Focused Ion Beam Microstructuring

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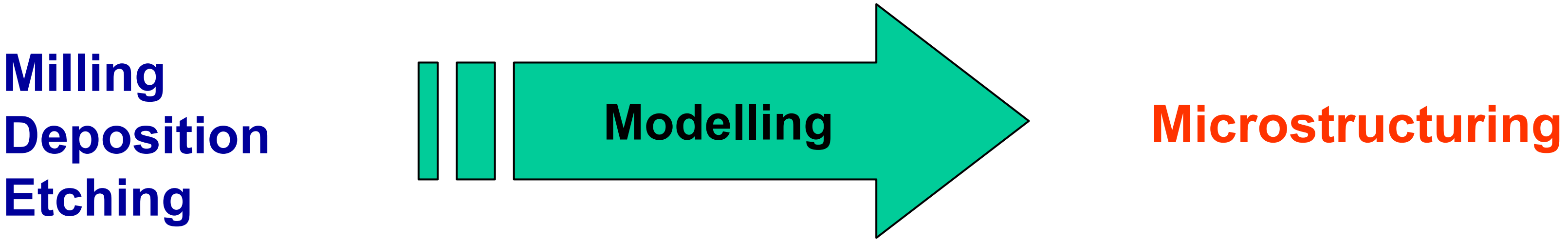


Milling
Deposition
Etching

Modelling

Microstructuring

State of the Art

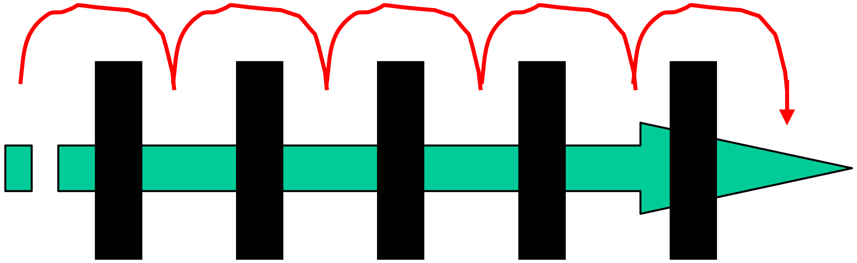
- TEM lamella preparation
- Cross sectioning
- Failure analysis

Emerging applications

- MEMS device fabrication, modification
- Scanning probe microscope tips
- Micromedical device structuring
- Micro- and nano-print master fabrication (e.g. diffractive optical elements)
- Arbitrary shapes…

Hurdles to get over

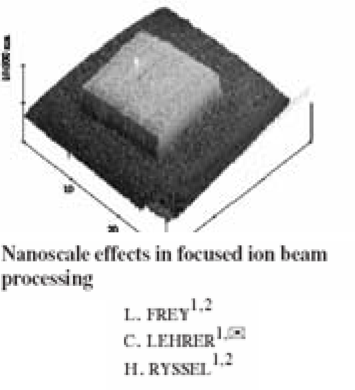
Milling
Deposition
Etching



Microstructuring

Accuracy and prediction

Swelling

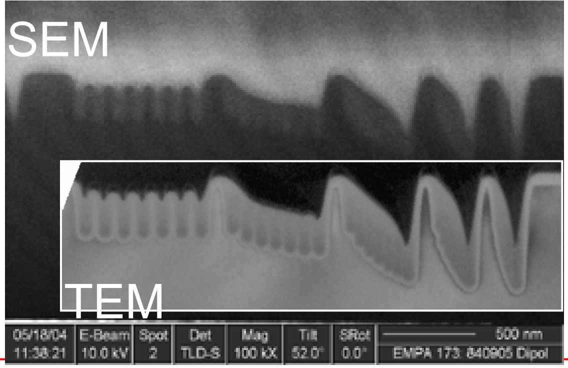


Nanoscale effects in focused ion beam processing

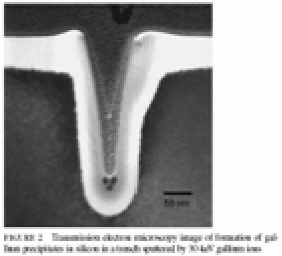
L. FREY[1,2]
C. LEHRER[1,✉]
H. RYSSEL[1,2]

Amorphisation

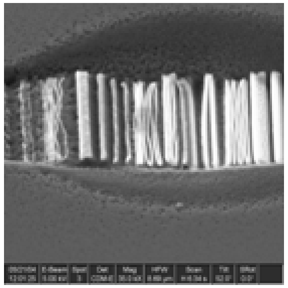
Redeposition
Geometric effects
Beam shape effects



