Collaborative project*

Project acronym: SNM

Project full title: "**Single Nanometer Manufacturing for beyond CMOS devices**"

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Deliverable: D4.4 ("Demonstration of large area multi-beam fabrication of SN structures")

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3	IMEC	**IMEC**	RES	Belgium
4	Mikrosistemi Ltd	**µS**	SME; End-User	Bulgaria
5	Universität Bayreuth	**UBT**	HER	Germany
6	Technische Universiteit Delft	**TUD**	HER	Netherlands
7	Spanish National Research Council	**CSIC**	RES	Spain
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9	École polytechnique fédérale de Lausanne	**EPFL**	HER	Switzerland
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12	Imperial College London	**IMPERIAL**	HER	UK
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14	Oxford Scientific Consultants Ltd	**OSC**	SME	UK
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16	University of Liverpool	**ULIV**	HER	UK

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<tr><td colspan="11">SNM
Work Package 4
Deliverable: 4.4 (“Demonstration of large area multi-beam fabrication of SN structures.”)</td></tr>
<tr><td>Lead beneficiary number</td><td>6</td><td>Nature</td><td colspan="2">R</td><td>Dissemination level</td><td colspan="5">PU</td></tr>
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<tr><td rowspan="3">Person-months by partner for the Deliverable</td><td>TUD</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
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• WPG1 Leader: A. Knoll
• Coordinator: Ivo W. Rangelow</td></tr>
<tr><td rowspan="2">Criteria and Achieved Results</td><td colspan="5">Criteria</td><td colspan="5">Achieved result</td></tr>
<tr><td colspan="5">Demonstration of large area multi-beam fabrication of SN structures.</td><td colspan="5">Deposition of structures was done in two multi beam systems, the 196 beam SEM and the 25 beam SEM. The smallest dimensions that we achieved so far are around 50-60 nm, which is mainly due to focus issues. From the single beam depositions we know that SN-structures are feasible. But both multi beam machines are prototypes and still need improvement. A faulty stage and a dying electron source prevented us to do proper large area deposition. We expect SN-structures to be written with the 25</td></tr>
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		beam system as soon as the blanker is in operation (planned for week 9).
Description of the Deliverable	**Executive summary.** Two multi beam SEM solutions were designed and realized in Delft, a 196 beam system and a 25 beam system. The first is a dedicated system, and difficult to service. The latter is a new system developed within the SNM project. It is a flexible and versatile solution which enables an easy change from a single beam SEM to a multi beam SEM. With both systems we deposited structures using Electron Beam Induced Deposition (EBID), and both systems are designed for single digit nanometer probes. However, we did not manage to achieve single nanometer structure deposition yet, caused mainly by the fact that there is not yet a proper multi beam imaging mode available in the 196 beam system. That causes difficulties in focusing the beams properly. The knife edge sample we used and the transmission imaging is a solution into the right direction, but definitely needs to be improved. The big promise of the 25 beam system is that it allows for beam blanking. This way single beam images can be made from which the focusing is easy to judge. However, the deflector plate has not been installed yet, such that the first EBID experiments were done with improperly focused beams. The smallest structures deposited with these multibeam systems were around 50-60 nm. We can certainly improve on this, as the system is designed for a 1.6 nm probe size with 50 pA in each beam, and a pitch at the wafer of 0.4 µm. With a proper interferometric stage large area deposition will also be possible with a deposition speed at most 25 times that of a single beam SEM. **1. 196 Multi-Beam Scanning Electron Microscope (MBSEM)** Electron Beam Induced Deposition (EBID) is a high resolution direct write lithography technique, that is capable of writing single nanometre patterns and it is suitable for the fabrication of high resolution NIL stamps. A gas precursor is led into the SEM chamber, adsorbs to the substrate surface, where it is dissociated by the electron beam into a volatile component, that is pumped out of the system, and into a non-volatile part, that sticks on the substrate. By scanning the beam over the substrate, following a certain pattern, structures with resolution in the sub-10 nm range can be deposited. A main disadvantage of this technique, being a serial writing technique, is the low throughput. In order to overcome this limitation, we are developing a Multi Beam Scanning Electron Microscope (MBSEM) with 196 beams, shown in Fig. 1. It is intended to enhance the throughput by a factor of 196 [1,2].	

