TU Delft

2-20 nm Lithography with Electron Beam Induced Deposition

Kees Hagen

with contributions from

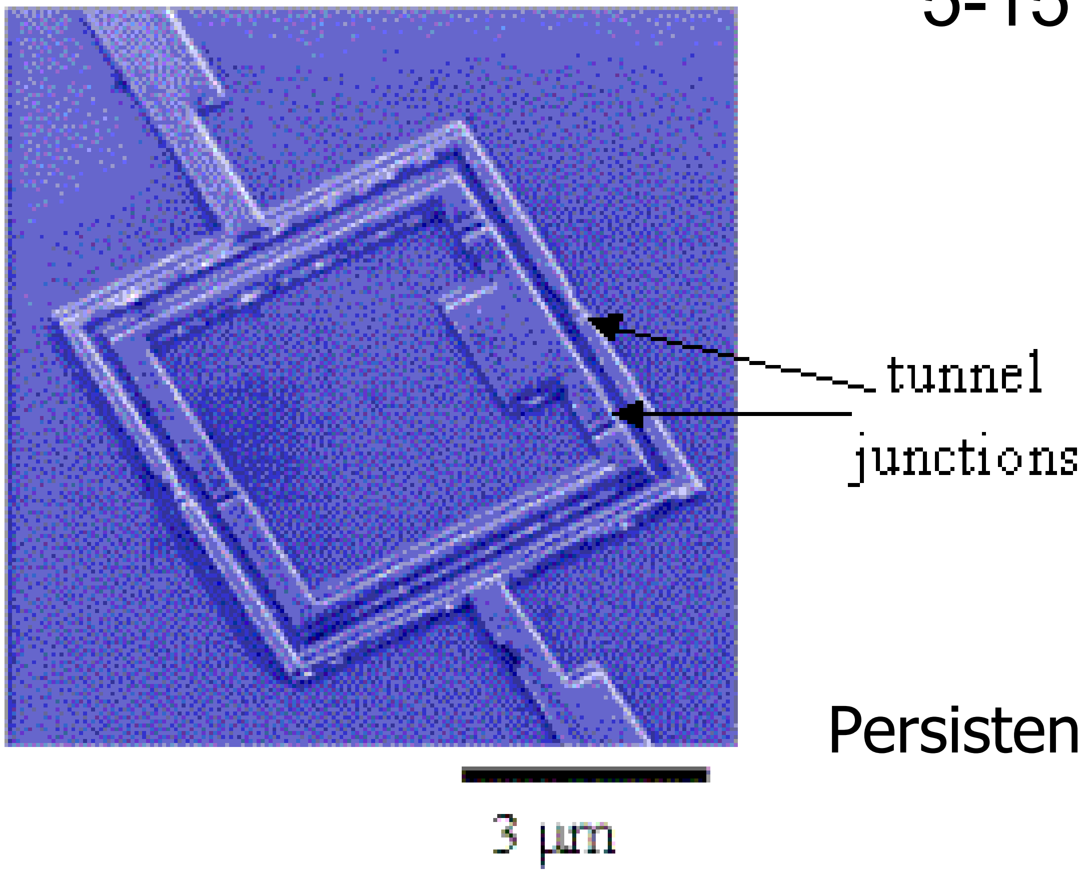
Willem van Dorp, Martijn van Bruggen, Bob van Someren, Pieter Kruit

(at Delft University of Technology),

and

Peter Crozier (at Arizona State University)

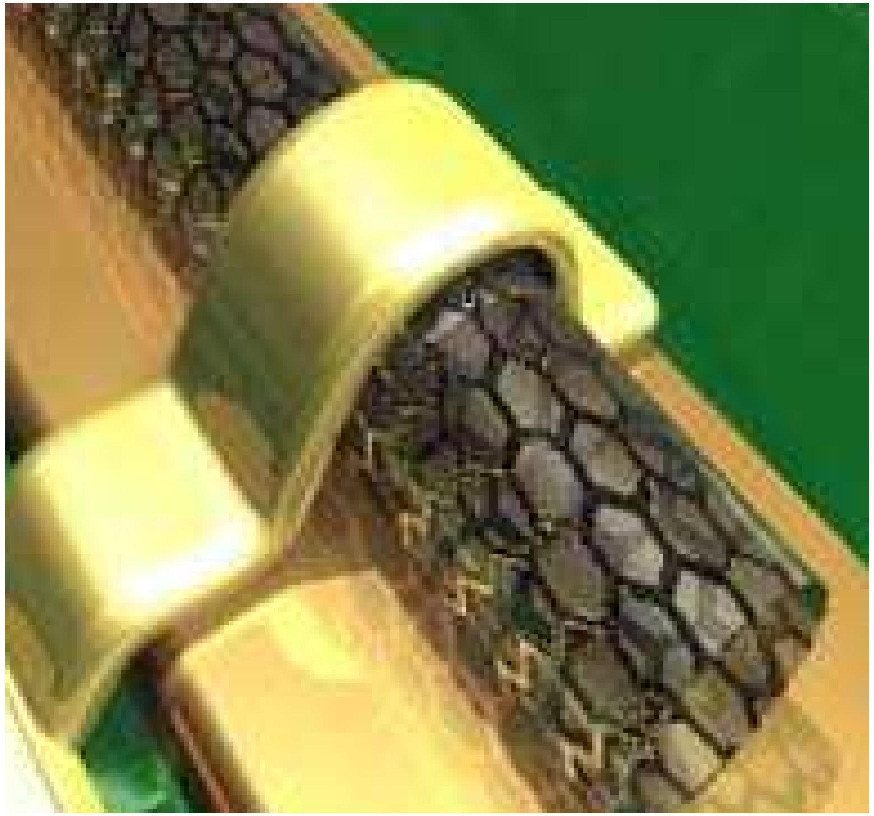
5-15 nm smallest dimension

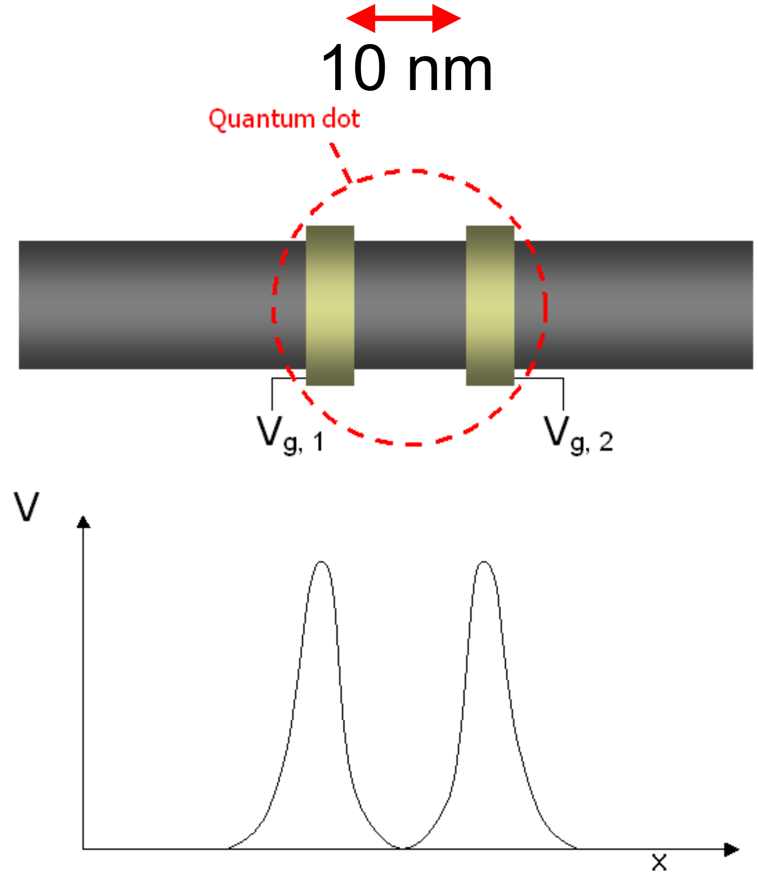


Persistent current qubit

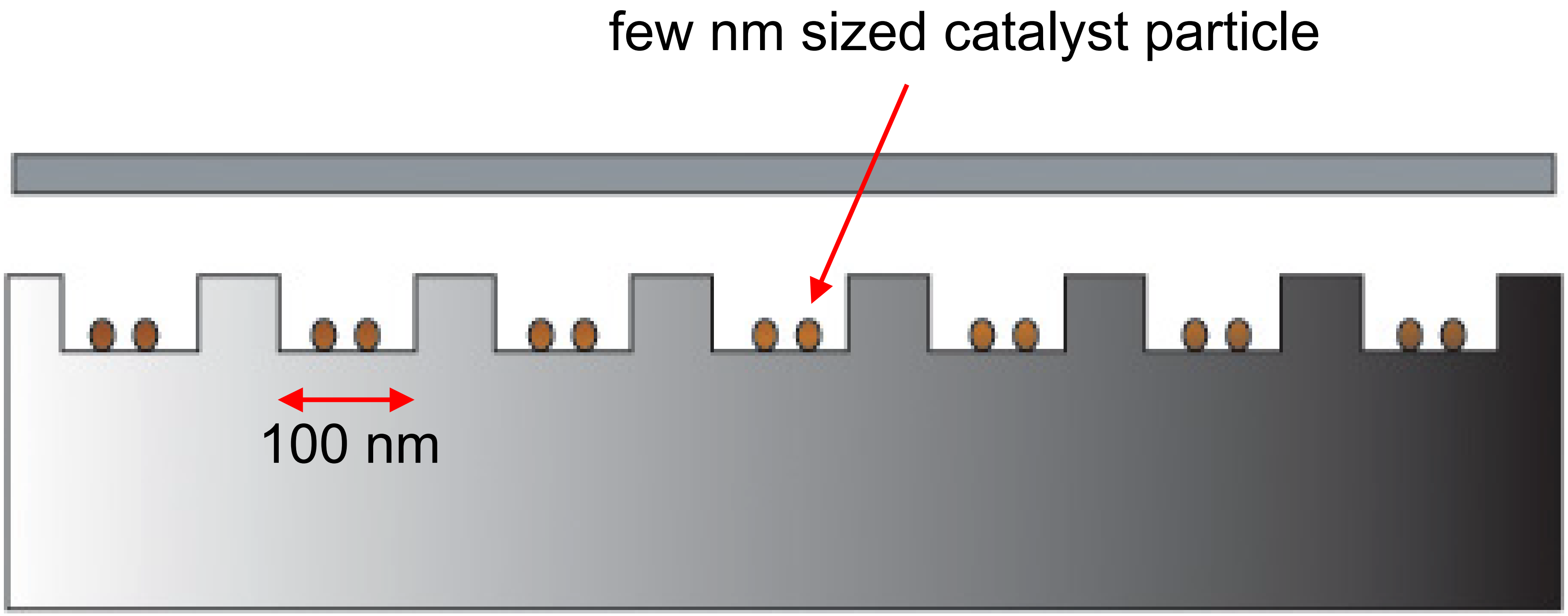
From: the Quantum Transport web-site, TU-Delft

Need for nanostructures in nanoscience

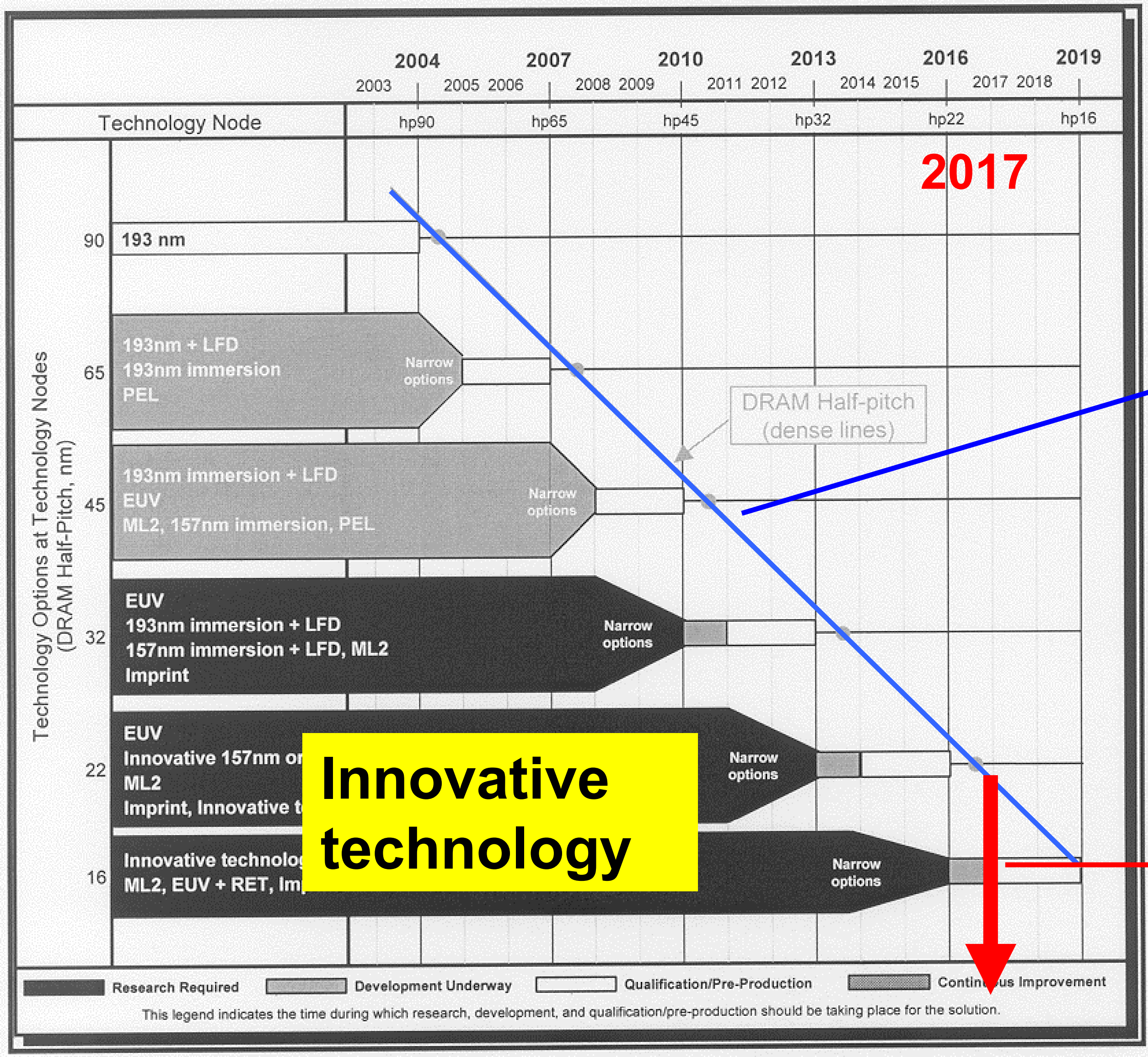




Courtesy Molecular Biophysics group in Delft


few nm sized catalyst particle
100 nm

nm feature size in semi-conductor industry



ITRS roadmap DRAM half-pitch

2-20 nm lithography

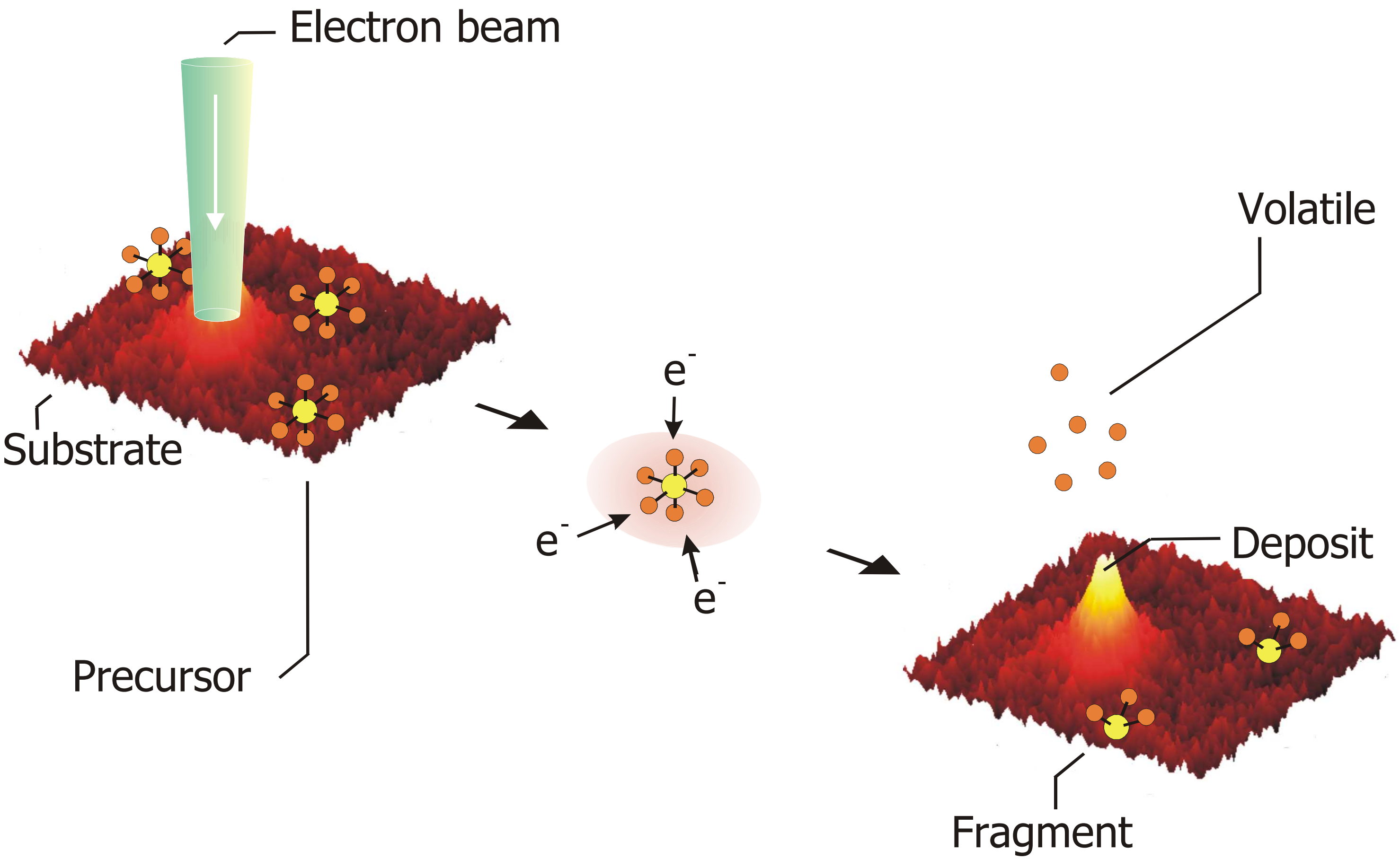
Notes: EPL is a potential solution at the 65, 45 and 32-nm nodes for one geographical region, and PEL is a potential solution at the 32-nm node for one geographical region. RET will be used with all optical lithography solutions, including with immersion; therefore, it is not explicitly noted.