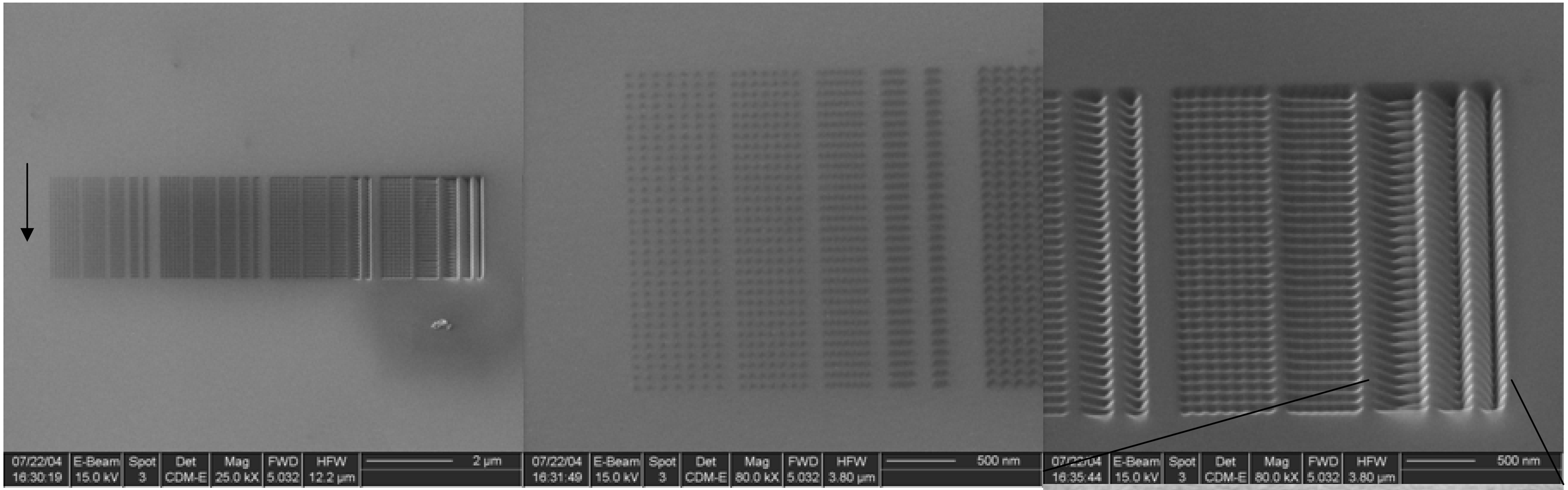
Ga precipitation



Others?
(overspray)

