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The SEM-FIB Workbench

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Abstract: The Nanorobotics series developed by Klocke Nanotechnik extend Scanning Electron or Ion Microscopes to material processing systems. The included automation allows the whole field of handling, assembly and manufacturing like known from a normal desktop system – now with nano-precision, including various kinds of image generation by using different sensors. Applications are in the field of Material Research, Forensics, 3-Dimensional SEM/FIB, Tribology, Semiconductor, e-beam Lithography or X-Ray imaging up to complete NanoFabrication.

1. INTRODUCTION

The Nanorobotics series developed by Klocke Nanotechnik since 1992 includes products on three different levels (Klocke Nanotechnik):

Level 1: more than 200 Nanorobotics components;

Level 2: a series of individual machines like microassembly stages, micro tensile machines, 3D-Nanofinger, different SPM-Lithographers or several SEM-FIB applications;

Level 3: Universal Testing Benches for product development, prototyping, reverse engineering, failure analysis and testing with nano-precision. Or complete micro production systems including micro adhesive bonding, designed for 3D-handling & assembly of microparts with up to 1 nm resolution.

This modular system allows to configure a solution instead of starting a development. These configurations are mostly by orders more precise than other existing solutions.

The actual presentation will pick out one important Nanorobotics item of product level 2: the “SEM-FIB workbench”. Even this single example shows the wide range of applications created by the Nanorobotics kit system.

2. BASIC SYSTEM CONFIGURATION

Any kind of Scanning Electron Microscope (SEM), Focussed Ion Beam (FIB) or Dual Beam system can be expanded to a material processing system and an analytical Nano-Workbench by using between 1 or up to 6 closed loop Nanorobotics Manipulators from Klocke Nanotechnik with single nm resolution (Fig. 1). The system configuration is delivered as turn key solution installed stationary in the SEM/FIB.

The manipulators are equipped with docking stations that allow an easy removal within a few seconds and a cost sparing dual use in air.

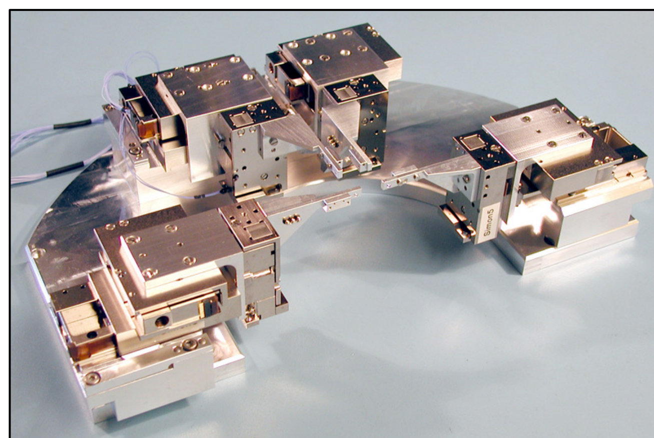

Fig. 1. Four absolute positioning Nanorobotics manipulators, each with 20 x 20 x 10 mm^3 stroke at 1 nm resolution

These Nanorobotics manipulators are so universal to use, that all following applications can easily be reached by adding further components or modules to this basic equipment.

3. THE MATERIAL RESEARCH SEM:

Various tools for cutting, scraping and manipulation can be added to the manipulators, e.g. for:

3.1 Carbon copy paper industry:

A 5 µm diameter ink bubble on carbon paper is touched with the needle, pierced and opened (Fig. 2). By touching the individual ink bubble with the manipulators the elastic behaviour of the bubbles skin is measured. Since the movement is scaled in nm the wall thickness of the bubble can be determined:

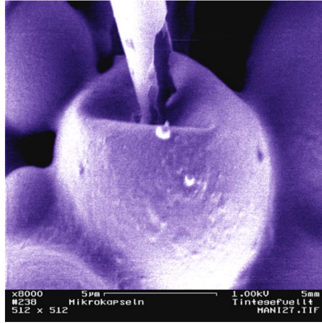

Fig. 2. A 5 µm diameter ink bubble on carbon paper, addressed with a hollow needle

3.2 *Pharmaceutical industry:*

For the development of new skin creams the liquidity between individual layers of human skin has to be tested. For this a Nanorobotics manipulator detaches small pieces of frozen human skin layer by layer in the SEM (Fig. 3).