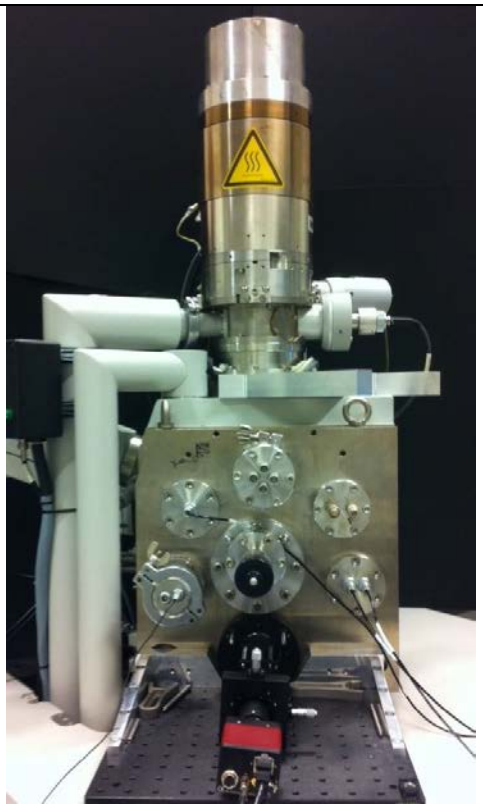

Fig. 1 The Multi Beam Scanning Electron Microscope (MBSEM)

The optical schematic of a commercially available FEI Nova Nano Lab 200 Scanning Electron Microscope (SEM) is shown in Fig. 2. Electrons are emitted from a Schottky (or thermal field emission) source. A first condenser lens, C1, images the source in a plane close to the Coulomb tube (CT), where beam shift & tilt coils can adjust the position of the electron beam exactly on the optical axis of the system. A second magnetic lens, C2, focuses the beam in a plane above the variable aperture (VA), that limits the current in the beam. A set of two magnetic lenses INT (INTermediate) and HR/UHR (High-Resolution/Ultra-High-Resolution) focuses the beam at the sample. The beam can be scanned over the sample by means of scan coils, located above the HR/UHR lens. In such a configuration, one way of splitting the beam into multiple beams is by replacing the original source module with a multi electron beam source module. Fig. 3 shows the optical schematic of a scanning electron microscope in our present multi-beam configuration. The source module is replaced by a multi-beam source module. The emission angle of the beam is bigger than in a standard SEM, but such that the brightness is still constant within the emission cone. An aperture lens array (ALA) splits the beam into an array of 14x14 beams and focuses each beamlet in the accelerator lens (Acc.) plane. The aperture lens effect is formed on the ALA by means of the E-2 electrode, while E-1 provides a zero strength lens (ZSL) that can correct for the field curvature. The accelerator lens, consisting of three macro-electrodes (Einzel lens), images the source in a plane above the C2 lens, in the Coulomb tube. The C2 lens creates a common crossover in the variable aperture plane, that is imaged in the UHR coma-free plane by the INT lens. It is extremely important that all the beams have a common crossover in the coma free plane of the UHR lens. In this way, the off-axis aberrations of the

UHR lens can be neglected and the contributions of the off-axis aberration of the other lenses will be demagnified by the objective lens (UHR). The magnification of the system can be changed by tuning the strength of the C2 lens.

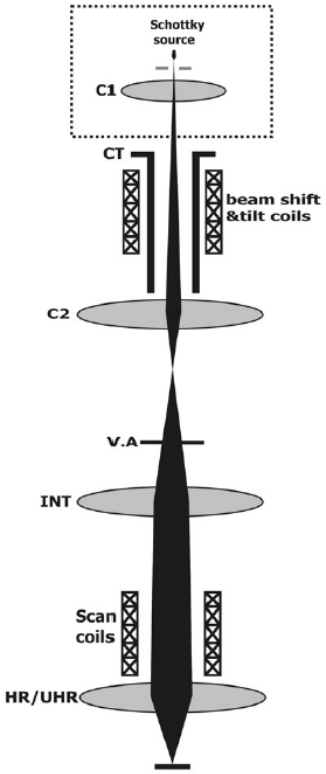

Fig. 2 Optical schematic of a commercially available FEI Nova Nano Lab 200 Scanning Electron Microscope (SEM)

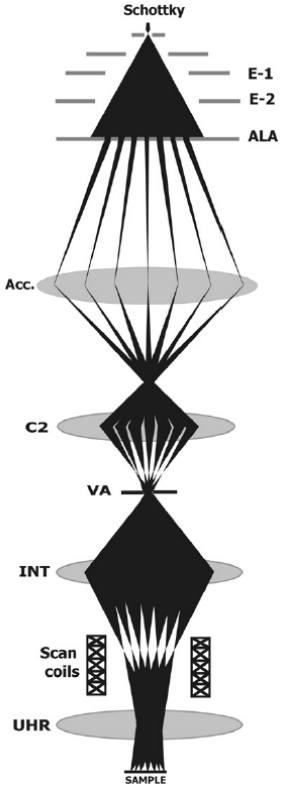

Fig. 3 Optical schematic of the Multi Beam SEM (MBSEM)

Fig. 4 shows the variation of the total probe size and the on-axis contributions at the sample as a function of the half opening angle of the beam at the sample. The smallest achievable probe size is 1.2 nm, corresponding to a half opening angle of 7.8 mrad.