RET — resolution enhancement technology EUV — extreme ultraviolet EPL — electron projection lithography

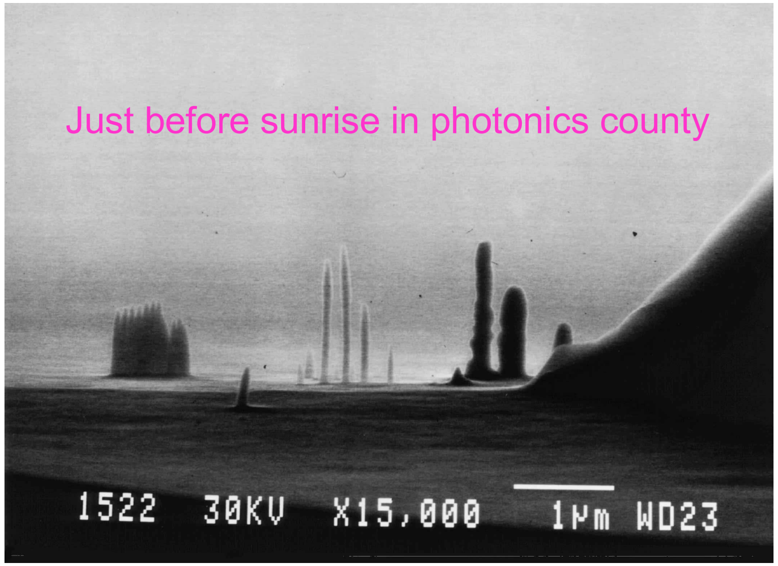
ML2—maskless lithography PEL—proximity electron lithography LFD—Lithography friendly design rules

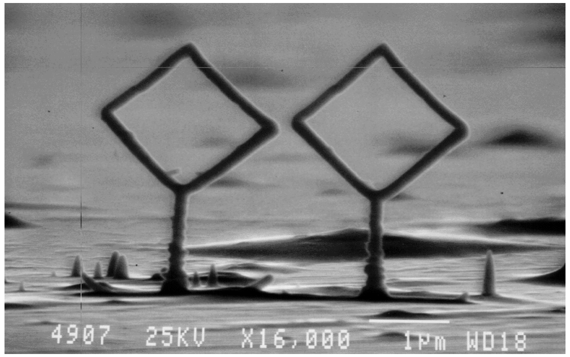
Figure 53 2004 Lithography Exposure Tool Potential Solutions **UPDATED***

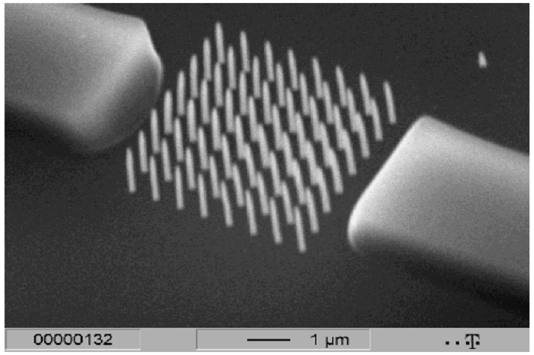
Electron Beam Induced Deposition (EBID)



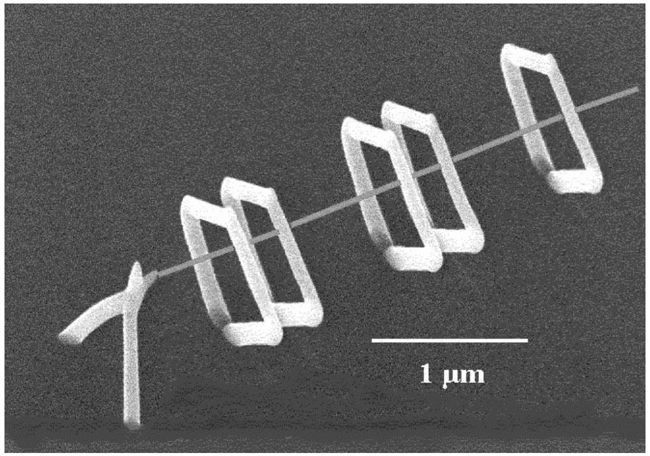
Some examples of what you can do with EBID

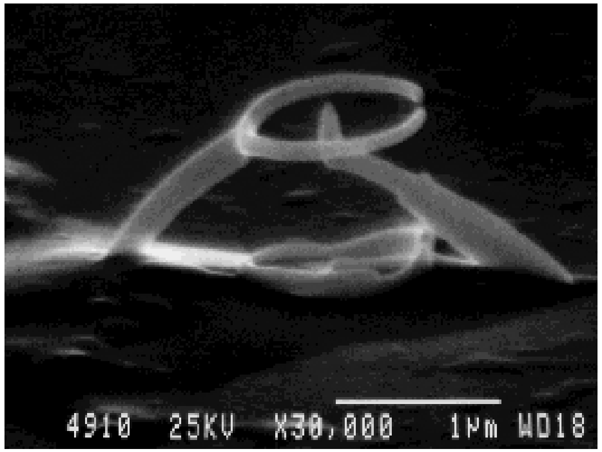


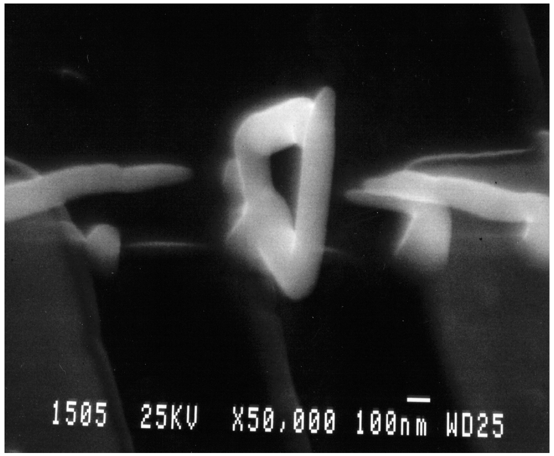




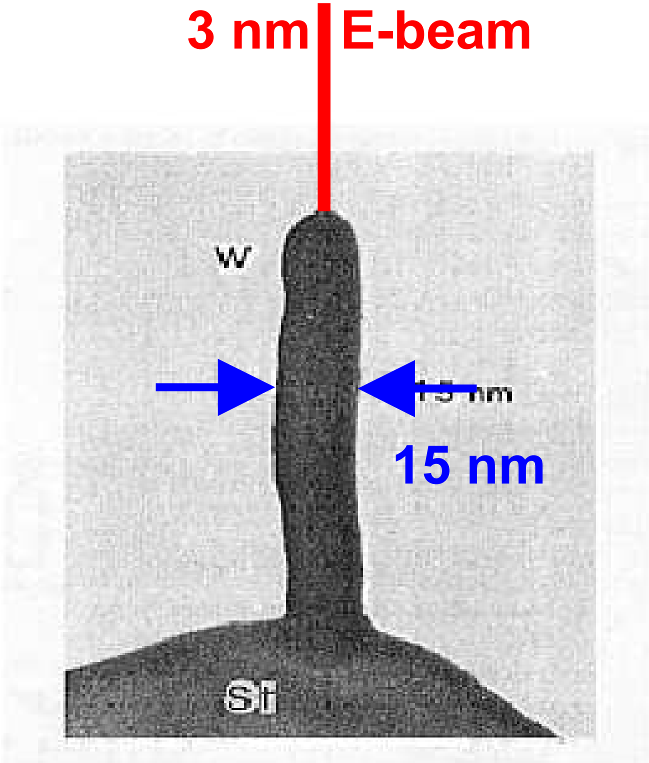
[From: Dr. H.W.P. Koops]





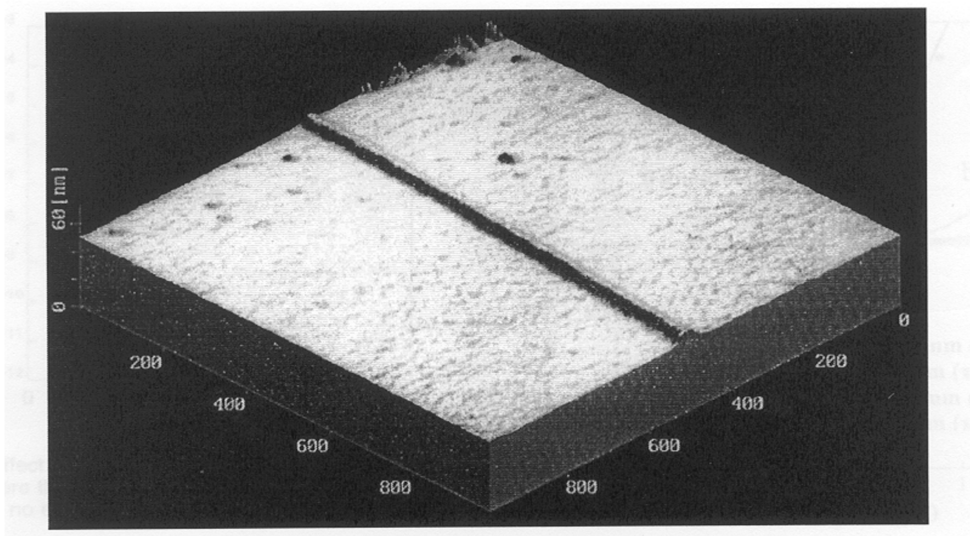


How small can one make EBID structures?



15 nm W tips on Si in a 120 kV TEM [Matsui et al.]

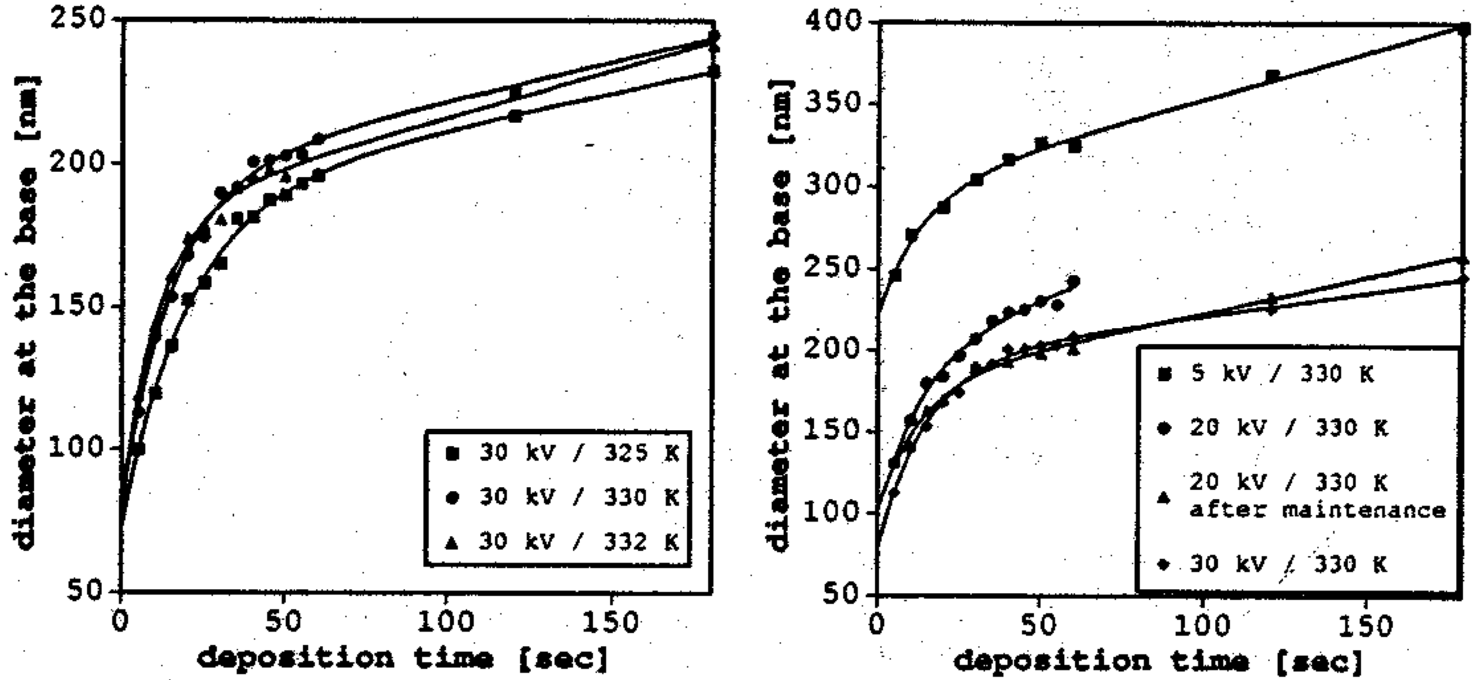
Electron beam probe size: **3 nm**



15-20 nm metal lines in a 50 kV SEM [Koops et al., Komuro et al.]

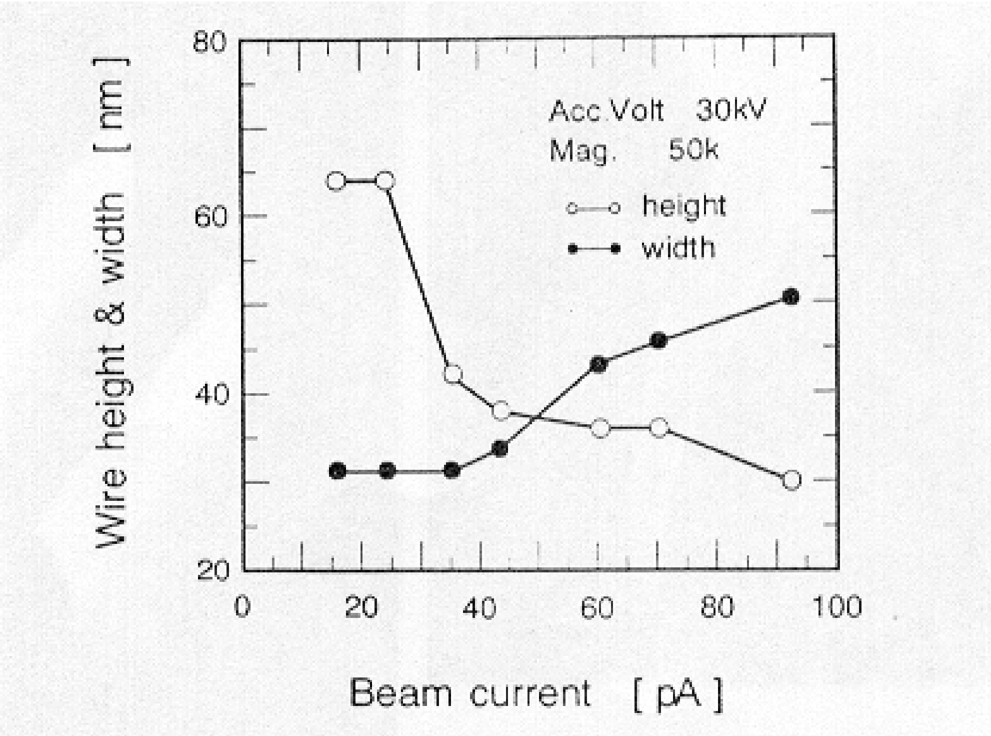
Electron beam probe size: **2 nm**

EBID resolution before 2000



The dot diameter evolution in time.

