THE SEM/FIB WORKBENCH: Automated Nanorobotics system inside of Scanning Electron or Focussed Ion Beam Microscopes

I. Burkart, R. Kaufmann, V. Klocke*

* Klocke Nanotechnik, Aachen, Germany, info@nanomotor.de

ABSTRACT

A good part of the understanding about material functions and process technologies was developed through preparation, handling and assembly of materials under light microscopes. But technology also depends on structure dimensions that are smaller than the wavelength of light. In light microscopy it is natural for everybody to use manual or automatic toolsets like tweezers, knives, hooks, probes and several different measurement tools. Without such handling, manipulation and manufacturing tools many present-day products and methods would not exist. No wristwatch, no in vitro fertilization, no mini-gearbox, just to mention a few. The operators of SEM, FIB or Dual Beam systems generally work without toolsets and call it natural, although the wavelength limit of light is no physical boundary for using such tools. It can be imagined how technology would be pushed when a SEM/FIB Workbench reaches the same degree of practicability and utilization as toolsets for light microscopes..

Keywords: Nanorobotics, Nanomanipulator, SEM/FIB Workbench, Nano-Workbench

1 CHALLENGES

In a standard SEM/FIB system no stereo image is available, the height information is missing and a field of view of a few millimeters does not allow to see the handling tools moving from parking positions into the center. Cutting a line into a slightly tilted sample surface becomes a nightmare, when the operator is left alone with manually operated Nanomanipulators. The development of valuable applications depends on the combination of several important features in one global system. The main challenges are:

- Nanomanipulators including automation, for movement of endeffectors, sample handling, Nanomanipulation,
- Plenty of different endeffectors for nano- probing, cutting, cleaning, force distance or wear measurements, gripping, sorting or material preparation and processing,
- Automatic in-situ tip cleaning process, e.g. for continuous nano-manipulation or nano-cutting,
- Automatic 3D tool position and sample position detection, 3D sample topography measurements,

- Modular design for fast configuration & teaching of nano-analytical or nano-handling processes,
- Precise control of all tool positions including SEM/FIB sample stage in global coordinates,
- SEM image assisted "Live Image Positioning",
- One common automation control for Nanorobotics and SEM/FIB.

Fulfilling all upper development tasks expands the SEM/FIB to a material processing system and a nano-analytical workbench and enables new applications from material research over live sciences, tribology, forensics, semiconductor technology up to nano-fabrication [1].

2 APPLICATIONS

Several examples of these new research and development fields will be described during the presentation. A few examples follow now.

The Figure 1 includes three rows with different applications realized in the same setup of this SEM/FIB Workbench:

1) Nano-Probing of Semiconductors or in this case of Gold55-Clusters arranged in chains [2]: The electrical conductivity along these gold chains is measured over different distances and compared with the conductivity of bare gold wires. The tip distance varies the chain length and the resistivity. Tunneling barriers get visible in these experiments and the results can be seen as first step towards a cross-bar device by single-electron charging.

2) Nano-tribology and similar measurements can be performed in high resolution (friction, reliability, current and heat load, elasticity, wear). The elastic structure in the top part of this image is one spacer out of an array with millions. Within this system it is possible to measure elasticity and stress tests at one single of these spacers. These spacers are used in display industry and normally are only tested as whole array. The stress tests at single spacers enable a statistics about the spacer efficiency. The thin wire between the two manipulator tips in the bottom right part of this picture is a single Carbon Nanotube burdened with a current for heat and stress tests as well as for conductivity measurements [3]. Another example from the field of bionics is to measure the elasticity during bending a leg of a fly above its top joint with a force distance curve.

