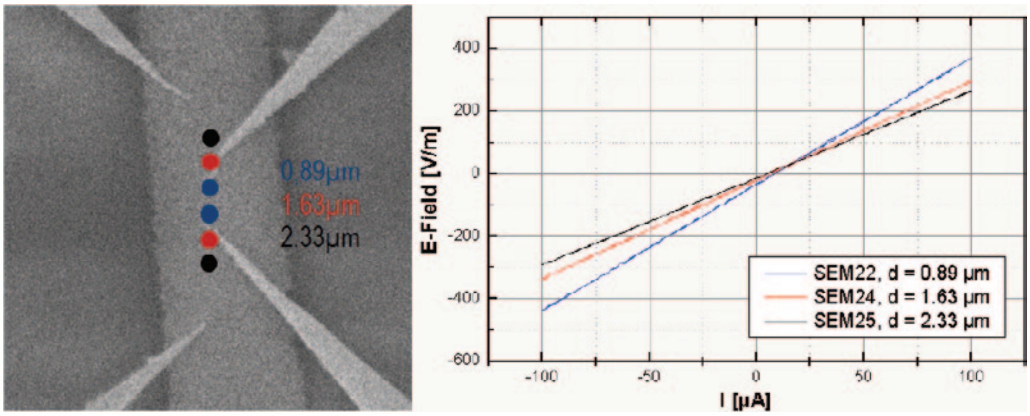


Figure 4: The four tips were navigated at a temperature of below 5 K under complete SEM control. After placing the tips on the Fe-nanowire (left), the conductivity of the nanowire was measured for three different distances of the inner two tips (right). Sample courtesy of H. Marbach, University of Erlangen (Germany).

BNC connectors and external third-party measurement electronics (Source Measurement Unit) for 4-point conductance measurements (Figure 4).

Scanning Probe Microscopy

STM is the key to advancing probing technology into the nanometer scale. It ensures extremely accurate probe positioning and STM-based safe tip approach of fragile probe tips having diameters in the range of a few tens of nanometers or less. STM imaging is required for final precise positioning of the probe tip when it shadows nanometer-sized structures in the SEM field of view or if the structures are even smaller than accessible by SEM.

All four probe modules of the LT NANOPROBE achieve state-of-the-art STM performance on metals (Figure 5) with pm stability and thus open up the route for new experiments beyond local electrical probing, such as dI/dV spectroscopy and atom/molecule manipulation (Figure 6). Furthermore, a fascinating experiment, the so-called multi-barrier scanning tunneling spectroscopy, that is, tunneling spectroscopy from one STM tip to up to three other STM tips via a floating sample, is made possible by the very low lateral and vertical drift of tips and sample and high mechanical stability.

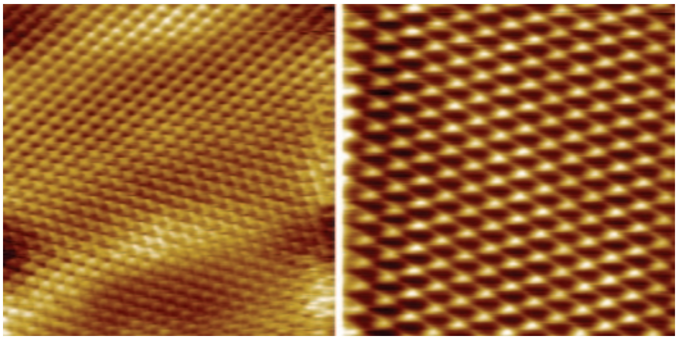


Figure 5: STM measurements with atomic resolution on metal surfaces Au(111) (left) and Ag(111) (right) at a temperature of $T < 5$ K.

To evaluate the system performance, scanning tunneling spectroscopy measurements have been performed. As a very simple but reliable experiment, superconducting Niobium has been used as a tunneling tip on a Au(111) sample. Modulation spectroscopy measurements at a temperature below 5 K reveal the superconducting gap with a width of approximately 3 meV (Figure 6). Deviations of the gap shape and width from BCS theory can be attributed to a non-clean Nb tip and related parallel tunneling processes (for example, ohmic shunt). Nevertheless the measurement represents physical proof of (i) the tunneling tip being superconducting and (ii) at a temperature significantly below T_C.