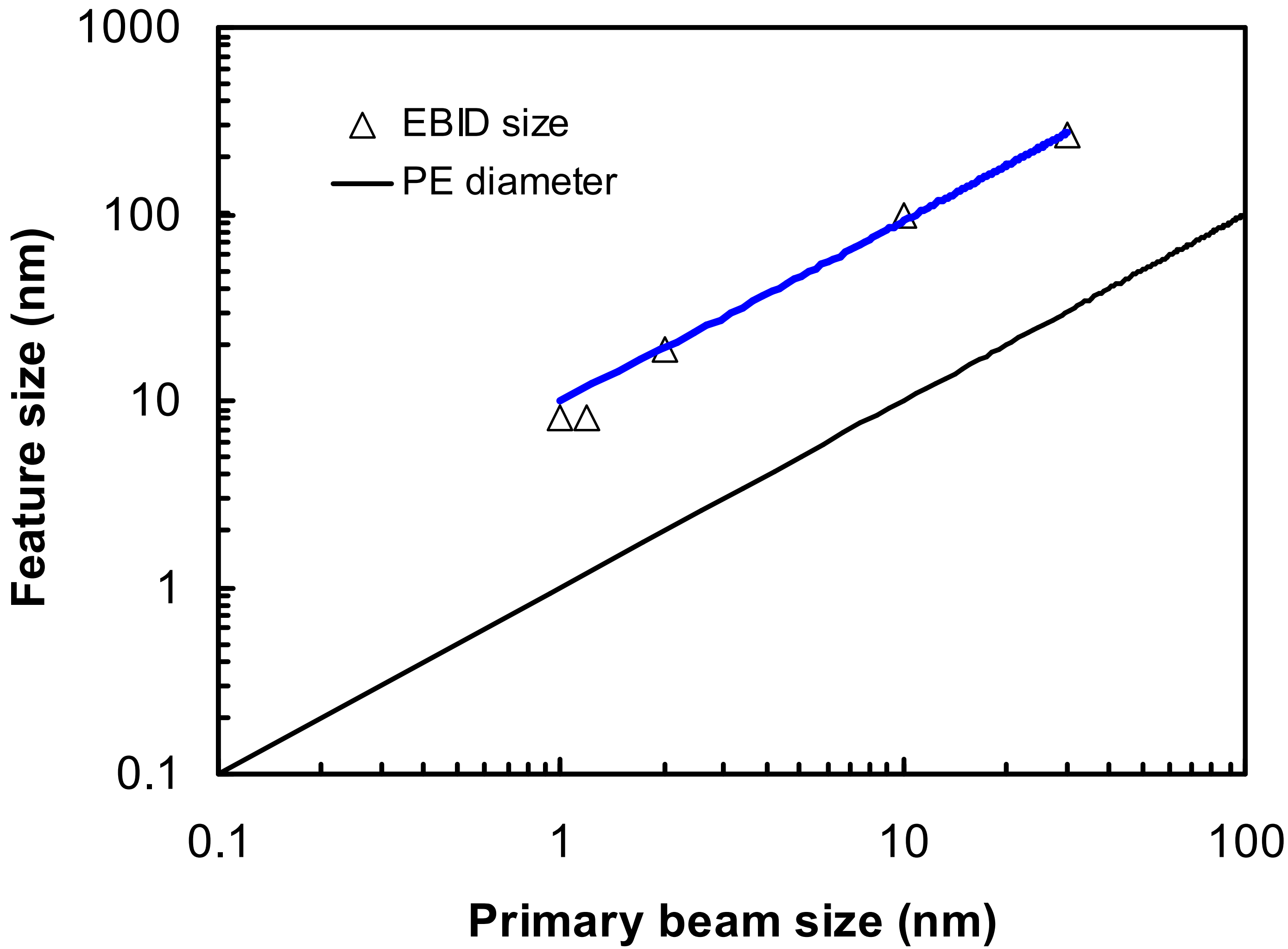
from Kohlmann-von Platen, K., and Chlebek, J.
Resolution limits in electron-beam induced tungsten deposition.
Journal of Vacuum Science and Technology B 11 (1993),2219.



The dependence of the width of a carbonaceous wire on the electron beam current

From Miura, N., and Ishii, H. Electron beam induced deposition of carbonaceous microstructures using SEM. Applied surface science 113/114 (1997), 269.

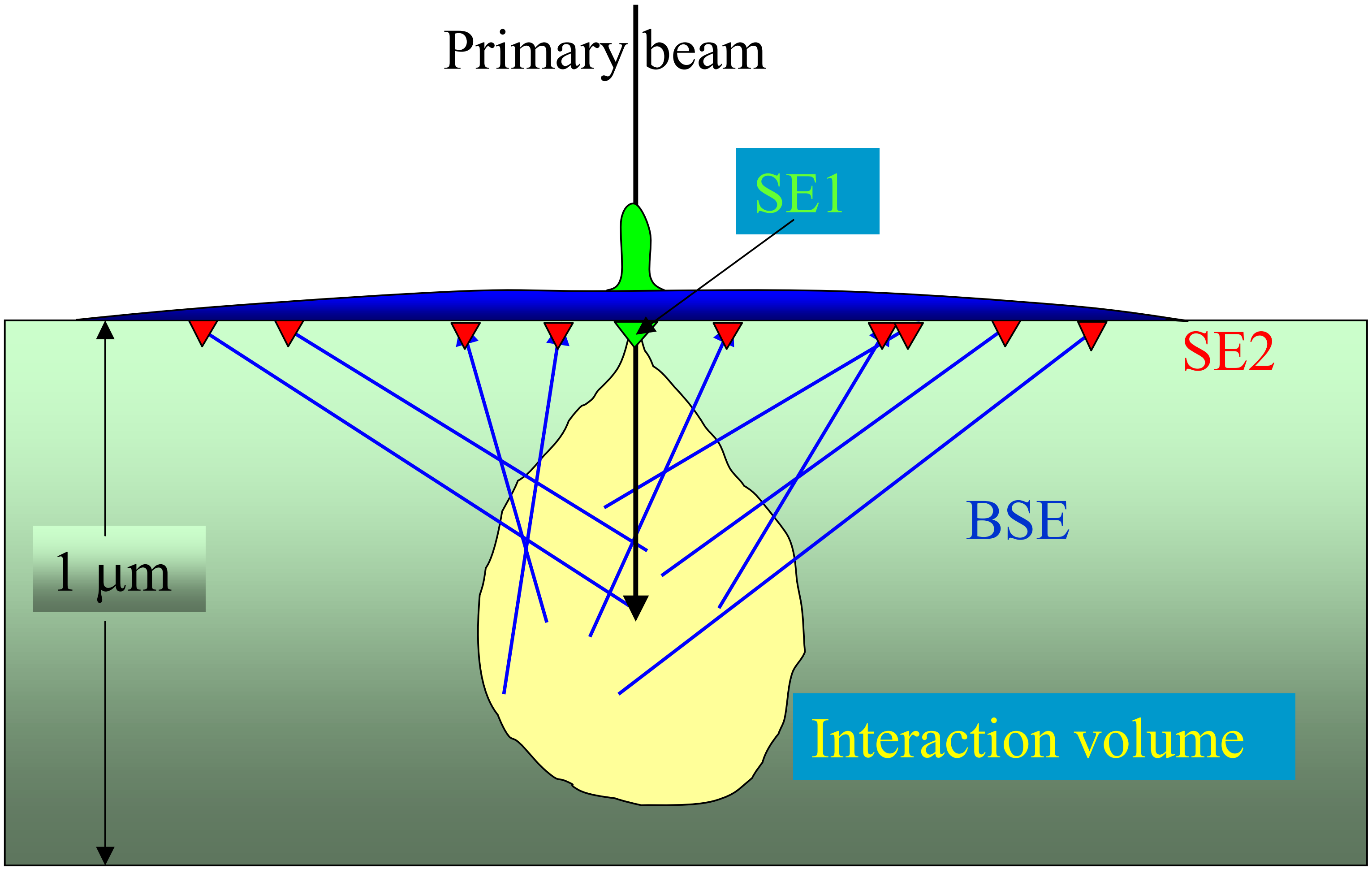
Why are EBID structures always larger than the beam size?



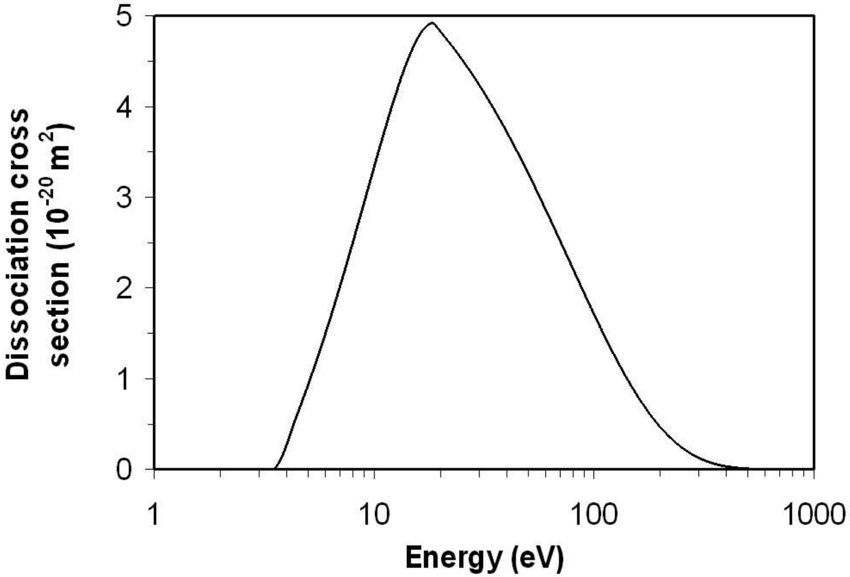
General belief:

this is due to the secondary electrons!

Electron-substrate interaction

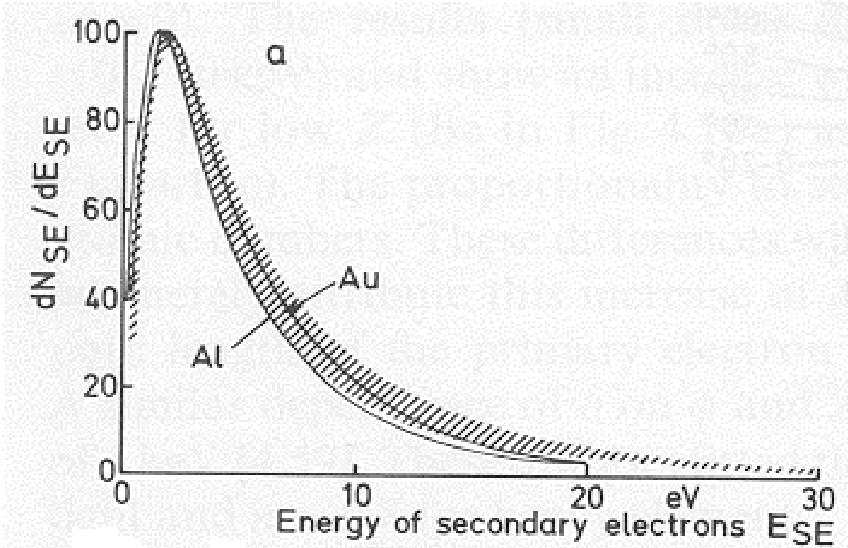


Electron-impact dissociation



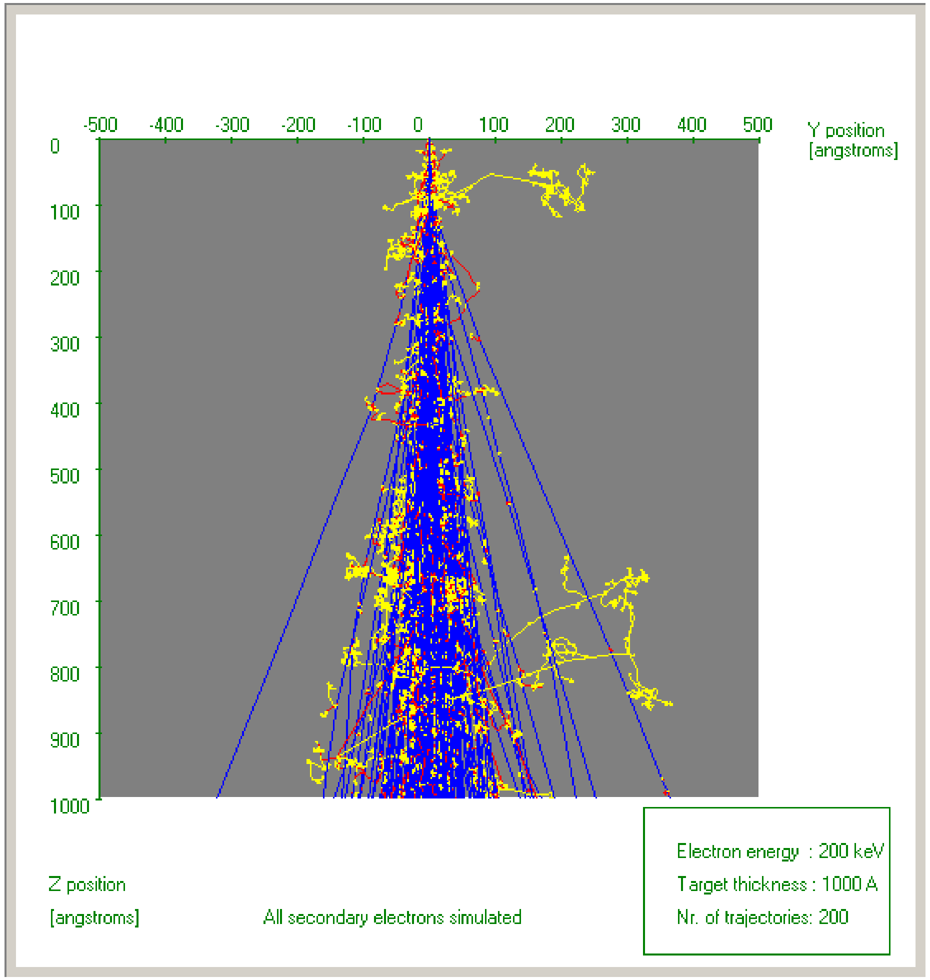
The electron impact dissociation cross section versus electron energy for C_2H_5 (shifted to lower energies)

from: Alman, D., Ruzic, D., and Brooks, J. A hydrocarbon reaction model for low temperature hydrogen plasma and an application to the Joint European Torus. Physics of Plasmas 7 (2000), 1421.