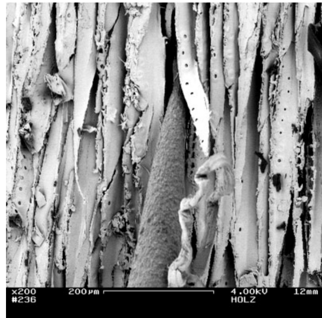

Fig. 3. chipping of frozen human skin

3.3 *Surface coating industry:*

The adhesion of 300 nm small palladium spheres laminated onto a thick copper film is tested by selectively pushing single spheres with a probe tip until the adhesion breaks. Dependent on the failure mode, the bonding of the spheres is judged: it only fulfils the requirements if the adhesion breaks between the copper and the substrate, not between spheres and copper.

4. THE FORENSIC SEM:

The combination of Nanorobotics manipulators with a SEM allows trace analysis on a previously unknown level. A public example is the determination whether an undamaged car lamp was glowing during a crash, or not. If the lamp is hot (by glowing), small melting points will occur between the windings of the filament, touching each other due to the high acceleration of the crash. To see those melting points, the filament has to be stretched with two micro-hooks, moved by manipulators (Fig. 4).

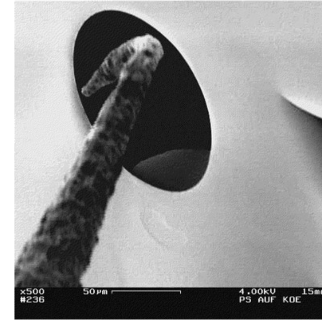

Fig. 4. A micro-hook, moving into a small hole

Quantitative nano-scaled results can be acquired for Forensic investigations with the “Dimensional SEM” described below. One example is the 3D-metrology of scratches in bullets, traceable to international scale standards.

5. THE DIMENSIONAL SEM:

A special Nanorobotics system from Klocke Nanotechnik can expand any SEM or FIB to a "Dimensional SEM/FIB" with Nanometer precision. The metrology features of a SEM/FIB are expanded to the third dimension by measuring points, linescans, scans along a 3 dimensional path (inner and outer contours), or complete 3D surface topographies.

5.1 *Automotive industry:*

The trial to measure quantitative dimensions of small structures in a wet clutch from automotive industry with standard profilometers and optical profilometers failed. Only the Dimensional SEM could deliver profiles and 3D-topography datasets of these structures (Fig. 5). These quantitative results are traceable to international scale and roughness standards.

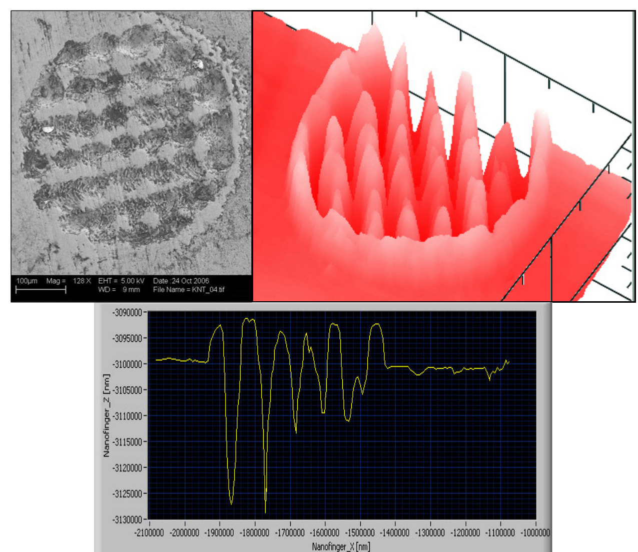

Fig. 5. SEM image of a wet clutch, 3 dimensional dataset and a Linescan through this area

In Fig. 5 the SEM image can show the area of interest but fails to give a height information of these structures. The 3D-scan in Fig. 5 was performed with the "Dimensional SEM" around one imprint field as identified in the upper left SEM image. The quantitative structure information is visible in linescans that can be performed through these structures and deep into the holes (bottom image in Fig. 5). Only the Dimensional SEM could prove, that within one imprint field each imprint has a different depth. The fine structures resolved by the linescans offer more information about the production process of the imprint structures and its side effects, like grains around the imprints and material pressed aside.