3) The left SEM image is measured by a "Dimensional SEM" module quantitatively, in the middle

image as 3D-Topography, in the right image by scaled line scans. In addition roughness and dimensions can be measured [4]. This 3D-Measurement device combines the capabilities of a Profilometer and a coordinate measuring machine with Centimeters of stroke and nanometer resolution. Since it is part of the SEM/FIB Workbench it can not only be used as measurement tool like an AFM, its functionalities can be integrated into application processes. One example therefore is the usage for detecting the slope of a sample surface that shall be treated by nano-cutting.
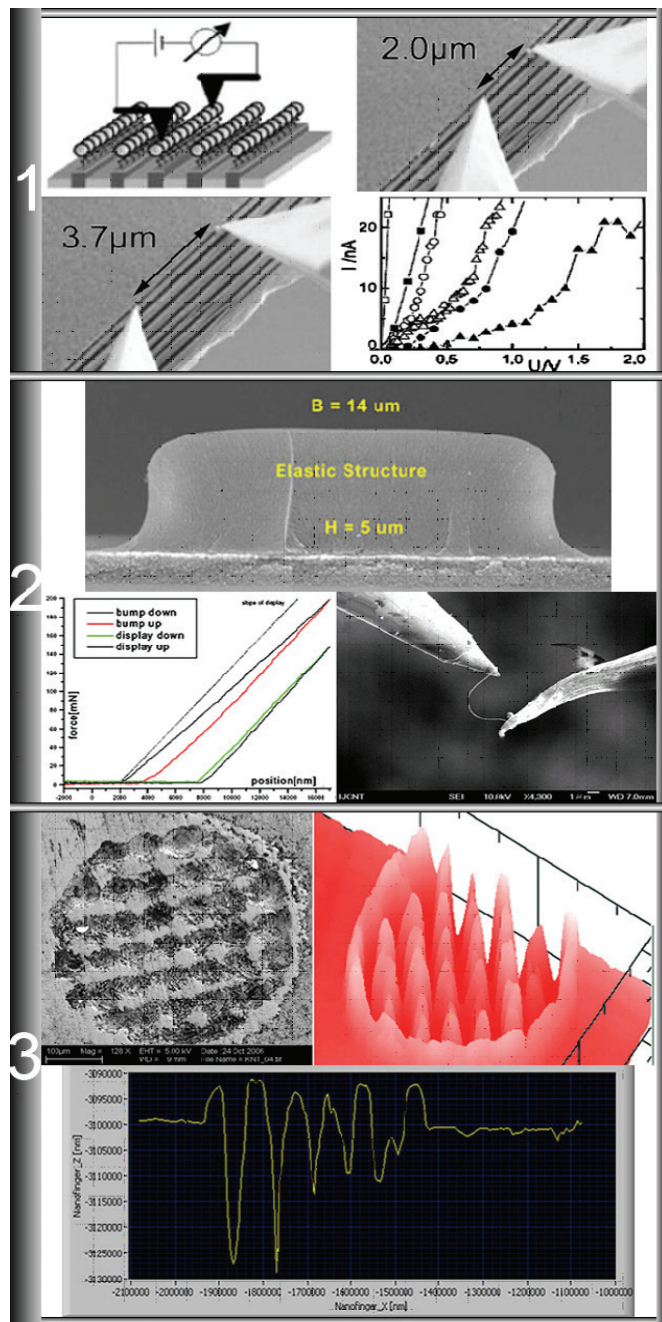

Figure 1: First set of three examples for in SEM/FIB Nanorobotics applications in the field of 1) nano-probing, 2) nano-tribolgy, 3) 3-dimensional measurements.