Fig. 5 shows the off-axis contributions to the probe at the sample of all lenses of the MBSEM, calculated for a half opening angle at the sample of 7.8 mrad, namely the case in which the on axis beam probe size is 1.2 nm. The relevant contribution is given by the INT lens, while those of the UHR are practically negligible because of the common crossover in the coma-free plane of the objective lens.

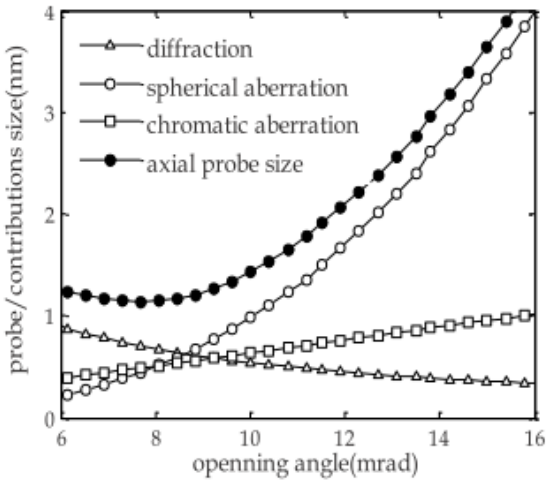

Fig. 4 Variation of the total axial probe size and the on-axis aberration contributions to the probe as function of the beam half opening angle at the sample.

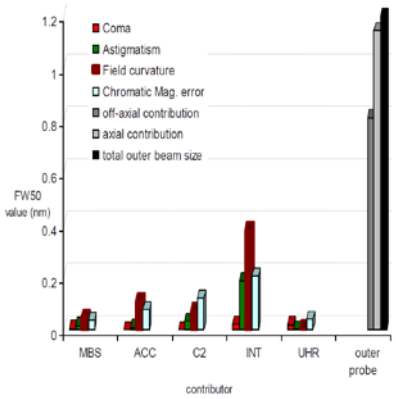

Fig. 5 Off-axis contributions to the outermost probe of all lenses in the MBSEM [2].

With the Multi Beam Scanning Electron Microscope, high throughput Electron Beam Induced Deposition can be performed. We demonstrated the patterning of EBID dots using the Multi Beam SEM (MBSEM), shown in Fig. 6 [3]. These dots were deposited on top of a $W/Si_3N_4/W$ membrane using the $MeCpPtMe_3$ gas precursor, at 15 kV. The dots have a diameter of about 70 nm, and the average pitch is 436 nm and the total field of 14x14 dots measures 5.7 µm x 5.7 µm.

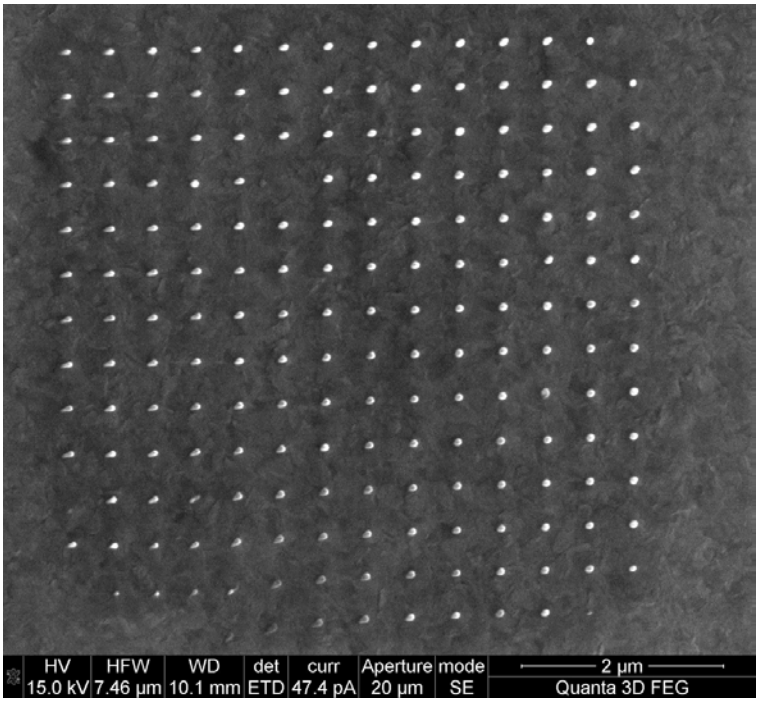

Fig. 6 Single-beam SEM image of an array of EBID dots deposited in the Multi Beam SEM (MBSEM) [3]

Experimental set up

The Multi-beam FEI Nova Nano SEM 200 is equipped with a SECOM Delmic door [4], which is an integrated solution for correlative light and electron microscopy, as shown in figure 7. The electron beam is scanned onto a sample surface, from which BSEs and SEs are emitted and collected by the detectors. The sample is placed on a piezo driven stage, which also hosts a light objective lens. If the sample is a scintillator, such as a YAG screen, the electrons are converted into photons, which are collected by the light objective lens underneath the sample. An optical path guides the light into the CCD sensor of a camera, that can be placed outside the evacuated SEM chamber. In the multi-beam SEM, where standard imaging with ETD or TLD detectors is not trivial, the SECOM platform provides an easy and fast way to do transmission imaging.