5.2 Optical industry:

The SEM image in Fig. 6 shows an array of v-grooves made in silicon as glass fiber guides within a medium sized area. This image only resolves the sample laterally, without any height or e.g. angle information. The 3D-image generated with the Dimensional SEM of the same area is shown directly in comparison:

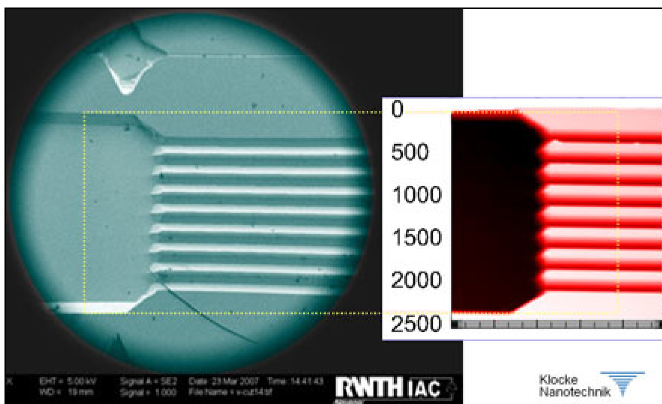

Fig. 6. SEM image of a v-groove array and 3 dimensional dataset performed with the Dimensional SEM

6. THE AFM-STM SEM:

Even a complete AFM or STM scanner head can be fixed as endeffector at the Nanorobotics manipulator in a SEM and moved from its parking position onto those sample areas that were previously identified in the SEM image.

7. THE TRIBOLOGY SEM:

Micro-Tribology is a wide and important field for future production technology. In-SEM measurements are realized for example as:

7.1 Movement stress tests, e.g. of elastic micro structures:

Typical samples therefore are electrostatic comb structure etched into silicon. One Nanorobotics manipulator moves this comb structure periodically along its elastic path by a probe tip and measures the force with a calibrated force sensor. The durability of the force-distance diagrams describes the mechanical quality of the comb structure.

7.2 Current or heat stress tests, e.g. at CNTs:

A single CNT is picked out of a bunch with one Nano-robotics manipulator in the SEM. A second manipulator is fixed at the other end of the CNT by e-beam welding. Then a rising current is applied either to measure the power rating or to induce a temperature by the resistivity of the CNT.

7.3 Elasticity tests at microstructures:

The SEM image of Fig. 7. shows an elastic microstructure that is one out of millions carrying a bigger object. But it is unknown how many of these small elastic structures really carry the load and how many of them are defective. With the Nanorobotics any single microstructure can be addressed with a calibrated force sensor, and a Force-Distance curve with 1 nm distance resolution can be prepared on each single microstructure.