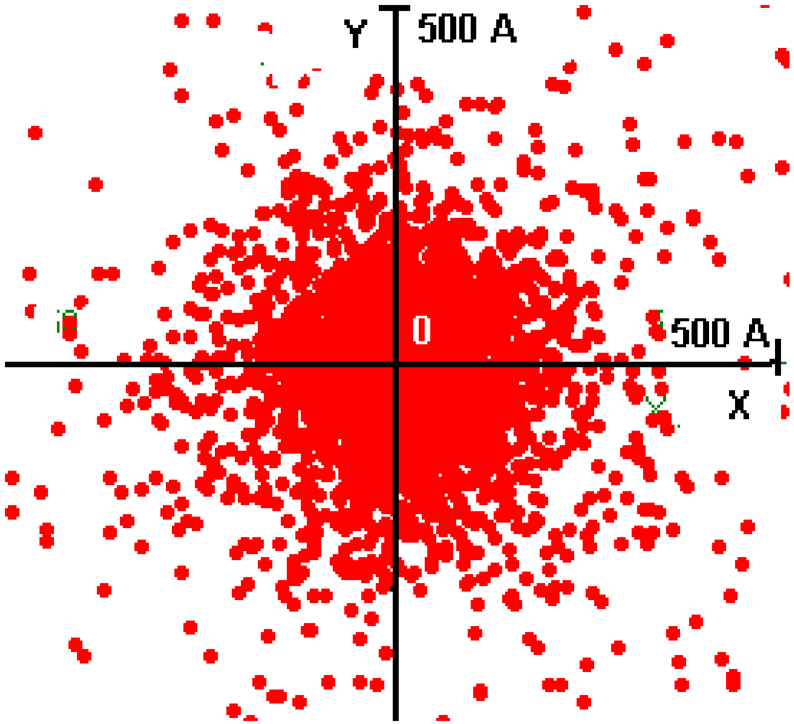


The energy spectrum of secondary electrons

Monte Carlo simulation of SE exit points



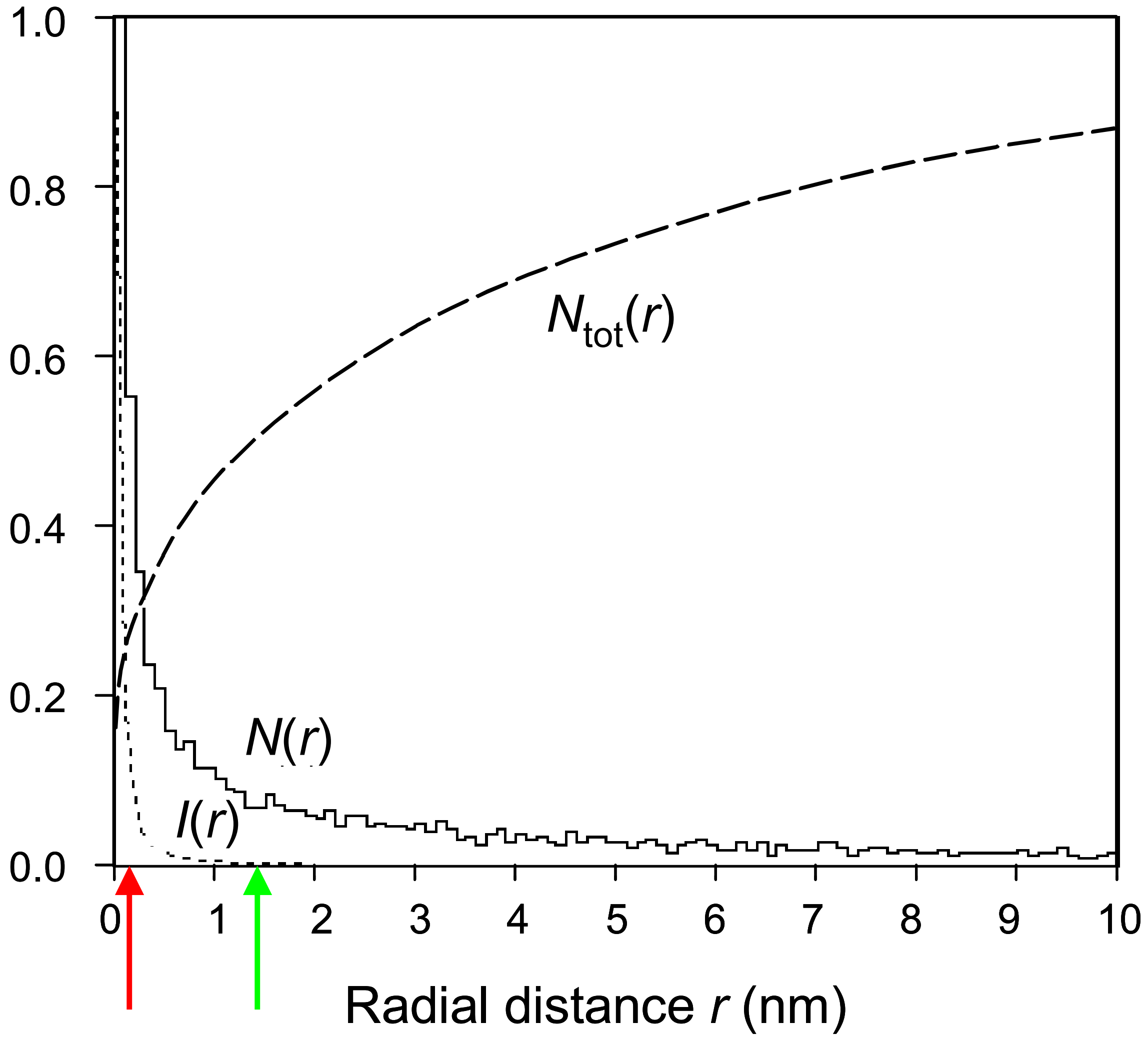
Electron trajectories in the substrate



SE surface exit points

$$f_{SE}(x,E)$$

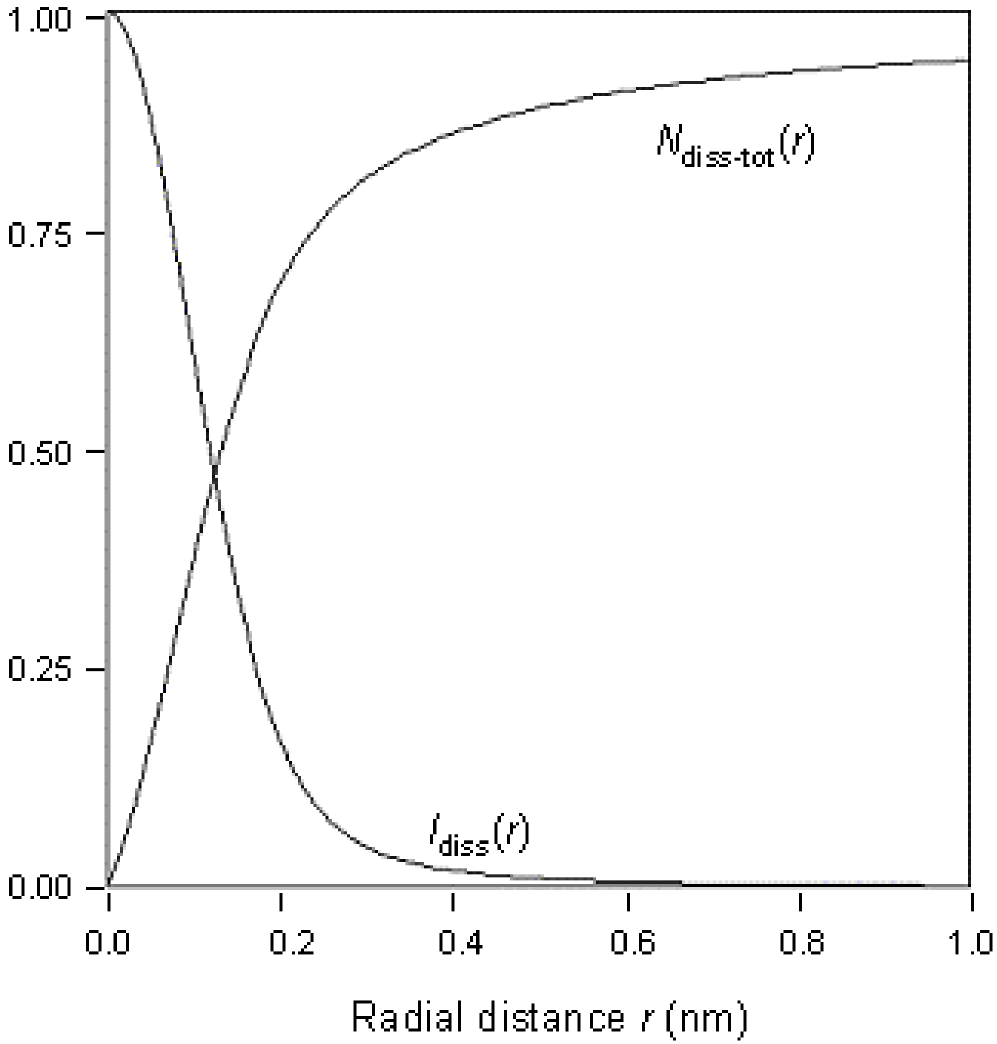
Monte Carlo simulation of SE exit points



Distribution of exit points of secondary electrons (all energies) from a 0-diameter 20 keV beam:

FWHM << 1 nm

FW_{50} = 3 nm

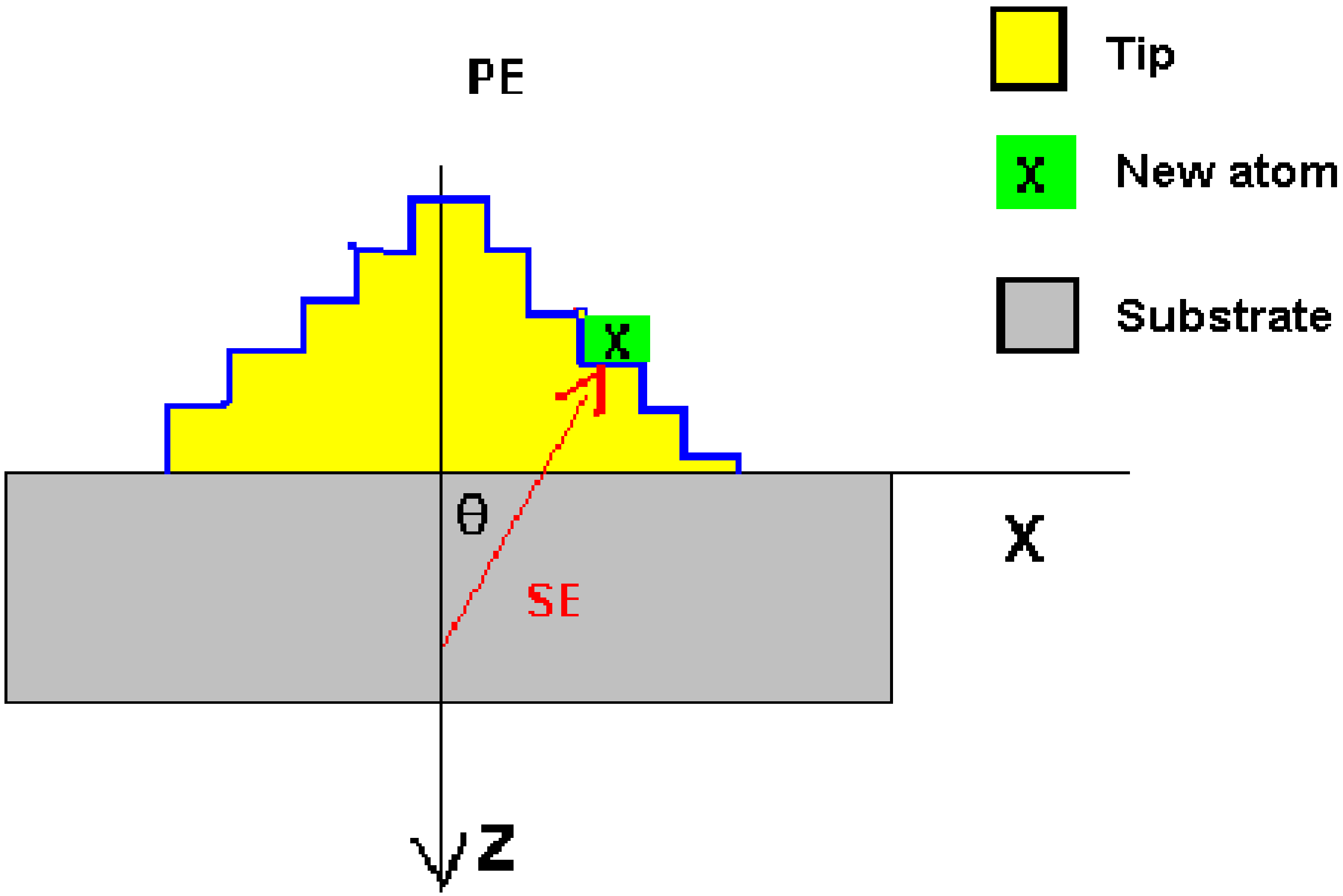


Distribution of exit points of secondary electrons weighted for dissociation efficiency from a 0.2 nm-diameter 20 keV beam:
FWHM= 0.24 nm
FW_{50} = 0.3 nm

Conclusion:

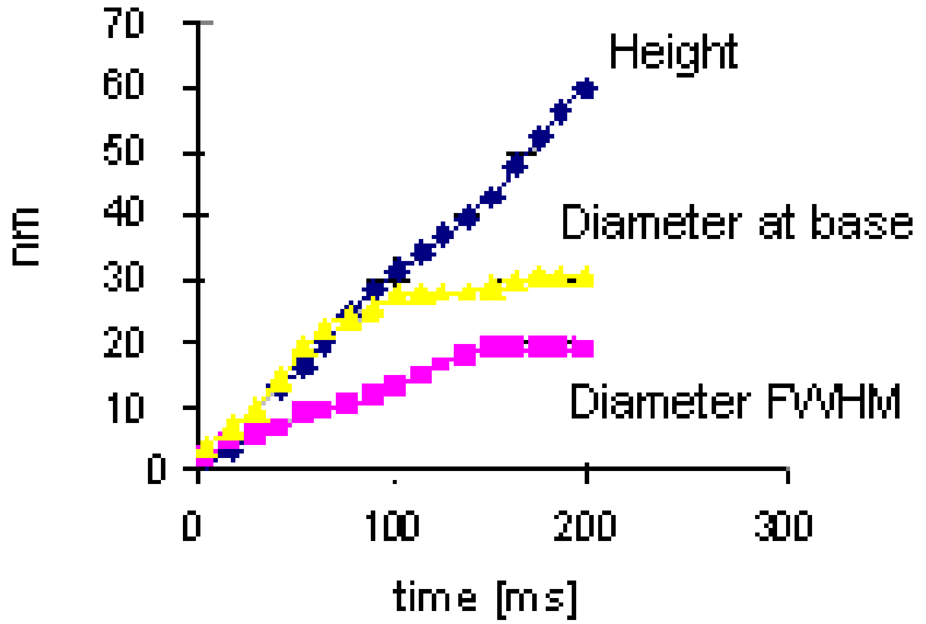
it's not the secondary electrons, or is it?

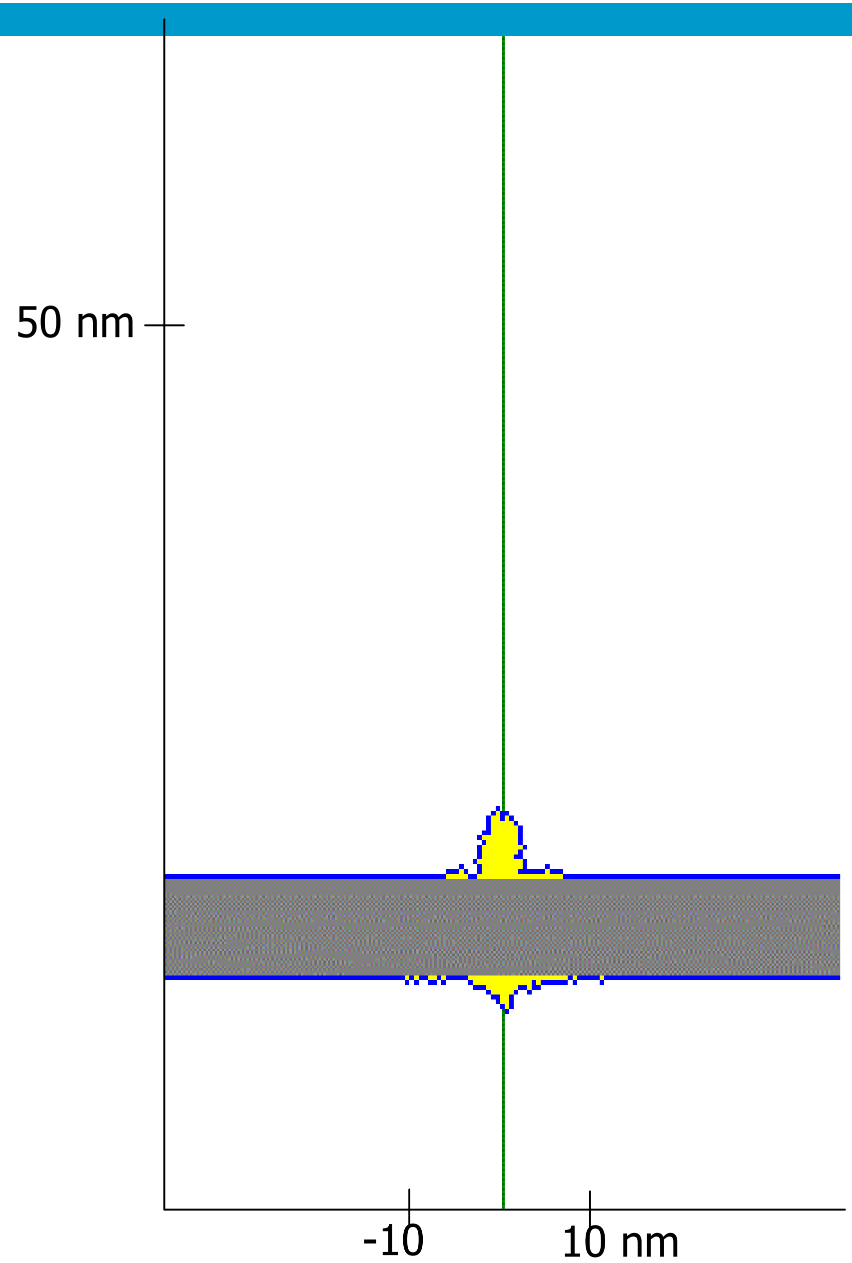
Dynamic Monte Carlo simulation of the growth process



Simulated growth of a C-dot on C

Cellular automata / Monte Carlo simulation, zero beam diameter, 10 nm thick C-foil, 200 keV PE