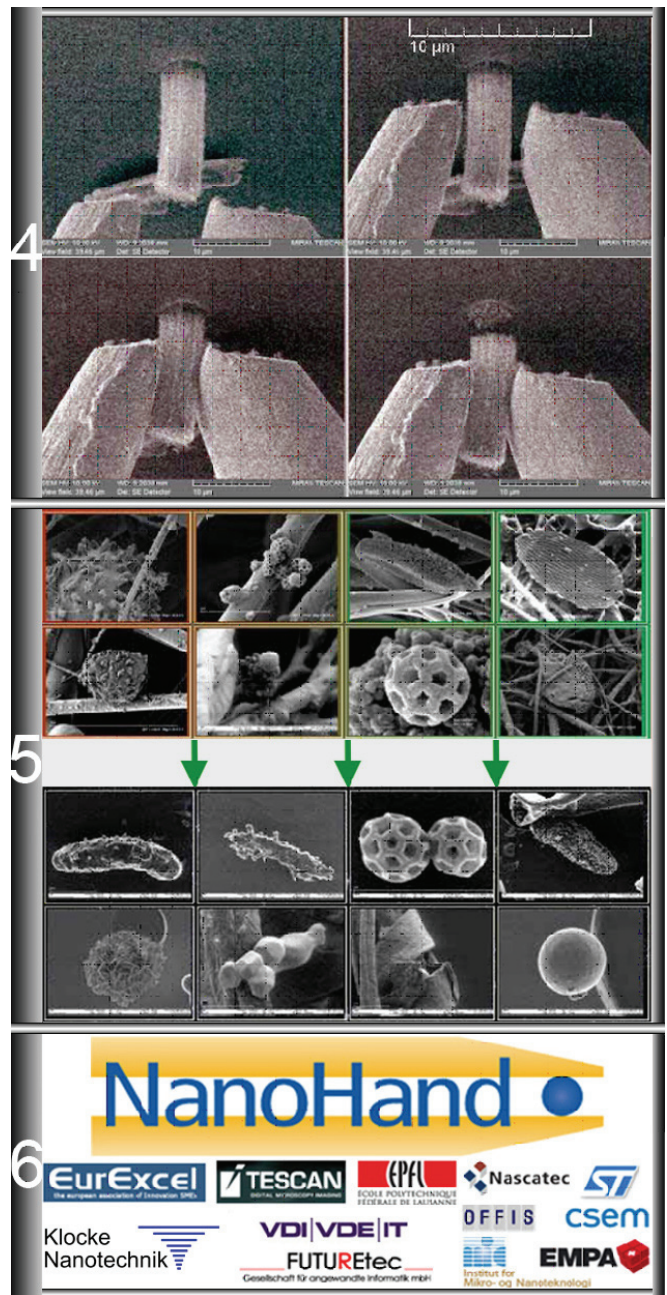In the following Figure 2 three more realized applications of in SEM/FIB Nanorobotics are shown:

Figure 2: Second set of three examples for in SEM/FIB Nanorobotics applications: 4) gripping of Carbon Nanotubes, 5) particle sorting, 6) the "NanoFab".

4) Gripping of a rigid CNT bundle and separation from the ground needs by orders more force then a microgripper normally can apply. The pictures show that it is possible with this gripper to shear the whole bundle of CNTs aside and break all of them shortly above the ground. For smaller structures other grippers were developed, partly also with force feedback. Similar tasks are for example the

Nanomanipulation and modelling of CNT devices as described in [5].

5) Particle sorting from source area (top image set) to clean target area (bottom image set) is a general application, needed in many different disciplines: from environmental research over crystallography and space research up to forensic research. The automatic process of particle sorting is the same for all disciplines, and only grip and release is executed manually. Therefore this process offers a high throughput also for industrial applications.

6) Parts of the SEM/FIB workbench were developed in the European Research projects "NanoHand" and "Hydromel", in particular the "NanoFab". This module includes automatic handling systems with in total up to 18 degrees of freedom as part of the SEM/FIB workbench [6]. The results of these projects were judged so promising, that a follower project is funded now for developing further new applications. This funding includes the invitation to participate at our interdisciplinary research and development network free of charge by defining new application tasks and by sending samples for the development.

3 COMBINED APPLICATIONS

Figures 1 and 2 describe a set of individual applications. The tools for these applications can be used within the SEM/FIB Workbench together to form new applications on a higher level. One example is the combination of the "Dimensional SEM" module from Figure 1 with nano-cutting modules. At stereo light microscopes the closed loop operation of human brain and human hands enables to cut a line intuitively. In a SEM/FIB system a corresponding sensor and actuator system must be developed therefore. Before the cutting tool can remove material from the sample the slope of the area of interest on the sample is measured with the "Dimensional SEM" module. This topography information is added to the coordinate dataset for surface processing of the cutting tool. The following tools and processes are examples within a series of new nano-cutting modules that expand the capabilities of a SEM towards an FIB:

3.1 Semiconductor circuit editing

The following Figure 3 shows the cutting tool nearby a selected conductor before cutting. The result after cutting is visible in Figure 4. This process was defined and executed in a few minutes. This cut is smaller than a micron. Since the movement resolution is 0.5 nm and the stroke up to 20 mm the cutting areas can vary by orders of magnitude. Further examples on different ranges are described in the following chapters.
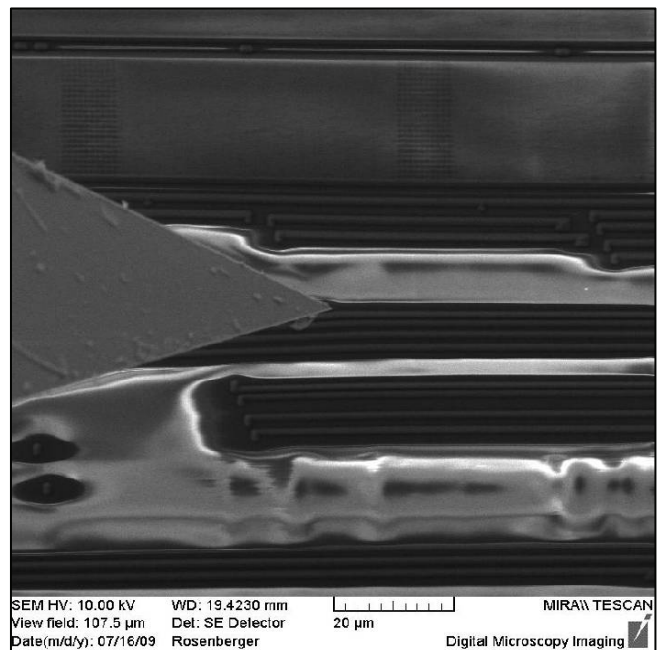

Figure 3: Cutting tool nearby a selected conductor before cutting.
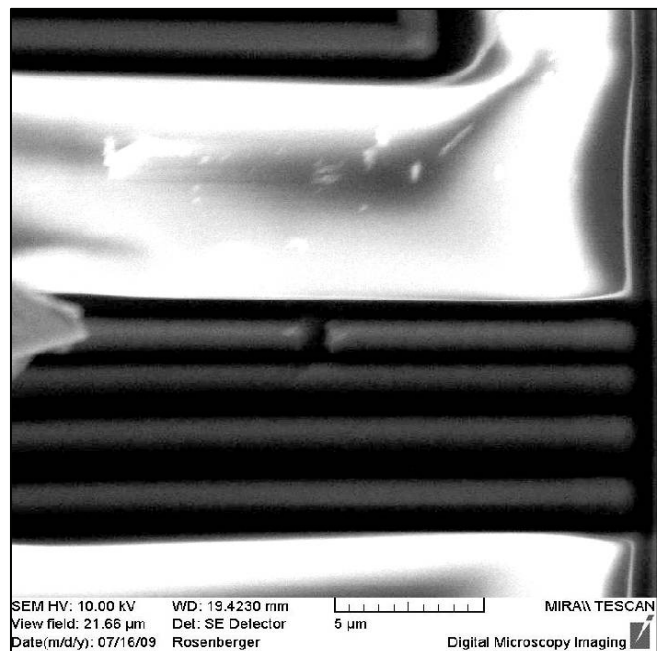

Figure 4: Conductor line after cutting.