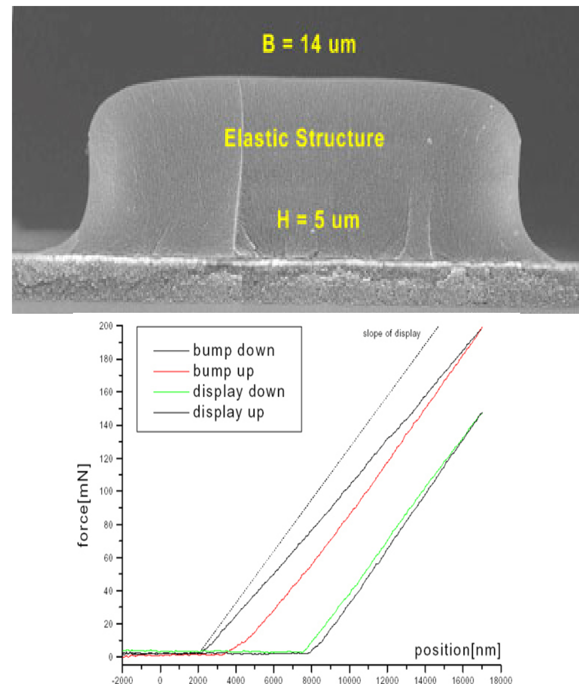

Fig. 7. SEM image of an elastic microstructure and measurement of Force-Distance curves on this single structure.

The force sensor used for these measurements is based on a crystal and converts mechanical pressure in electrical charge. The measuring range of this particular sensor is +/-50 N with a sensitivity of 119,5 pC/N. This leads to a resolution of about 1 mN. Other force sensors with µN or nN range are also included in the SEM-FIB Workbench. The force sensors with best resolution in the nN range are piezoresistive cantilevers that measure the bending forces of this cantilever through a piezoresisitve coating. The response curve of the cantilever is not linear, but can be calibrated within the system.

7.4 Elasticity tests by bending of nanowires:

The bending forces of Nanowires are much lower than the resolution of available force sensors. But a relative measurement of the flexibility of CNTs leading to comparable results is possible by quantitative bending, as shown in Fig. 8.

Fig. 8. Bending of a single Carbon Nanotube.

The absolute positioning manipulators move along a predefined path in 3D. The SEM image allows to describe the particular curve shape of the CNT and to measure the thickness of the CNT. The tips move towards each other until the CNT breaks. This last position is characteristic for the flexibility of the CNT.

Similar experiments at nanowires are described in a paper (Zhu, et al., 2005)

7.5 Reliability measurements by bond strain tester:

The quality of finest bonding connections within devices can be tested with a double head device: a Nanofinger, finding the sensitive bond wire automatically without bending it, carrying a hook that pulls at the bond wire to measure the stability of the bonding point. So even when the flexible wire is not at predictable positions an automatic measurement is possible, because the Nanofinger can find the wire in a non-contact mode, also when the wire is electrically isolated.

7.6 Friction and sticking of micro/nano-objects:

The smaller components are, the more important is their sticking behaviour. A simple setup allows to measure the sticking force between micro- or nano-objects on different surfaces. The object is placed onto the particular surface in the SEM, and one manipulator moves with a force sensor from the side against the object. A force distance curve with 1 nm movement resolution and e.g. nN force resolution describes exactly the friction behaviour until the object starts moving – visible in the SEM.

8. X-RAY IMAGING IN A SEM:

The X-ray ultraMicroscope from XRT Ltd. (sold by GATAN Inc.) provides X-ray images in absorption and phase contrast, to reveal fine internal structures and edge details. The "Advanced Target Positioner" realized by a Nanorobotics Manipulator is part of the projection X-ray system (Fig. 9). It has to keep the target position stable within a few nm over several hours.