For the Multi Beam EBID experiments this platform is used with the ultimate goal of focusing the beams, which cannot be done with the standard SE-detectors. We used a YAG screen coated with a 10 nm thick Al layer, that provides a conductive layer. On top of the Al layer, large areas at the center of the sample are patterned with W-dots and W-lines of different sizes, using EBL. These features provide 'knife' edges, i.e. sharp edges, that give a good contrast in transmission imaging, and help in judging the probe size of the focused beams..

The microscope is further equipped with an FEI gas injection system (GIS), filled with the $MeCpPtMe_3$ precursor, that can be heated to 40°C. The GIS consists of a reservoir, where the precursor is kept, and a needle, that can be placed in proximity to the sample surface and from which the Pt-based gas is led into the system.

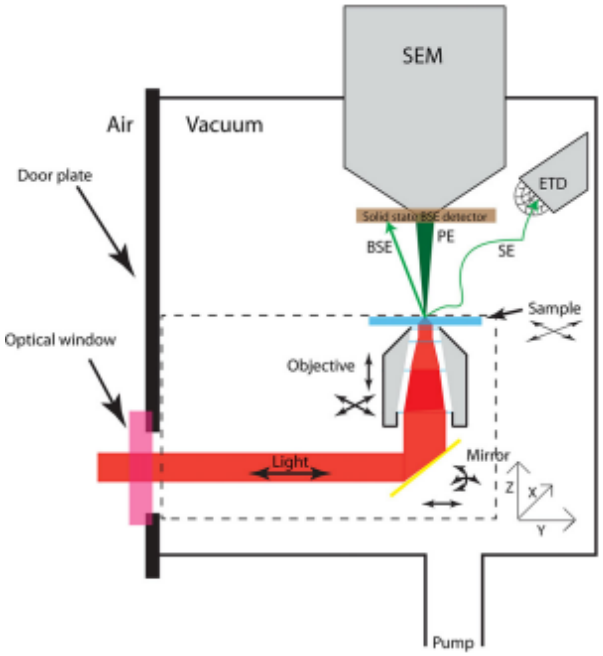

Fig. 7 Schematic illustration of a SECOM platform, with a light objective positioned in vacuum below the sample inside an SEM [4].

Unfortunately at the time of the experiments we ran into a variety of problems with this set up:

a. The precursor gas flow was limited.
   All apertures, except for the variable aperture, in the column were removed to enable multi-beam SE-imaging. Also pumping apertures were taken out, such that extra precautions had to be taken when letting the gas flow into the chamber, because a large pressure increase in the chamber led to a higher pressure in the column, all the way up to the electron source, causing it to shut down.
b. Piezo controls.
   The handmade SECOM door is equipped with a piezo stage which is not accurately to control. For example, step sizes and the number of steps in a stage move were not consistent. Therefore, large area patterning with proper stitching was very difficult to perform.
c. Schottky source and Aperture Lens Array at the end of its lifetime.
   When the experiments started, the tip was at the end of its lifetime. Therefore, there was no current uniformity over the array of 14x14 beams. Also, the imaging resolution worsened because of a decreasing source brightness. Replacing the source is not as easy as in a standard single beam microscope. The source and the beam splitting optics are one unit, and after a source change the optics has to be cleaned and re-aligned with respect to the tip. We decided to continue with the experiments even though the quality of the source was not optimal and rather replace the tip in a later stage. The replacement of the tip started in December and it is still not fully accomplished.

Results on large area patterning

The large area patterning, as described above, was difficult because of the problems encountered with the stage piezo controllers. First, the beams are focused by looking at the transmission optical image of the knife edge sample. Because of the poor quality of the source, the intensity of the 196 images is very different and the resolution is not optimal. Once the beams are focused, we blanked the beams and let the heated gas flow into the chamber until the pressure stabilizes. We un-blanked the beams and exposed the first region in spot mode for approximately 5 seconds. After that, we blanked the beams again, moved the stage to another position and un-blanked the beams again, exposing that area for approximately the same amount of time. Figure 8 shows the SEM image of the two exposed arrays of 196 EBID pillars. This SEM imaging is taken afterwards in a single-beam FEI Verios scanning electron microscope. The pitch between the beams is approximately 2 µm and the size of the pillars is smaller than 100 nm. Unfortunately, the control of the piezo stage was so problematic that it was impossible to expose two consecutive regions, to demonstrate the large area patterning.