3.2 Coarse Removal of Ceramic Materials

A special "Nano-Jackhammer" mode can treat a sample surface by impacts with accelerations of more than 50 G. Using a diamond tip allows to machine any kind of material up to the hardness of 9. The picture sequence of Figure 5 gives an example how this tool can remove an area of hard ceramic material with only 4 cuts. This process was again defined and executed in a few minutes.
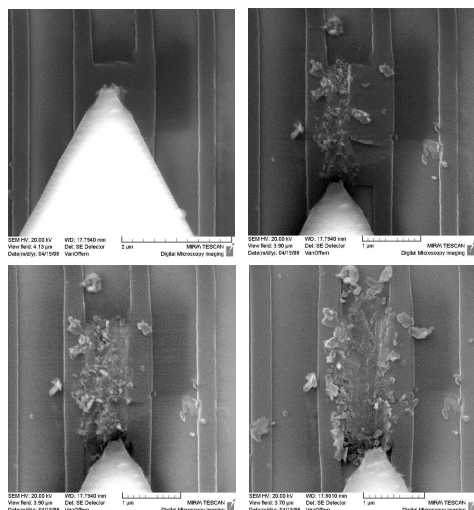
Figure 4: Top left: cutter above area to remove; Top right: after cutting one line; Bottom left: after cutting a second line right from the first; Bottom right: cutting both lines again, deeper down to the substrate.

3.3 Nano-Milling in Silicon

Cutting lines already needs a Global Coordinate system and full 3D-position control, enabled by the "Dimensional SEM" module. Measuring the sample topography also in an area allows the removal of complete areas out of a silicon sample in automation, as described in Figure 5.
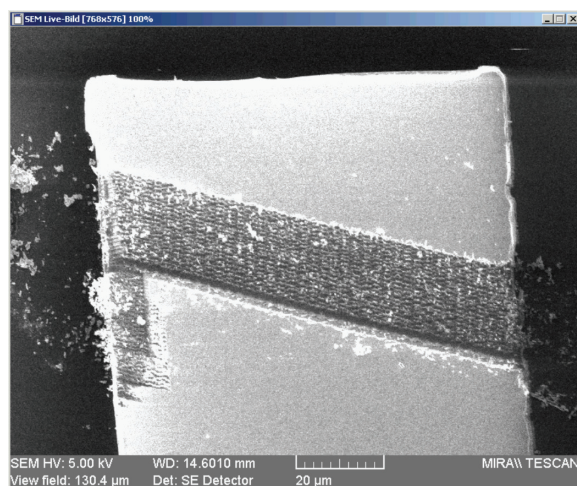

Figure 5: A non-rectangular area of material was removed from a silicon sample in automation. Previously the topography was measured.

3.4 Nano-Slicing of Textile Wires

Removing material out of a bulk sample is one process within nano-cutting. Another option is to slice samples that are placed on top of a substrate, e.g. nano-wires or complex structures like textile wires, see Figure 6:
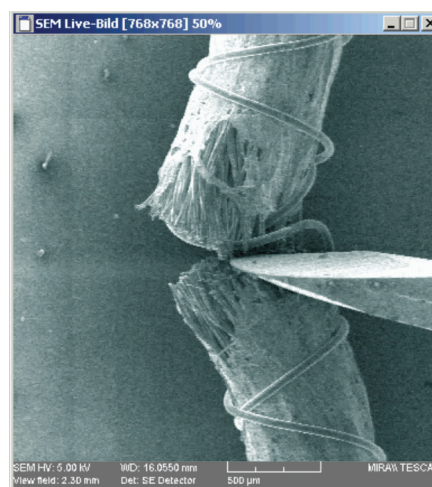

Figure 6: Slicing of textile wires to investigate into the sample structure within SEM/FIB systems.

4 CONCLUSIONS

The SEM/FIB Workbench was developed in a multidisciplinary team and forms now an application oriented system with a high degree of automation. Self finding tools use the 3-dimensional measurement capabilities to guide other endeffectors securely towards samples. This workbench offers for the first time an in-SEM/FIB system that is nearly as secure and easy to use as the tools used manually at light microscopes; this is the precondition for developing new applications. Endeffectors are realized for in-situ Nanomanipulation, object handling, material preparation, patterning & processing, micro/nano-manufacturing & assembly, together with new methods for characterization and nano-metrology. The automation level allows high throughput also for industrial applications. The SEM/FIB Workbench at its actual level is a base for new interdisciplinary research and development projects, and an actual funding eases the participation at this network.

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