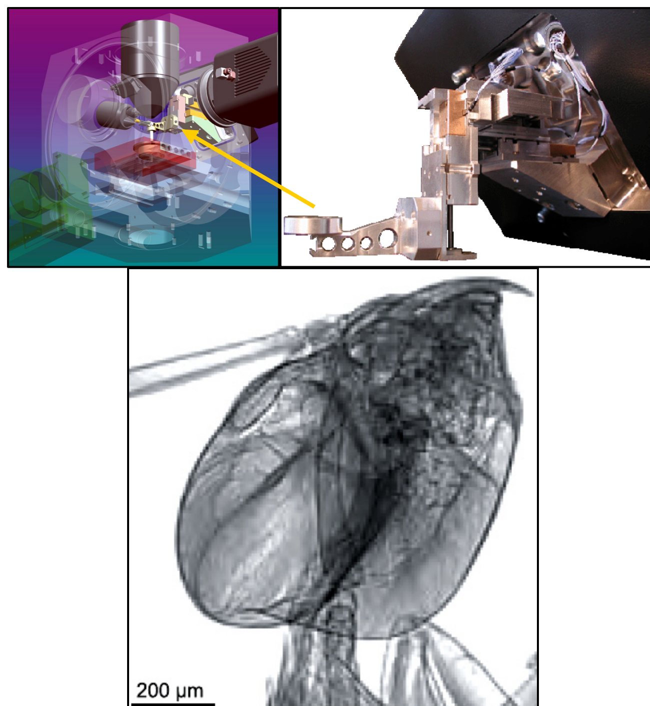

Fig. 9. SEM chamber design, Advanced Target Positioner, X-ray image of the head of an ant.

9. THE WAFER PROBING SEM:

Only a closed loop Nanorobotics system can move with 3 or more probe tips easily into a diameter of about 100 nm – with 1 nm resolution. Nano-probing allows the characterization of single devices and failure analysis (Fig. 10, 11). This work is described in a paper from TSMC, Taiwan (Wu, et al., 2006).

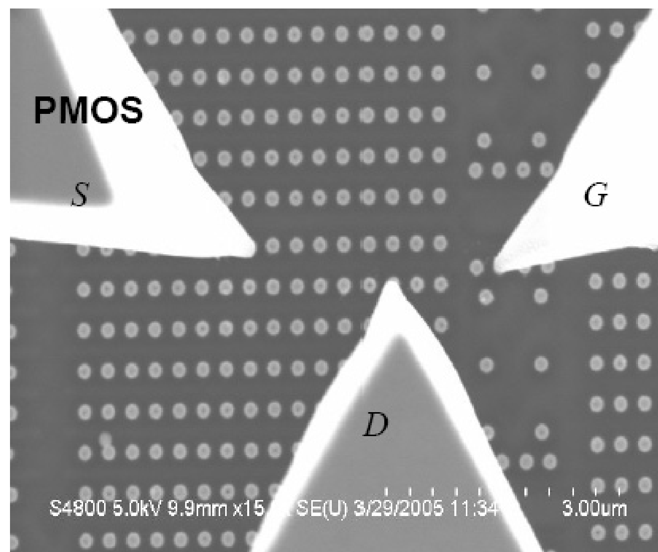

Fig. 10. Nano-probing of single transistors: The upper image shows the probe tips driven by the manipulators, in contact with 3 transistor pads.

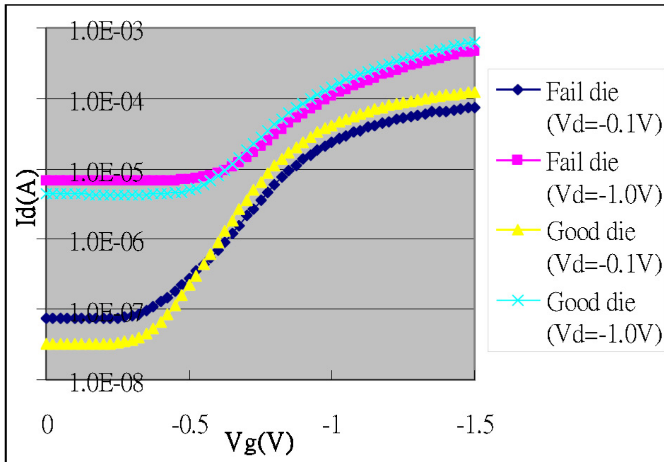

Fig. 11. Nano-probing of single transistors: The diagram proves the different device behaviour between the PMOS transistors of bad and good dice. The device of bad die has higher Ioff.

In-SEM Nano-probing is capable of directly measuring the behaviour of source/drain junctions with a single probe, resistance measurement of two contacts with two probes and full transistor characterization with multiple probes.

10. THE MASK REPAIRING SEM/FIB:

Mask repairing or e.g. reverse engineering in chip design is as important for the Semiconductor industry as Wafer Probing. Automatic in-SEM/FIB Nanorobotics combines fast visualization with Nanomachining and particle removal.