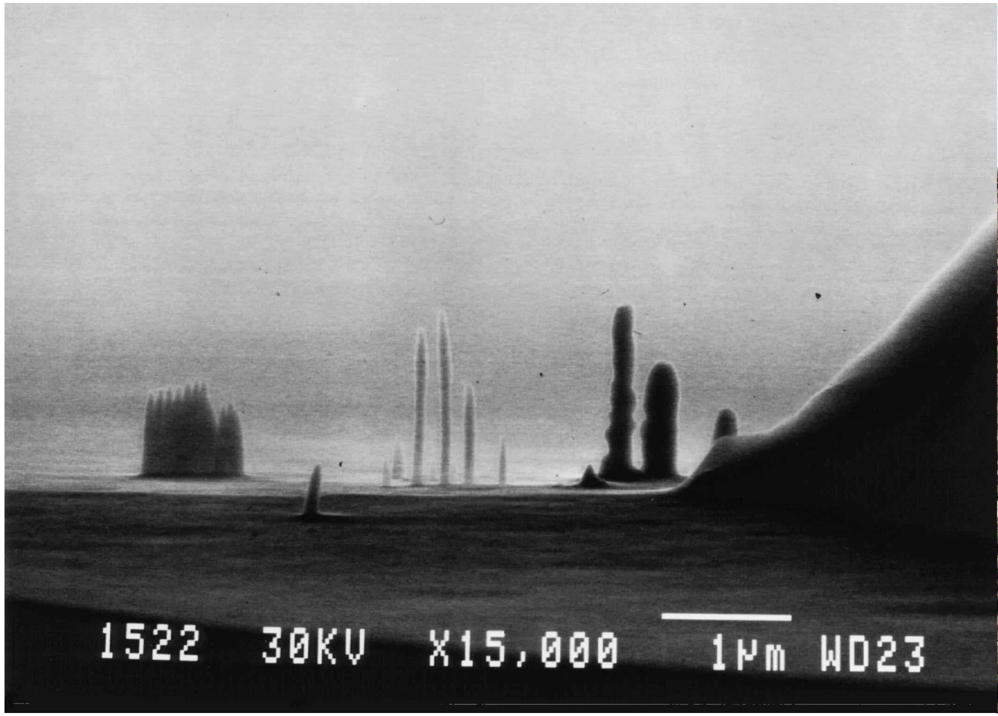




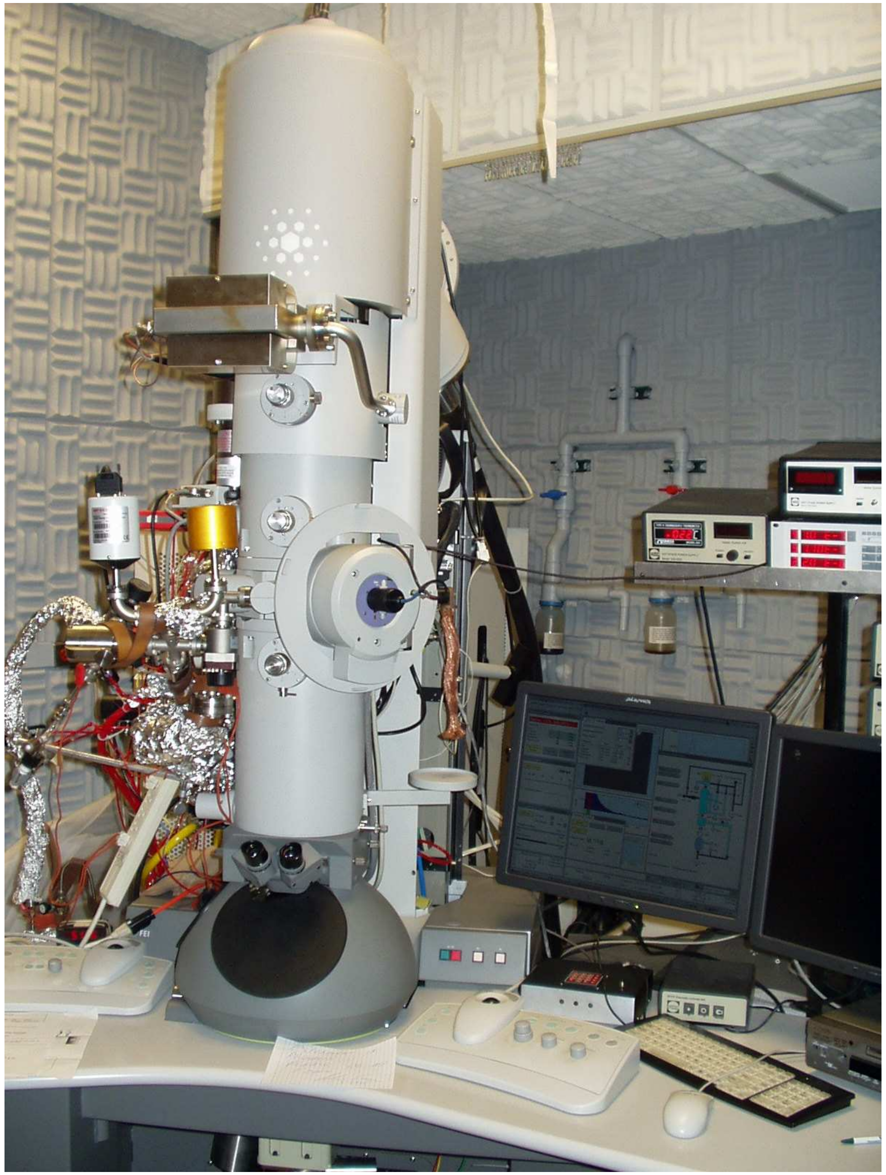
Conclusion: the secondaries do cause these broad structures for long deposition times!

However, we can stop the deposition in time!

ARIZONA



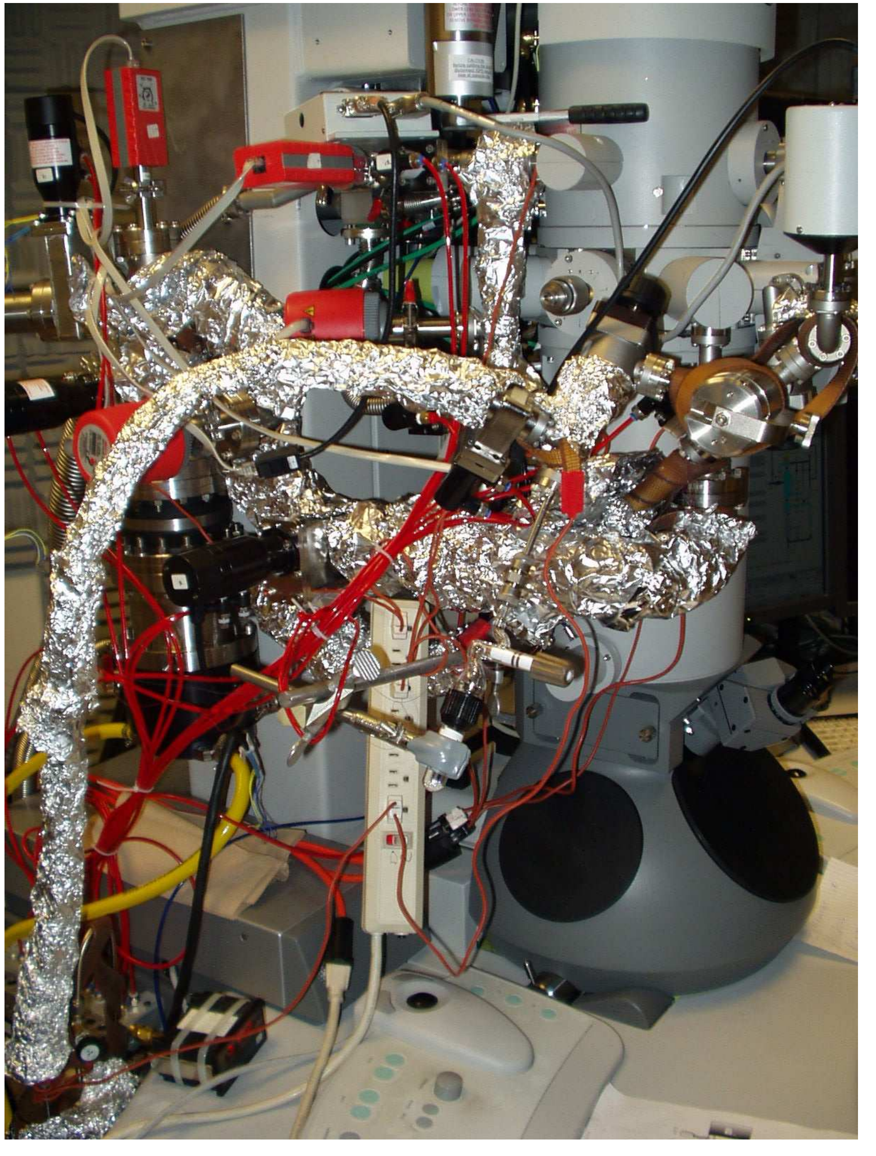
[From: Dr. H.W.P. Koops]

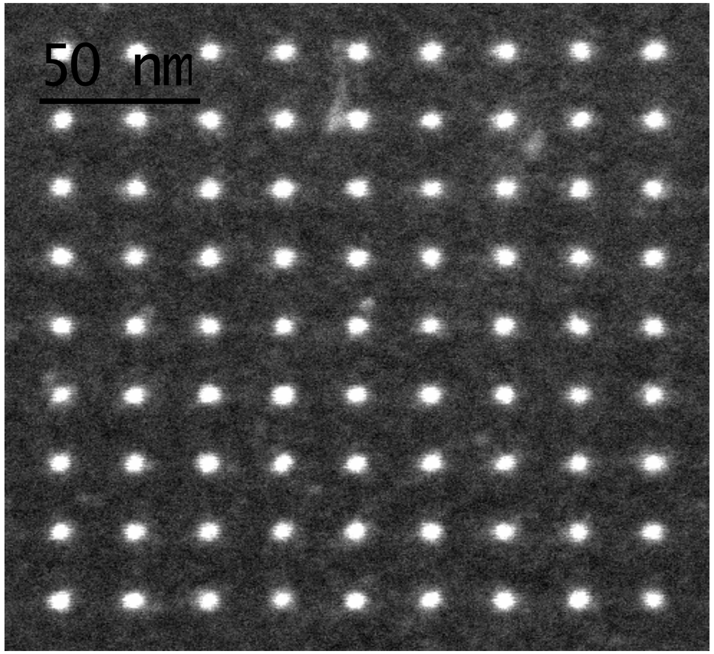


Environmental STEM

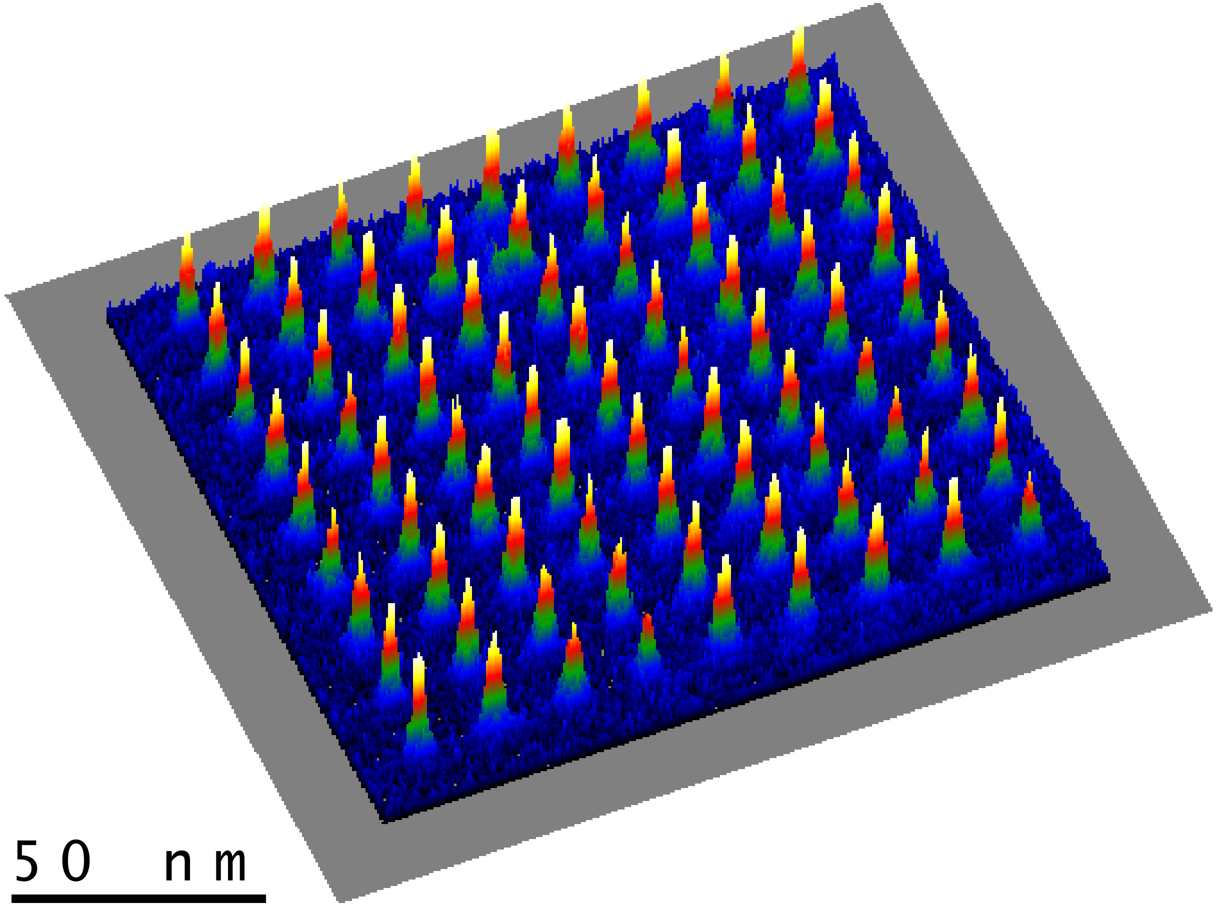
- Center for Solid State Science, Arizona State University
- 200kV, 0.3 nm beam
- Environmental cell, pressure typical 1 mTorr
- $W(CO)_6$ deposition on Si_3N_4 and C membranes
- Deposition at 107 C (sample holder temperature)