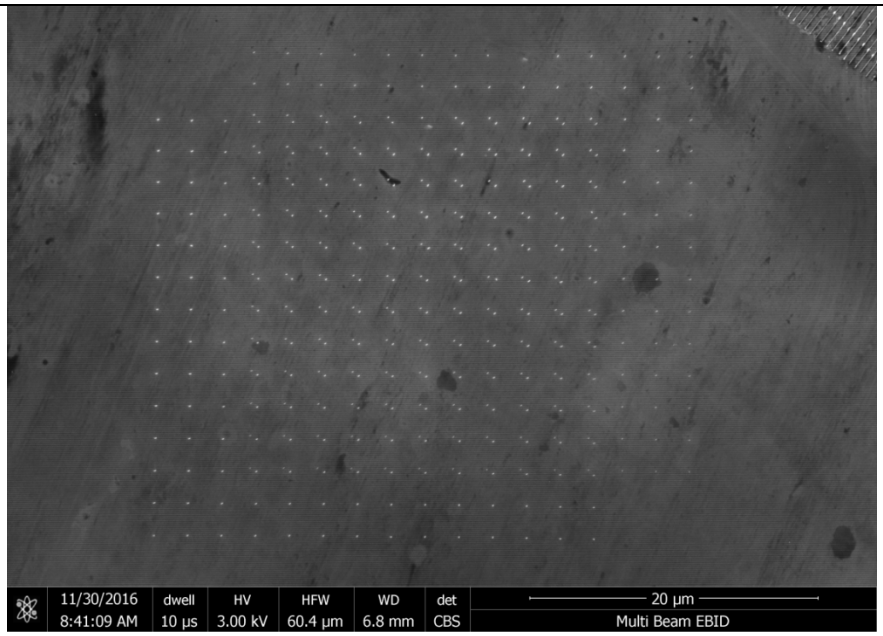

Fig. 8 First attempt of large area patterning by EBID in the 196 multi-beam SEM, done by exposing the sample once in one region and subsequently in a region next to it, by moving the stage in between.

Figure 9 shows a zoomed in SEM image of some of the pillars deposited by EBID in the two subsequent patterning steps. The pillars have an elongated shape, where the smaller dimension is 75 nm. This deformation can be a consequence of a small spatial drift of the stage or is due to improper focusing.

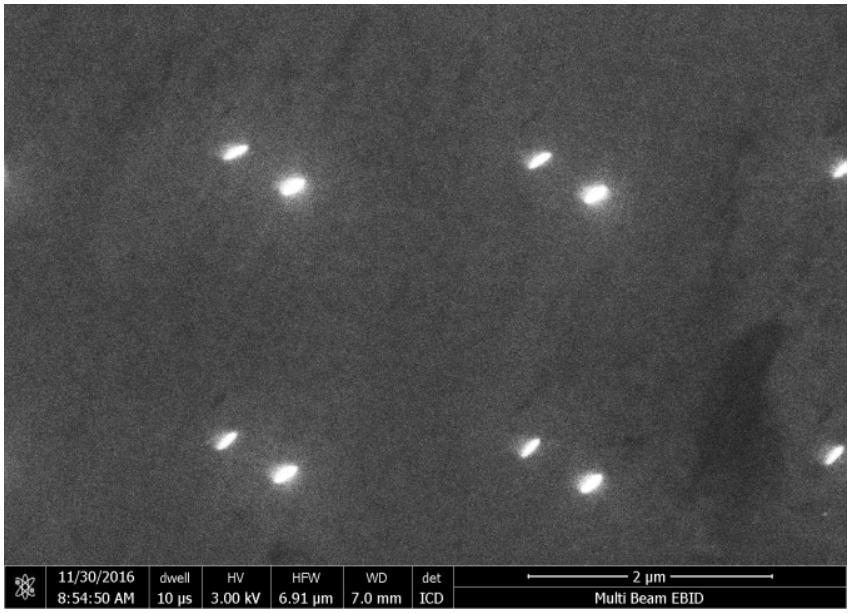

Fig. 9 Zoomed in SEM micrograph on some of the pillars deposited by EBID in the 196 multi-beam SEM.

Writing connected nanowires with multi-beam EBID

It is possible to write connected nanowires by EBID in the multi-beam SEM. The idea is to align the scanning direction with the beams grid and adjust the scanning area of each beam to the pitch. This strategy is shown in figure 10: on the left, neighbouring beams are scanned such that the end of a scanline coincides with the start of the next one. The scan direction, as shown in the image on the right of figure 10, is set to be along the grid.