11. FIELD EMISSION IN A SEM:

Measurement of field emission properties of Si-emitter by Nanomanipulation in a SEM. This work is described in a paper from NDL, Taiwan (Cheng, et al., 2007). The diagram shows the field emission behaviour of a single emitter for a 46 nm distance between emitter and sharp anode:

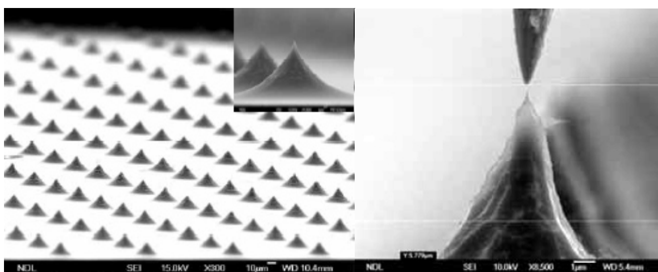

Fig. 12. SEM image of Si nanotips array with height of 20 µm and alignment procedure: The top tip is the Tungsten anode, the lower tip is one of the Si emitters.

The field emission is measured by aligning the emitter and the anode apex in a small separation by SEM (Fig. 12). The voltage to tip distance relationship is described in the next two diagrams (Fig. 13)

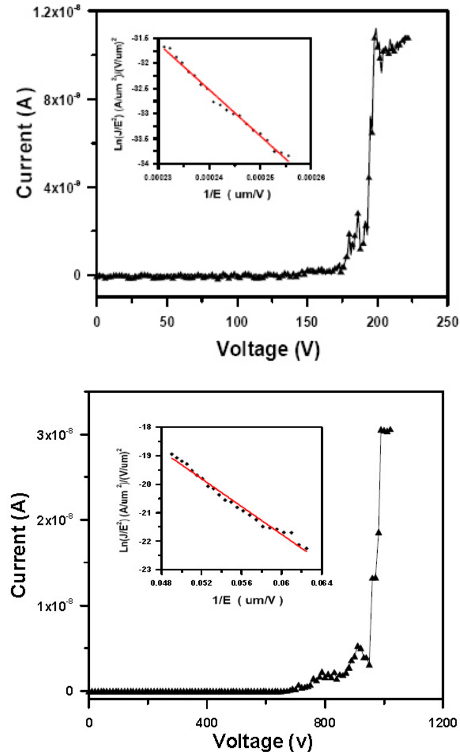

Fig. 13. Field emission behavior of a single emitter with a tip gap distance of 46 nm and below a tip gap distance of 50 µm.

12. THE LITHOGRAPHY SEM:

XY-positioning and stitching improvements for conventional SEM based lithography solutions are realized by a Nanorobotics sub-stage assembly, provided as OEM product by Raith, Germany. Four exposure fields with stitched patterns prove sub micron stitching accuracy. The red dotted line in Fig. 14 indicates the exposure field boundary. This work is described in an application note (Raith GmbH, 2004).

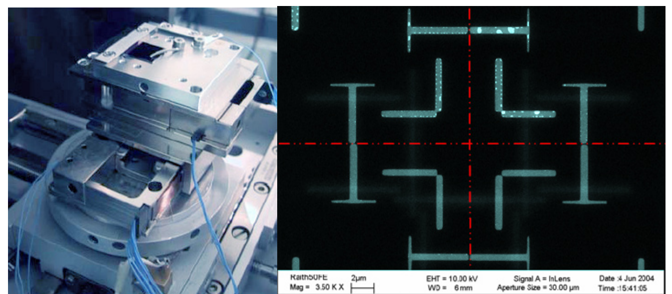

Fig. 14. Piezo electric sub-stage assembly in a FE SEM and stitched patterns of four exposure fields with sub micron stitching accuracy.