The Plumbing





W-dots on C-foil

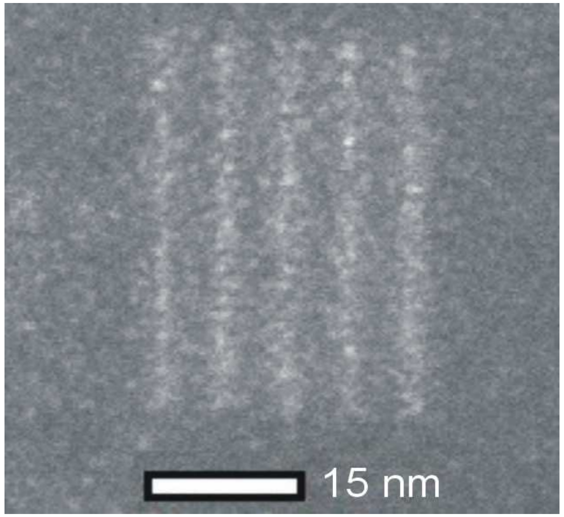


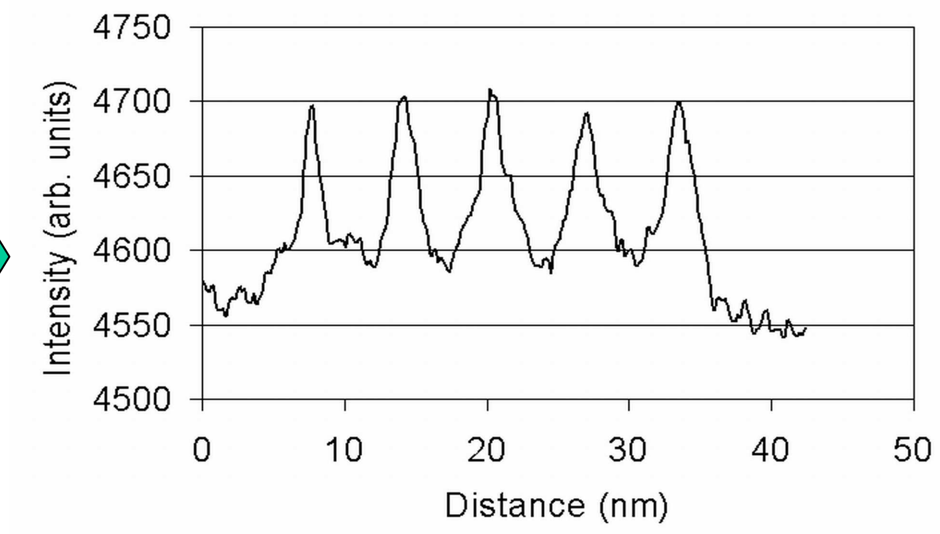
Dot diameter 4.5 nm

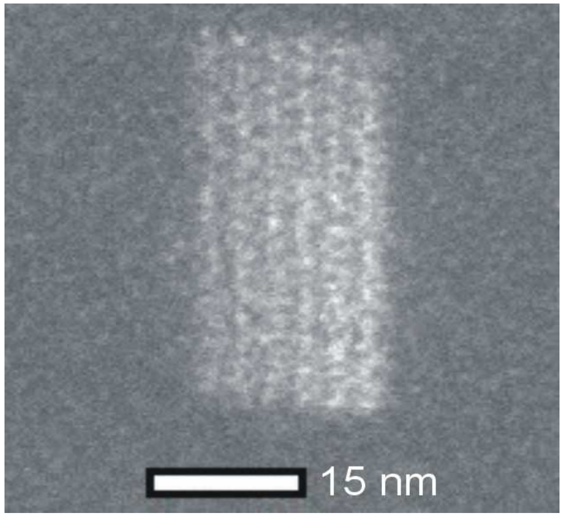
pitch 22 nm

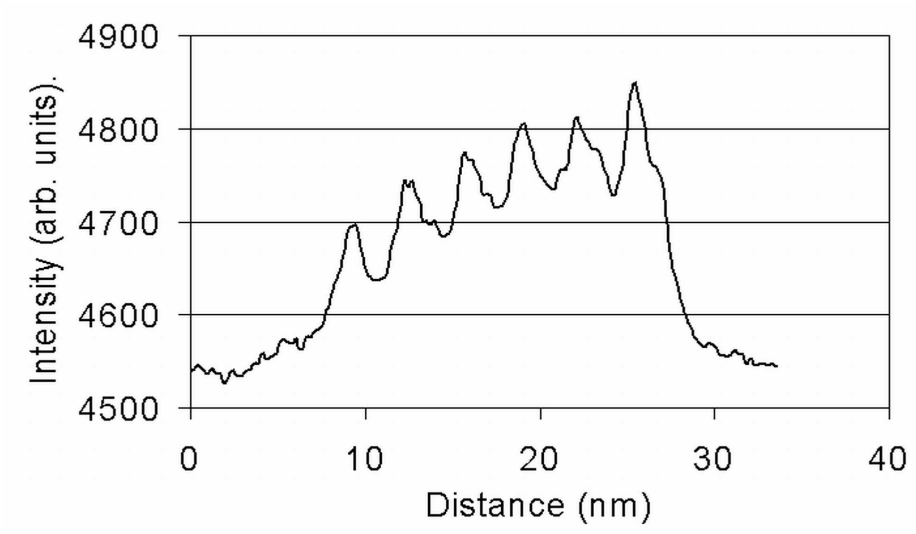
Z-contrast images

Lines and spaces in EBID



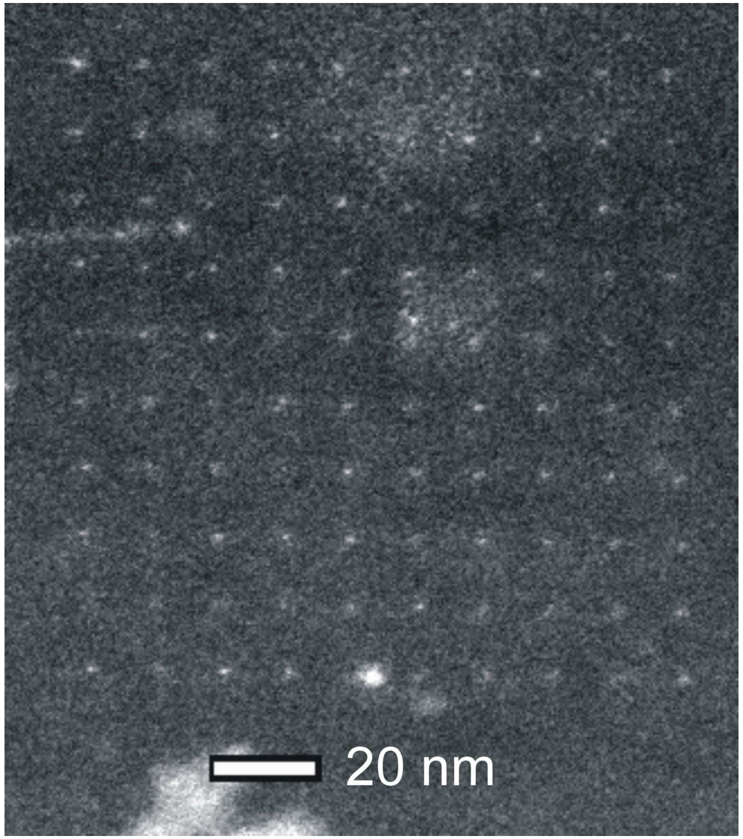


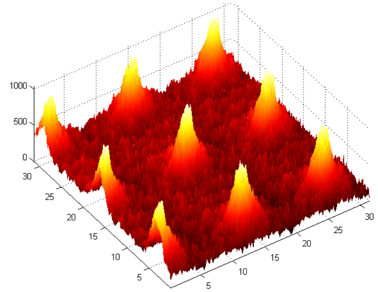


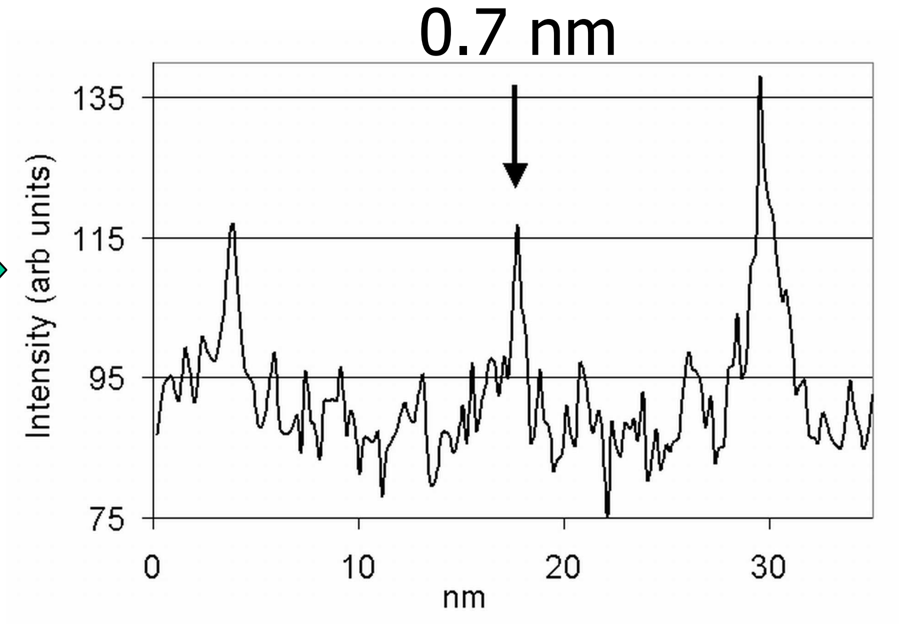


1.7 nm half pitch

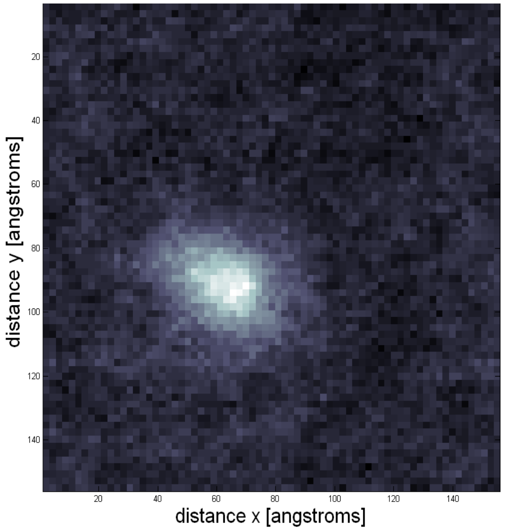
10x10 array of tungsten dots on SiN at 14 nm pitch

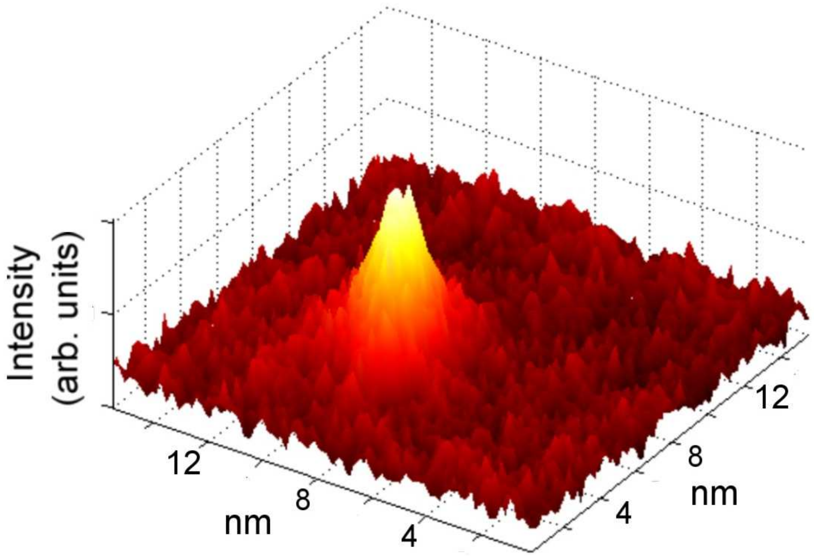


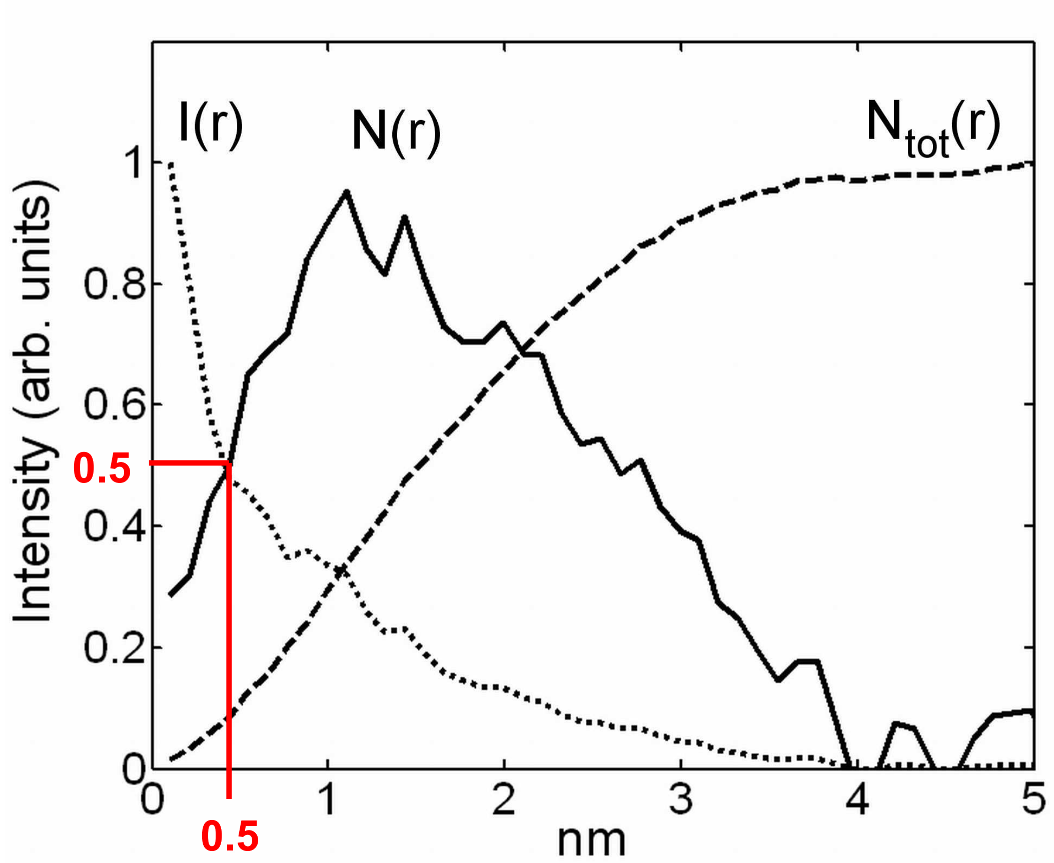




EBID WORLD RECORD : 1 nm AVERAGE DOT DIAMETER





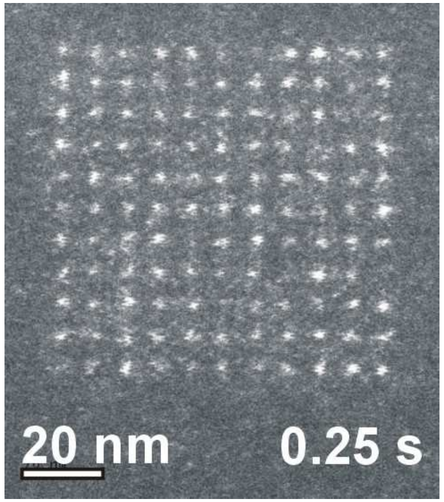


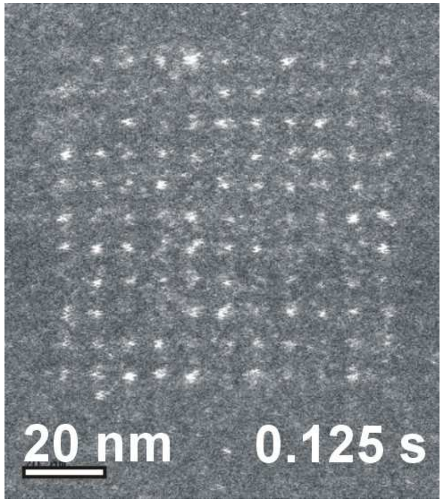
FWHM < 1 nm

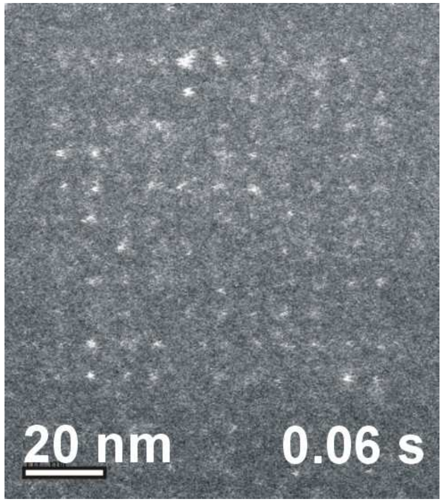
FW50% = 3 nm

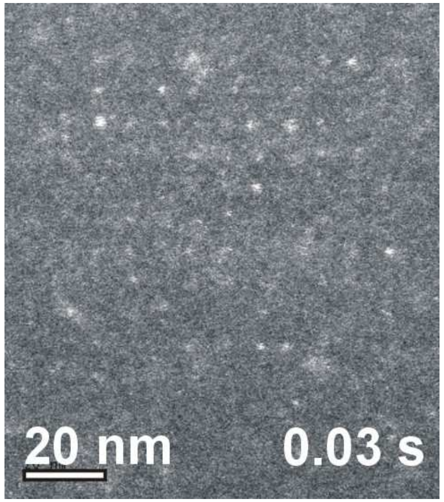
Statistical spread in deposited mass

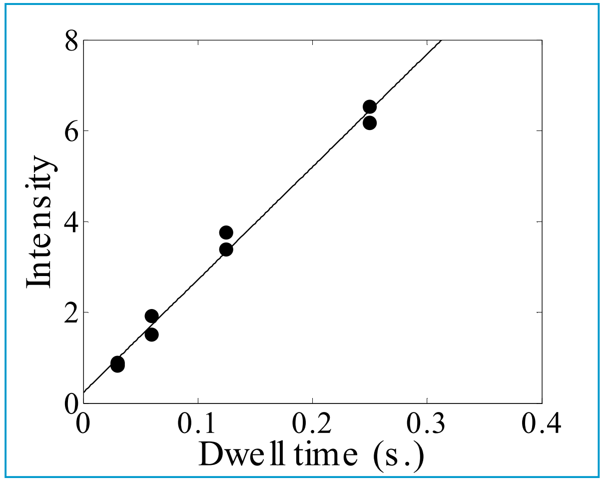
4 arrays of 11x11 W dots on 10 nm C foil