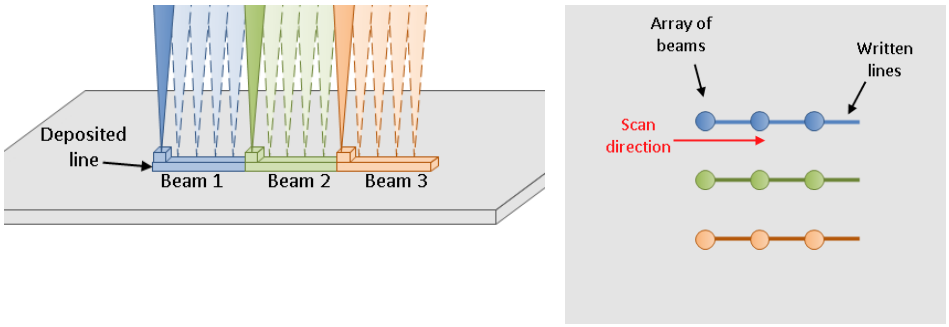

Fig. 10 Writing strategy for patterning connected nanowires with a multi beam system.

Figures 11 and 12 show the resulting 'connected' nanowires. The lines have a width between 60 and 80 nm, and the pitch is 1.8 µm. It is clear that the nanowires are not quite connected, because the scan direction was not exactly oriented parallel to a row of beams in the array of beams. Furthermore it is seen that the bright nanowires have actually lifted off the surface. This is a result of enhanced growth for those beams that contain more current than others in the very non-uniform current distribution within the array of beams. This problem will be solved after a source change and a change of the aperture lens array.

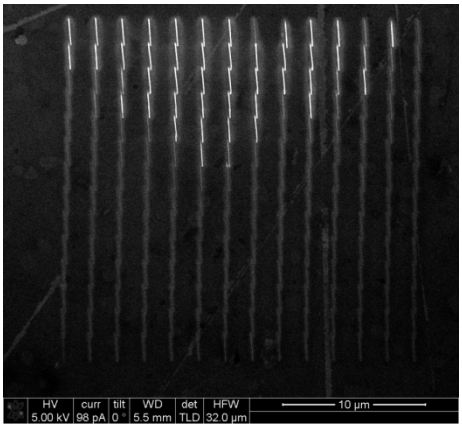

Fig. 11 Connected nanowires written with the 196 beams SEM.

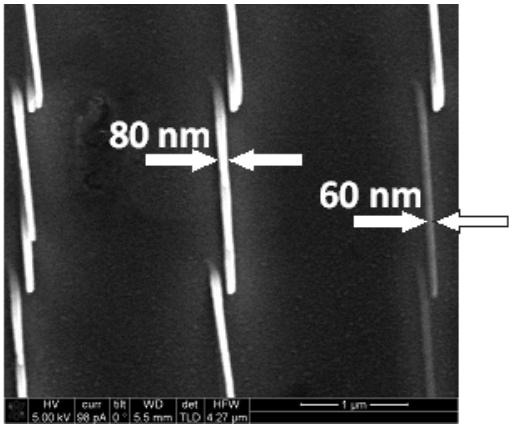

Fig. 12 Zoomed in image of the connected nanowires written with the 196 beam SEM. Here the difference in beam current intensity is noticeable, even between neighbouring beams.

High resolution Multi-beam EBID

To aim for SN structures the beams need to be better focused. In a number of experiments we tried to achieve that. But the electron source giving up on us and the limited sharpness of the knife edge structures on the YAG sample, posed a real challenge. Figure 13 shows some of the smallest dots deposited. The exposure time was 5 sec, the pitch of the dots was 1.9 µm.

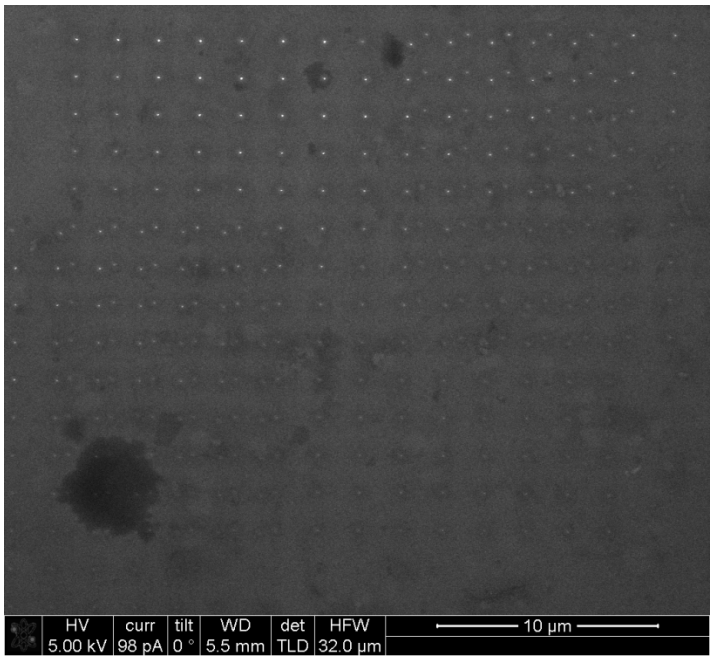

Fig. 13 Single beam SEM image of multi-beam deposited dots, at an exposure time of 5 sec and a 1.9 µm pitch.