13. THE CLOSED LOOP SEM/FIB SAMPLE STAGE:

The XY-stage described for lithography applications can be expanded to 5 D.O.F. in movement including X, Y, Z, rotation and tilt by absolute positioning Nanorobotics modules, e.g. as highest resolution replacement of a manual stage. Together with the Nanorobotics manipulators a complete and homogeneous system is realized in SEM/FIB chambers, the “Nano-FAB”:

14. THE IN-SEM NANOFAB:

Automatic microassembly of smallest components is a key technology. Klocke Nanotechnik is embedded with the "NanoFab" in a network of partners working in this field:

Fig. 15. The European Research Project "NanoHand"

All modules presented in the previous chapters can be part of this NanoFab. Several types of micrographs are included, partly equipped with high resolution force feedback (Fig. 16).

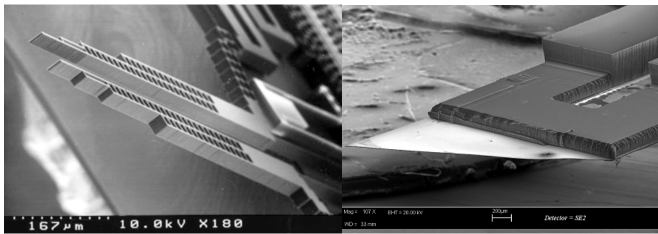

Fig. 16. Two different types of Micrograppers the left one is an electrostatic version, the right one operates electro-thermally

Production of Carbon Nanotube transistors, AFM tips sharpened by CNTs, or the production of GHz antennas are a few examples of using the NanoFab (Fig. 17).

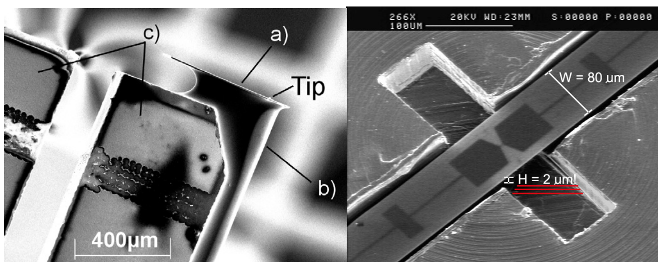

Fig. 17. Special probe tip and antenna production made possible with the NanoFab

The high throughput production of TEM lamellae for semiconductor analysis is another important example for using the NanoFab in automation:

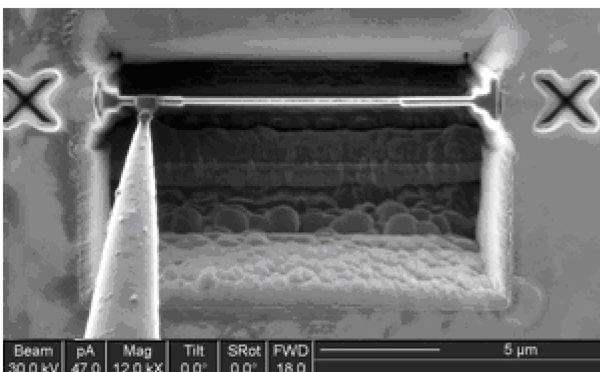

Fig. 18. TEM lamella preparation within the NanoFab

Fig. 18. shows a TEM lamella and a probe tip operating in the following automatic sequence:

- FIB moves lamella by pattern recognition into the center of the image. The lamella is already cut at its bottom, but not at both side walls;
- Tip is moved automatically in XY with the Nanorobotics manipulator e.g. beneath the left marker;
- Tip moves down with "Automatic Tip Approach" module with 1 nm increments in closed loop until a certain contact signal is reached;
- Tip is moved up e.g. 1 micron and moved in XY towards the lamella;
- Tip is moved down 1.2 microns to hover beneath the lamella;
- Closed loop tip movement from the side against the lamella;
- Connection of tip with lamella by MOCVD metal deposition;
- The FIB cuts the lamella on both side walls;
- The manipulator moves the lamella automatically to a target position.

The whole process is possible in automation at even at isolating samples. The movement speed of the tip is so fast that it is hardly visible in the SEM images.

15. CONCLUSIONS

The "SEM-FIB workbench" is the first commercial in-SEM NanoFabrication system allowing a wide range of applications by a homogeneous kit system: from a simple manipulator up to an automatic NanoFab.

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