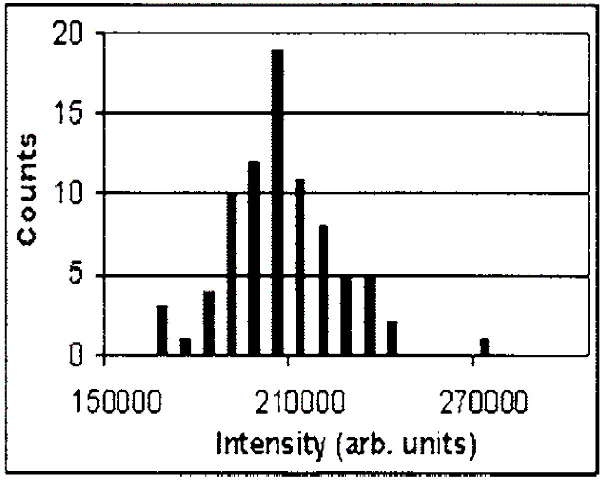


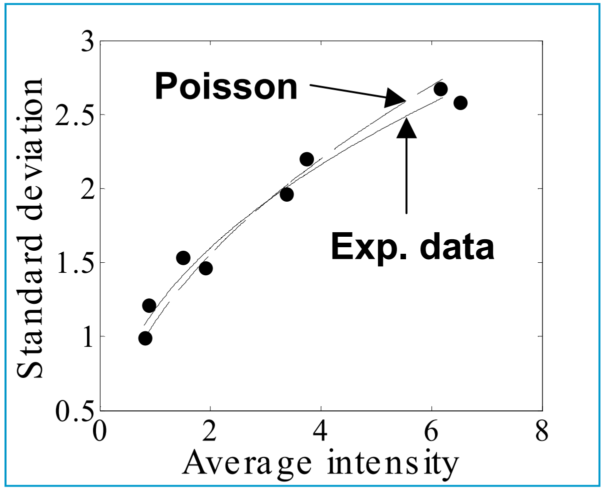




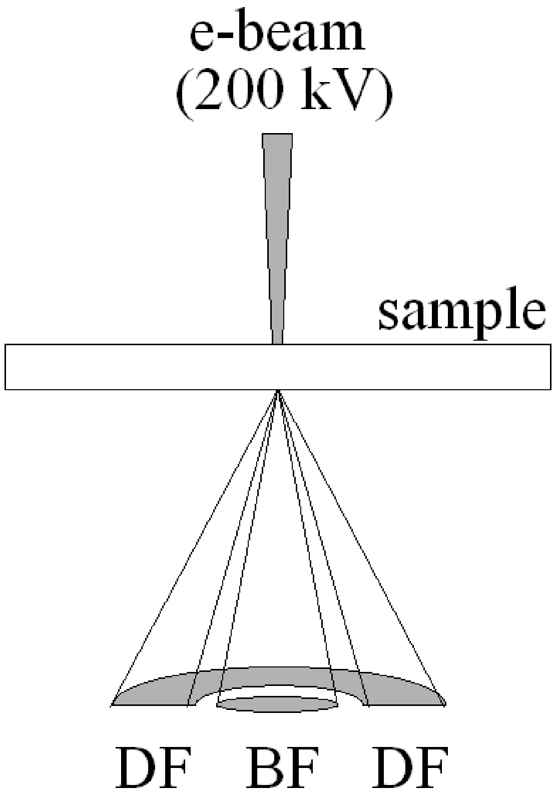


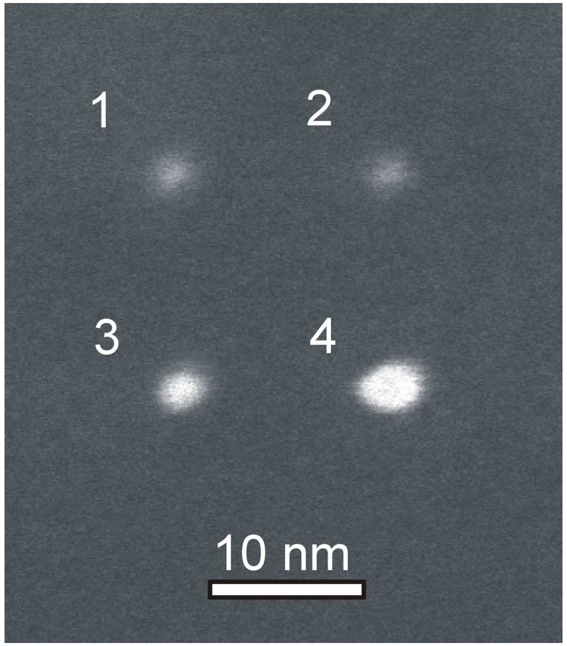


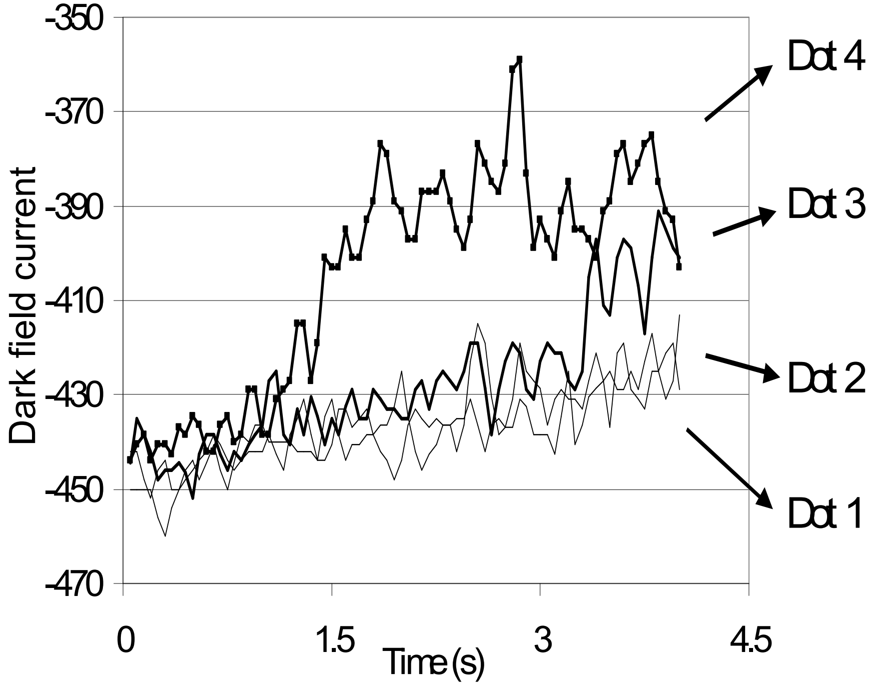




Z-contrast imaging or Annular Dark Field imaging



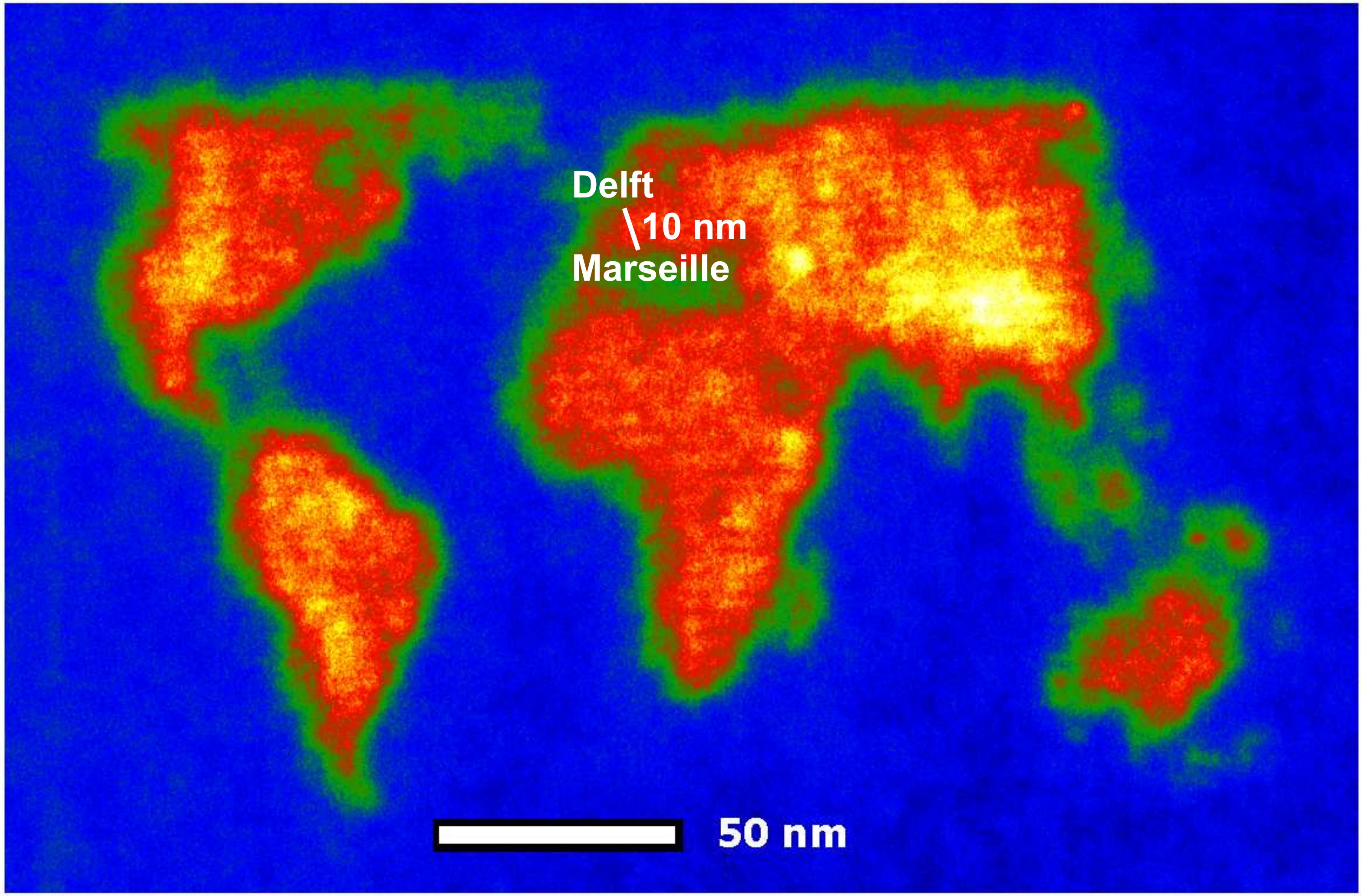




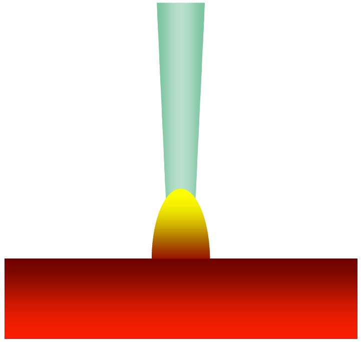
One can use the ADF signal to control the deposition

Application: create a Nanoworld

Delft-Marseille: only a 40 ps travel



Writing speed of EBID



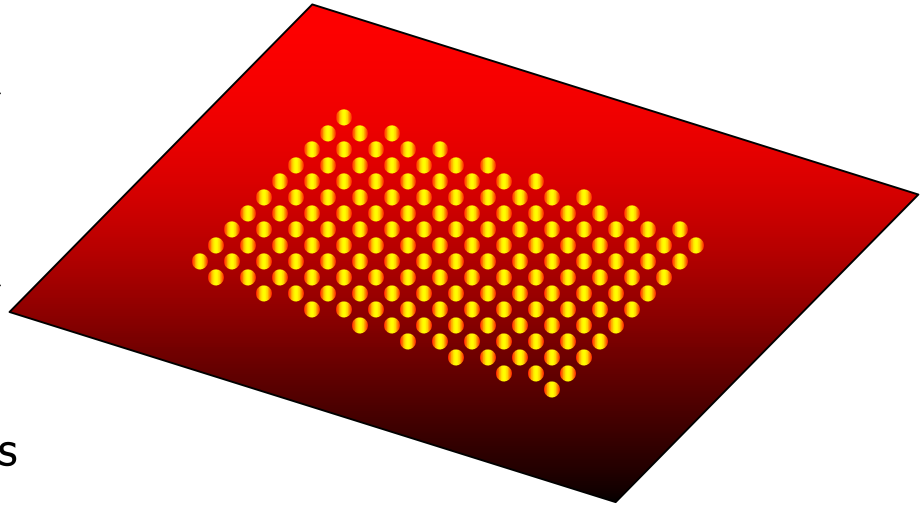
Current ≃ 0.1 nA.

10^{-14} C per dot

writing speed

≃ 10^{-4} sec per dot

≃ 10^{-2} μm^2 per sec



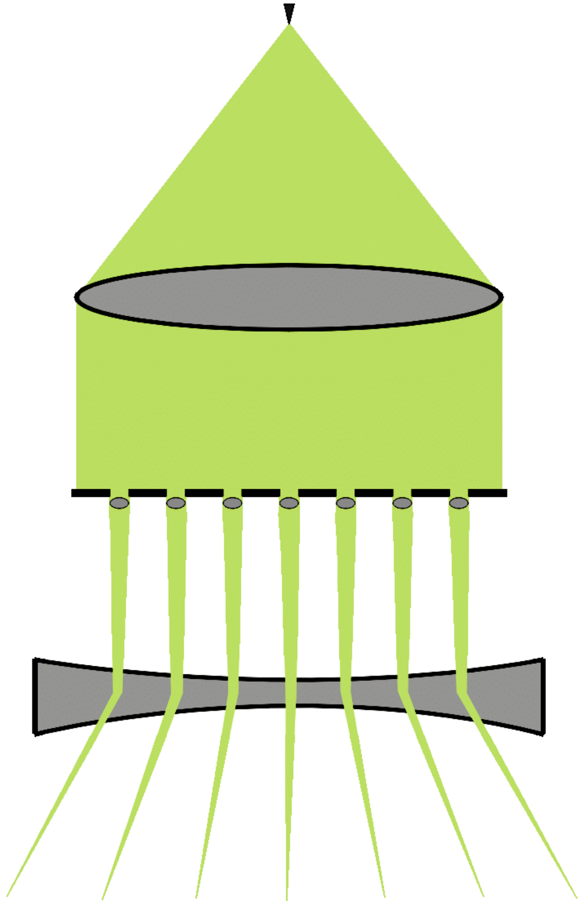
1 cm^2 would take

10^{10} sec = 300 years

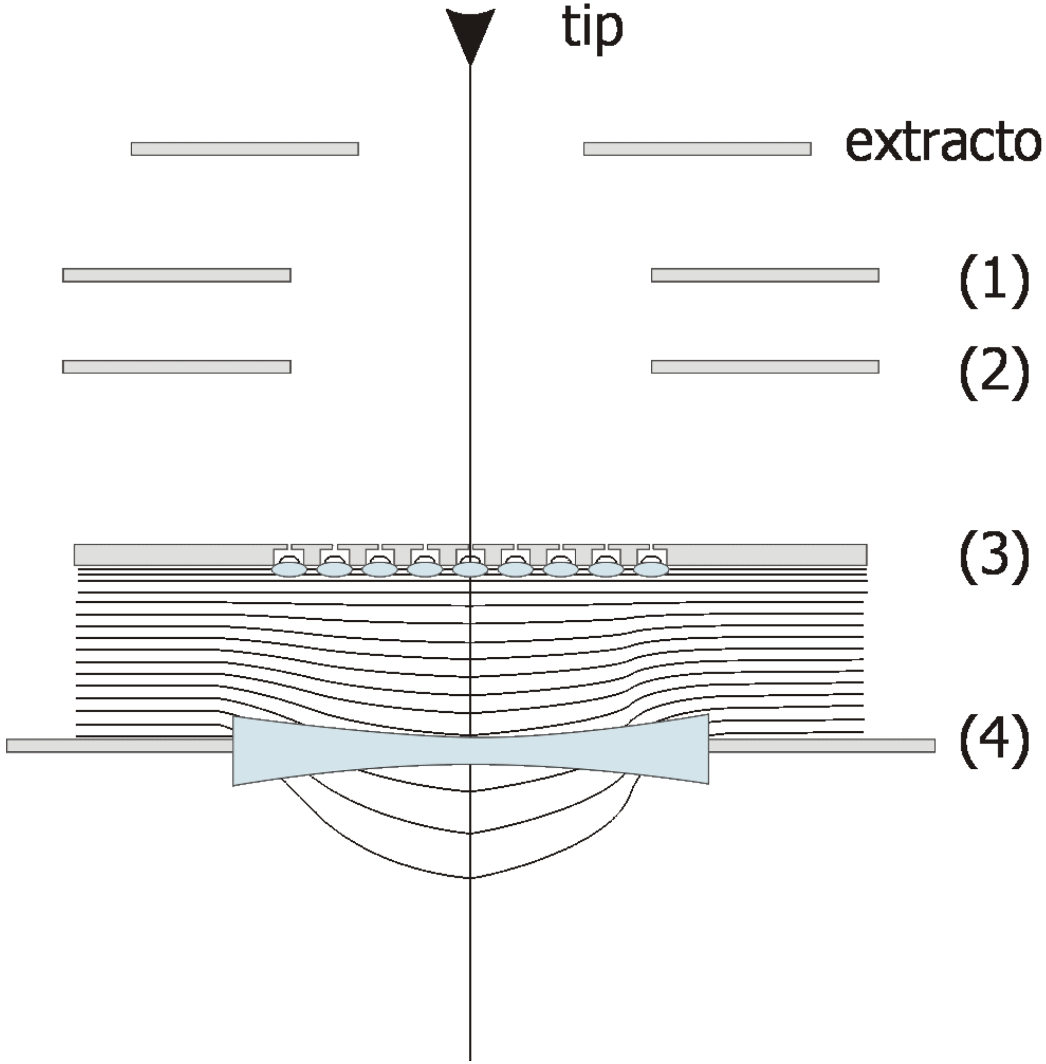
Conclusion

- more beams
- more current per beam
- more efficient process

Multi-beam electron source for EBID tool



100 beams of 1.0 nm

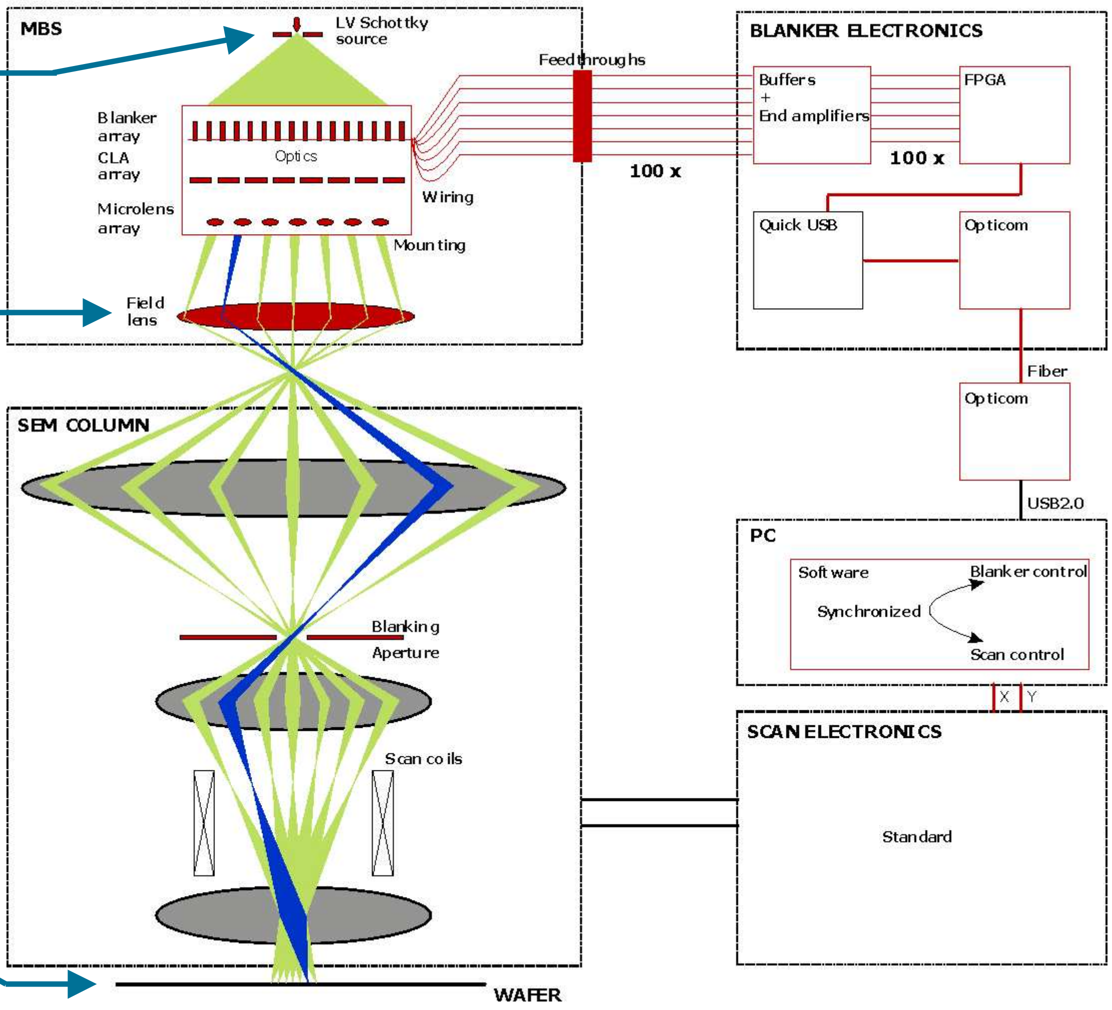


Multi-beam EBID tool

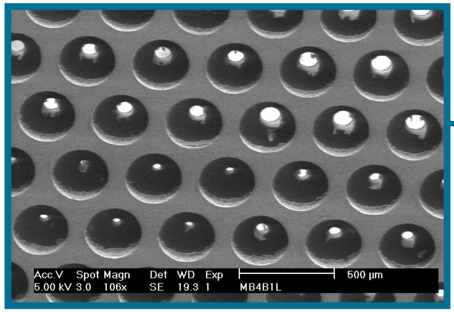
Schottky source: virtual source size ~ 30 nm