In figure 14 a zoomed-in image is shown of the one of the dots in figure 13, and the dot is seen to elliptic, probably due to astigmatism and/or drift. The smallest size is 57 nm.

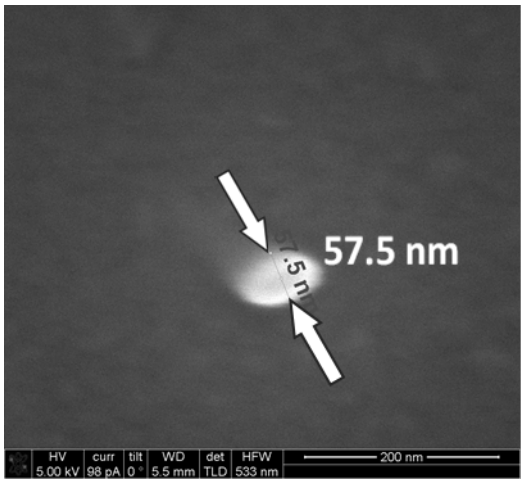

Fig. 14 A dot from fig.13 zoomed-in: the diameter is 57.5 nm, and there is quite some astigmatism present or drift.

We decided to stop these experiments and wait until the source is replaced, and a new aperture lens array is mounted. Instead we focused more on the novel beam splitting/blanking solution that we developed in this project, and do some EBID experiments with that.

2. 25 Multi-Beam Scanning Electron Microscope (MBSEM)

In our MS7 report and the D4.3 deliverable report we have described the design and fabrication of a novel chip-stack that can be inserted into the variable aperture port of an SEM to split the single beam into 25 beams, and allows for individual beam blanking. Here we only report on the first trials with that system to deposit patterns using EBID.
In figure 15 we show a single beam SEM image of a 5x5 array of pillars deposited using the Pt-precursor in a single 5 sec exposure. The pillars are visible as the white dots in the center of the black halo deposits.

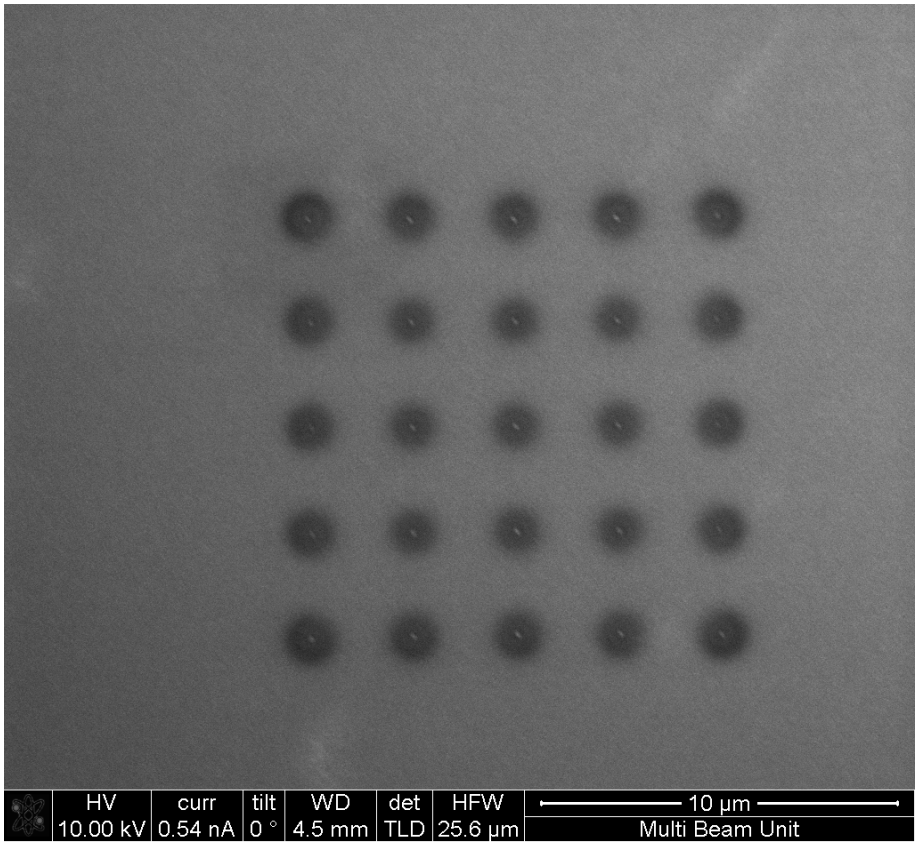

Fig. 15 An 5x5 array of pillars deposited in the novel 25 beams NovaNanoLab SEM, in a single 5 sec exposure.