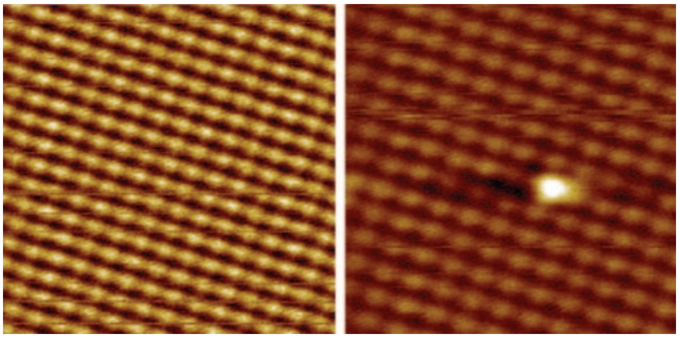


Figure 7: High-resolution QPlus-NC-AFM images of a NaCl(001) surface at $T = 4.4$ K. Imaging parameters: $f_{res} =$ 23.8 kHz, $A \approx 0.5$ nm, $Q \approx 20.000$, $U_{gap} = -200$ mV, left: $\Delta f = -1.7$ Hz, right: $\Delta f = -1.4$ Hz.

A further milestone in the development of the instrument was the implementation of the QPlus- NC-AFM mode for AFM imaging on insulating surfaces [1].

The QPlus measurement becomes important if nanowires or nanostructures are deposited on an insulating substrate for a better electrical decoupling of the nanowire from the substrate. In this case the QPlus sensor can be employed to locate the nanostructures and, after finding the structure, to carry out conductance measurements. The realized QPlus setup in the LT NANOPROBE enables NC-AFM measurements with atomic resolution on insulating surfaces (Figure 7).

Conclusion

The Low Temperature NANOPROBE defines a new class of analytical instrumentation that merges SEM navigated nanoprobing at LHe temperatures with high-performance STM imaging, spectroscopy, and manipulation. It thus may represent a "next generation SPM" for creating functional devices by SPM technologies and investigating electrical properties in one experiment. The measurements shown in SEM, STM, QPlus-NC-AFM, and STS at low temperatures represent a first performance proof for its suitability for advanced STM modes such as STS, IETS, SP-STM, atom manipulation, and multi-barrier scanning tunneling spectroscopy.

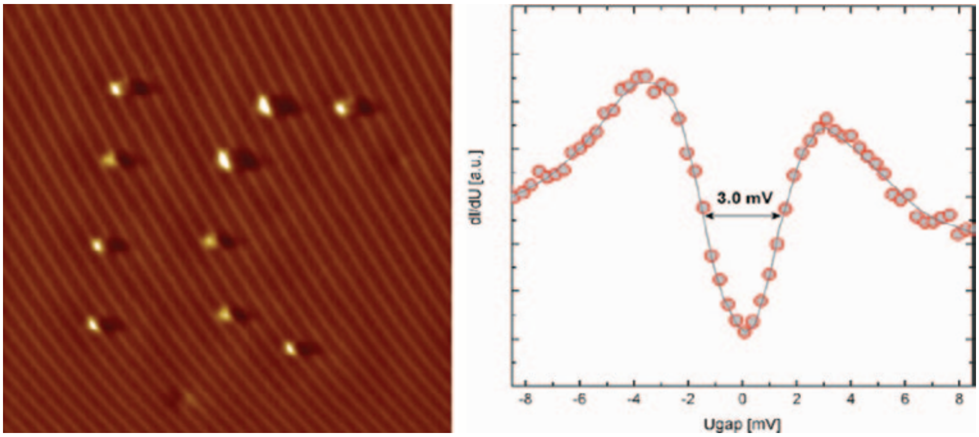


Figure 6: Left: atom manipulation of Ag atoms/clusters on an Ag(111) surface at $T < 5$ K. Right: Scanning tunneling spectroscopy measurement at temperatures below 5 K. Spectrum shows the superconducting energy gap of the Nb tip on a Au(111) sample. $U_{GAP} = 80$ mV, $I_{SET} = 40$ nA, $f_{MOD} = 540$ Hz, $U_{MOD} = 140$ µV.

Reference

[1] FJ Giessibl, *Appl Phys Lett* 73 (1998) 3956.

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