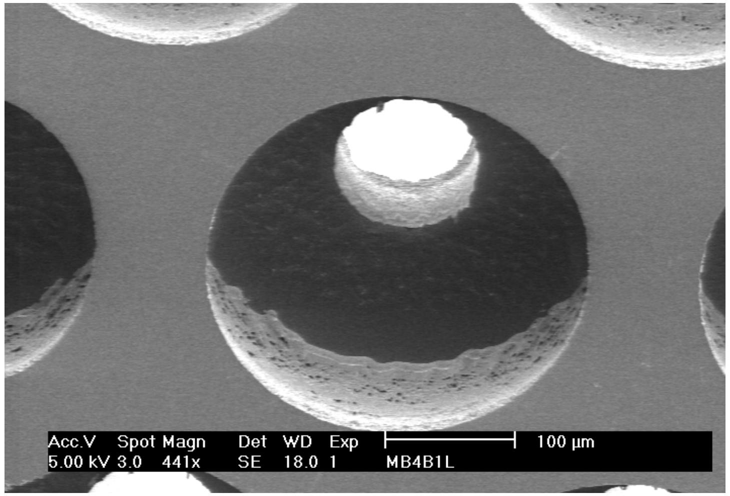
100 source images of 150 nm

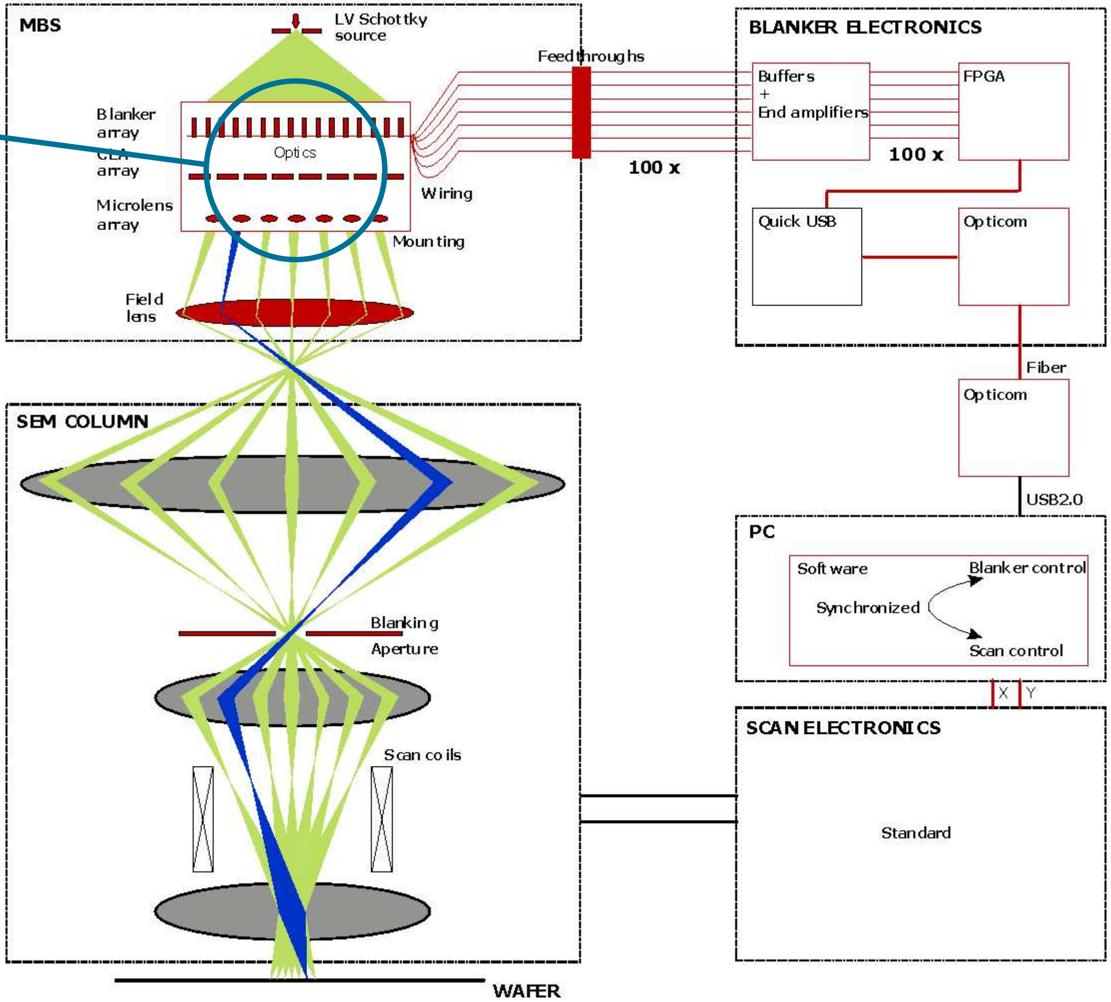
100 beams of each 1 nm diameter and 25-250 pA current at the wafer



Multi-beam EBID tool



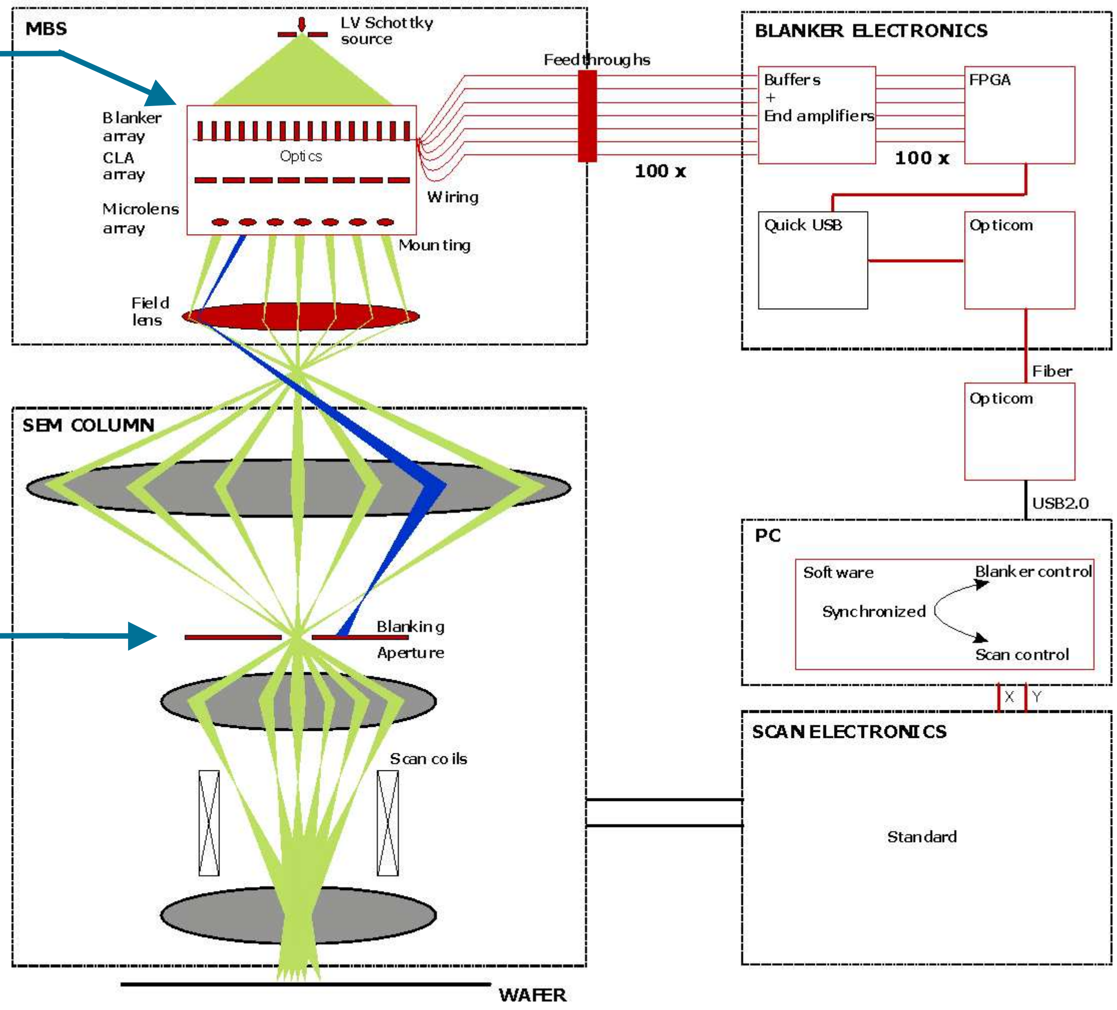




Multi-beam EBID tool

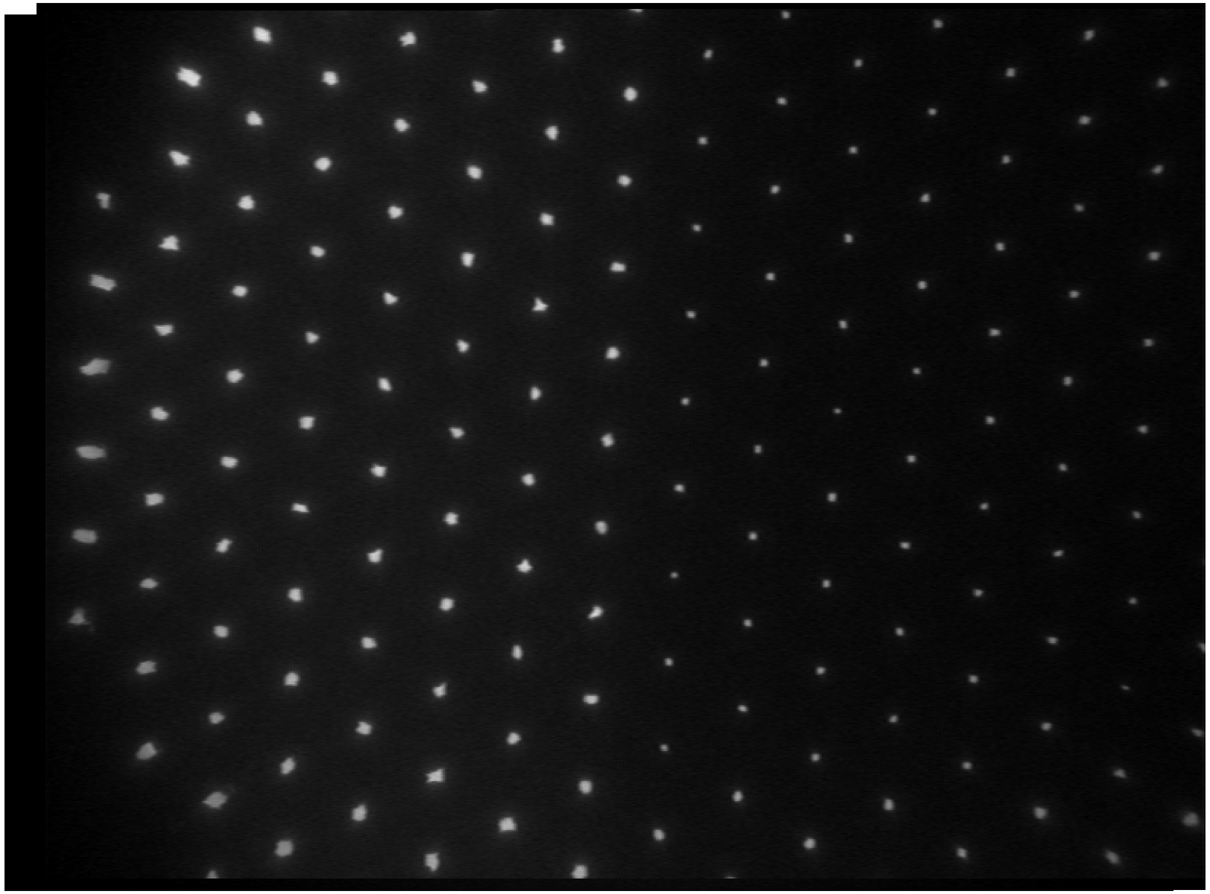
Beam blanker array

Blanking aperture



Experimental results: through-focus series of multi-beam source

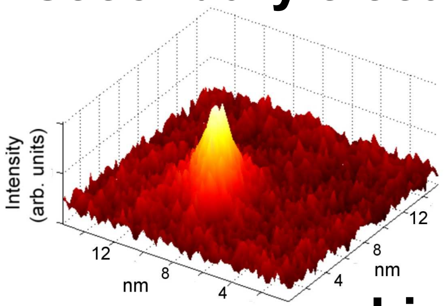
Effect of both negative lens AND microlenses



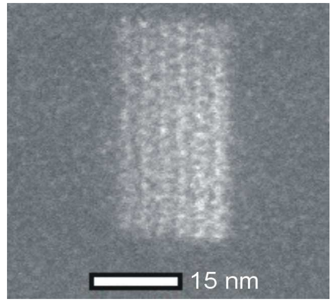
Requirements for the multi-beam EBID tool

Individual spotsize	≤ 1 nm
Individual beam current	≥ 25 pA
Number of beamlets	100
Total footprint at substrate	5 x 5 μm
Relative distortion in beam array	≤ 0.02
Beam drift	≤ 0.5 nm/s
Individual on/off switching frequency	≥ 260 kHz
Data rate	≥ 26 Mbit/s
Current stability	≤ 4 %
Uniformity variations over the array	≤ 4 %
Angle of beamlet incidence	<< 10 mrad

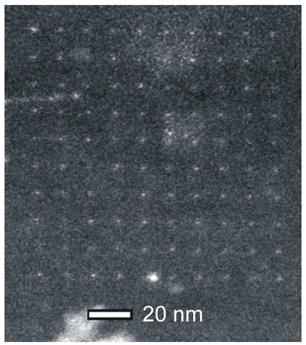
We now understand why structures were always broader than the electron beam: the secondaries cause a lateral growth, until the radius equals the secondary electron range.



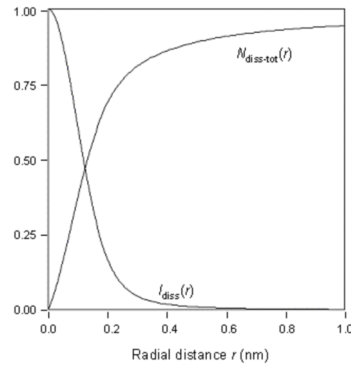
1 nm dots can be deposited with EBID:
one just has to stop in time!



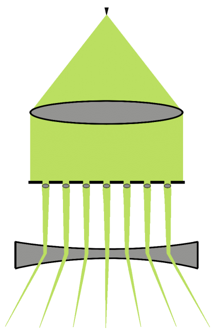
Lines and spaces of 1.7 nm pitch can be deposited!



Statistical spread in mass and position observed.



No fundamental reason why not smaller!



We are developing a multi-beam EBID tool