In figure 16 a zoomed-in image is shown of one of the pillars, with a diameter of 90 nm.

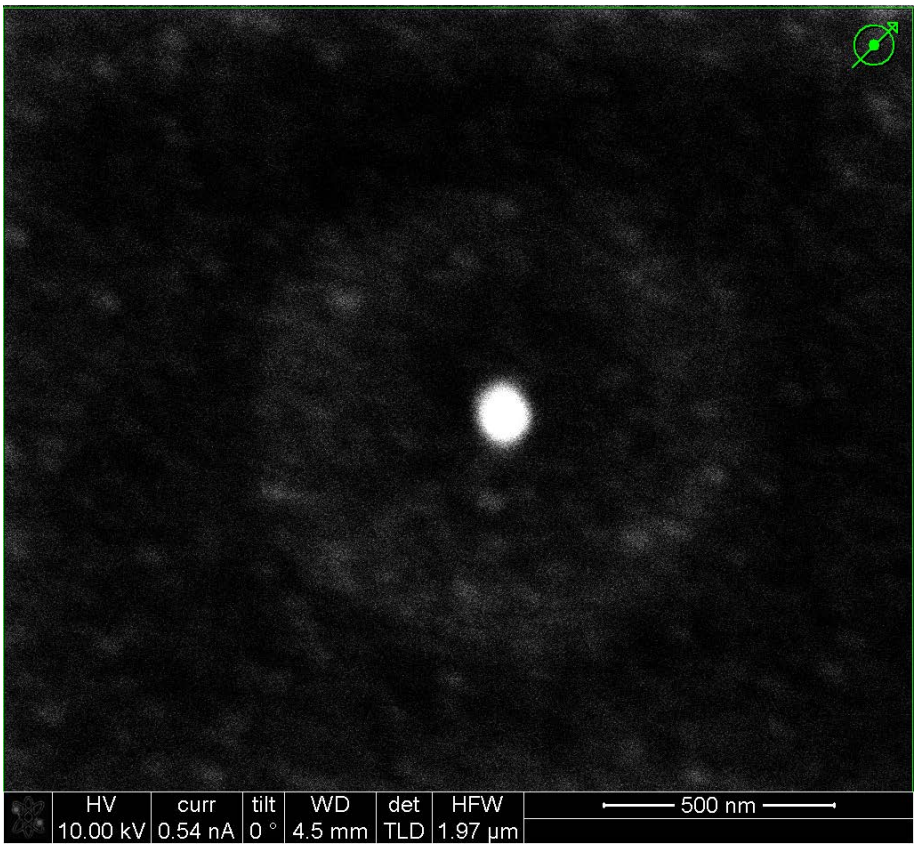

Fig. 16 Zoomed-in image of one of the pillars in figure 15. The diameter of the pillar is 90 nm

This is what we achieved so far. We are still working hard to make the individual beam blanking work. We are very close realizing that, in which case we will try to improve on the results shown here, and add them as an addendum to this report.

References

[1] A. Mohammadi-Gheidari, C.W. Hagen and P. Kruit, Multibeam scanning electron microscope: Experimental results, J. Vac. Sci. Technol. B28 (2010) C6G5.

[2] A. Mohammadi-Gheidari and P. Kruit, Electron optics of multi-beam scanning electron microscope. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 645 (2011) 60-67.

[3] P.C. Post, A. Mohammadi-Gheidari, C.W. Hagen, P. Kruit, Parallel electron-beam-induced deposition using a multi-beam scanning electron microscope, J. Vac. Sci. Technol. B29 (2011) 06F310-1 – 06F310-4.

[4] A.C. Zonnevylle, R.F.C. Van Tol, N. Liv, A.C. Narvaez, A.P.J. Effting, P. Kruit and J.P. Hoogenboom, Integration of a high-NA light microscope in a scanning electron microscope, Journal of Microscopy 252 (2013) 58-70.

Explanation of Differences between Estimation and Realization	The fact that the 196 beam system has no individual beam blanking, added to dying source and a faulty piezo stage, caused huge problems in focusing the beams and prevented filling a large area with single nanometer structure. In the development of the 25 beam system we had some delay due to vacuum seal problems of the new chip-stack assembly, and one process step that failed in the fabrication of the deflector plate (see also our D4.3 report). Although both problems were solved in the meantime, we have not been able to mount the deflector plate yet, and do more EBID experiments. This is still planned for the coming weeks.
Metrology comments	-