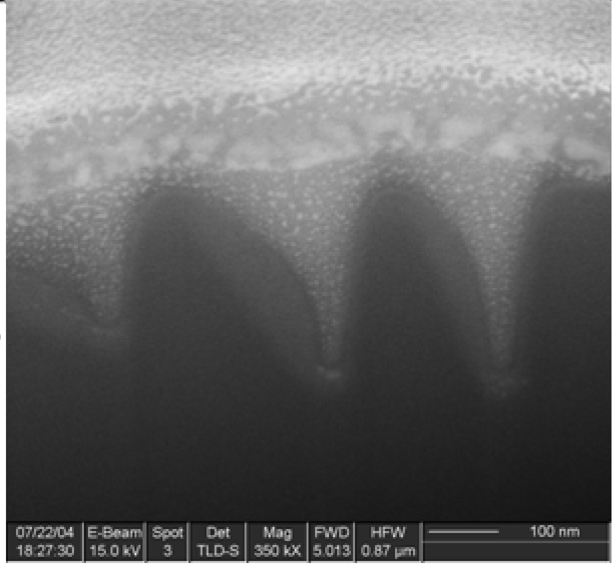


Single dots and single line writing

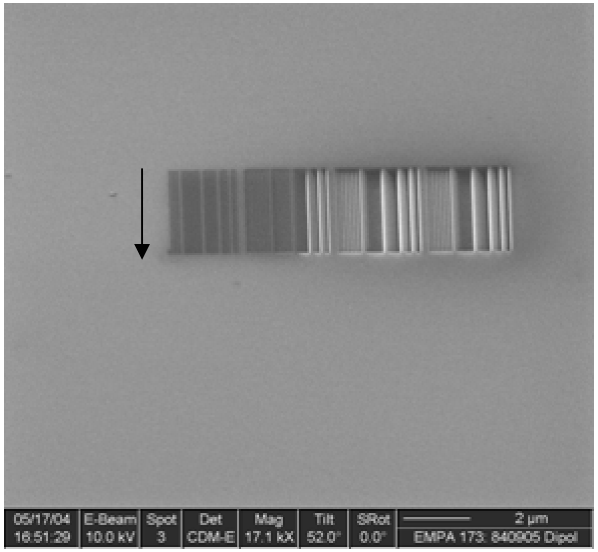


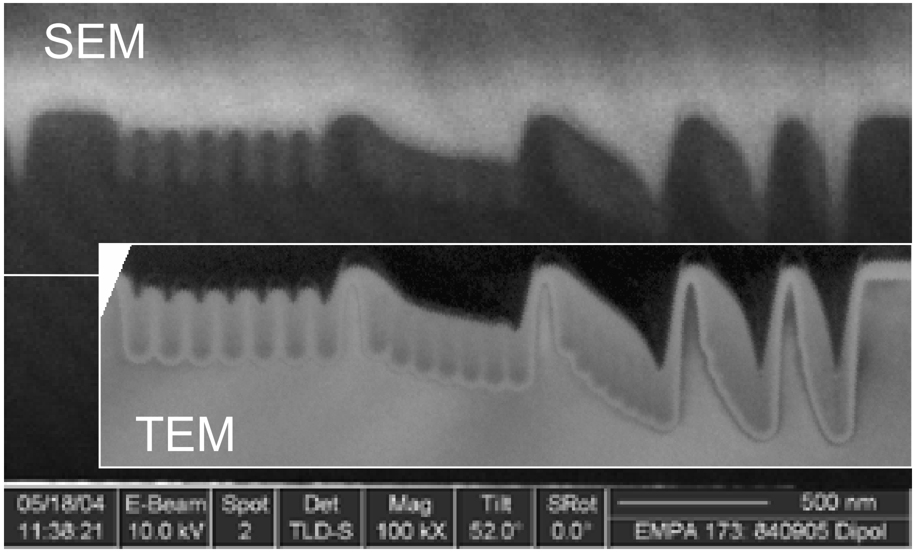
Probe EMPA 173

Single dots:
ion current 100pA
dwell times: 0.1, 1, 10, 30ms
Spacings (->): 102, 76, 51, 25.6, 12.8nm
overlapping effect – redeposition – self-focusing effects (grazing incident ions reflected)



Single lines writing





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dwell times: 0.1, 1, 10, 30ms
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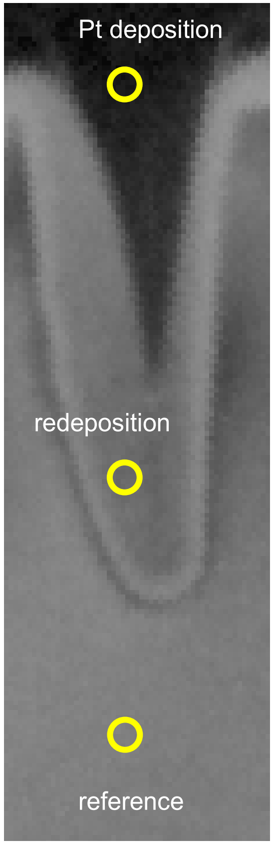
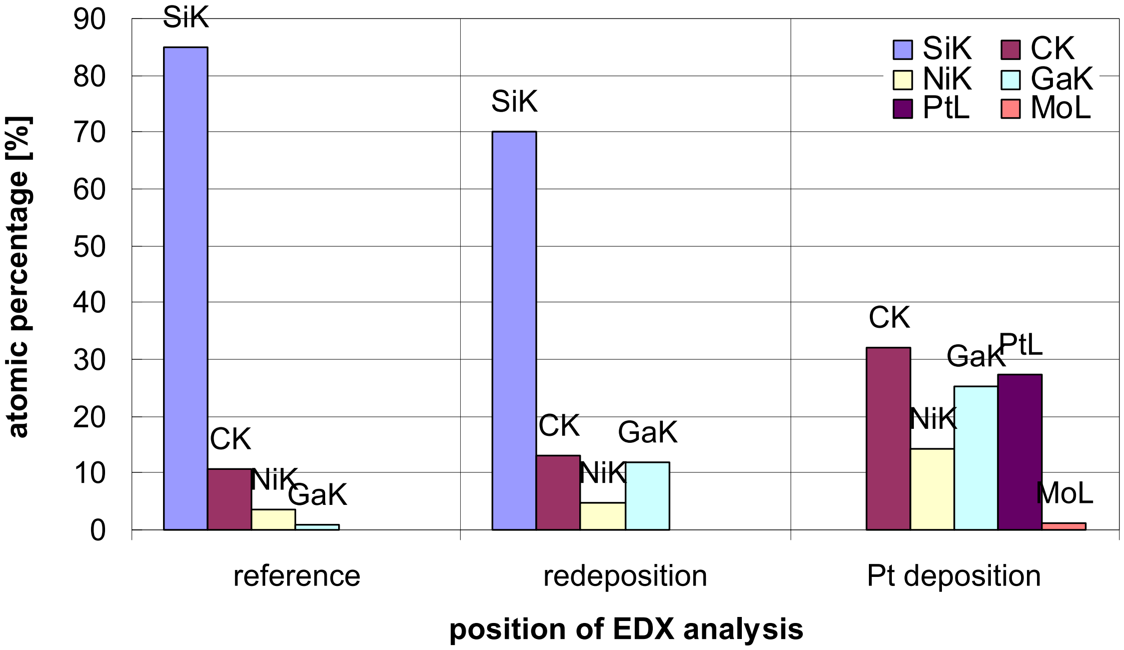
Milling

Chemical composition





TEM-EDX (energy dispersive x-ray) analysis

Milling strategies

Squares

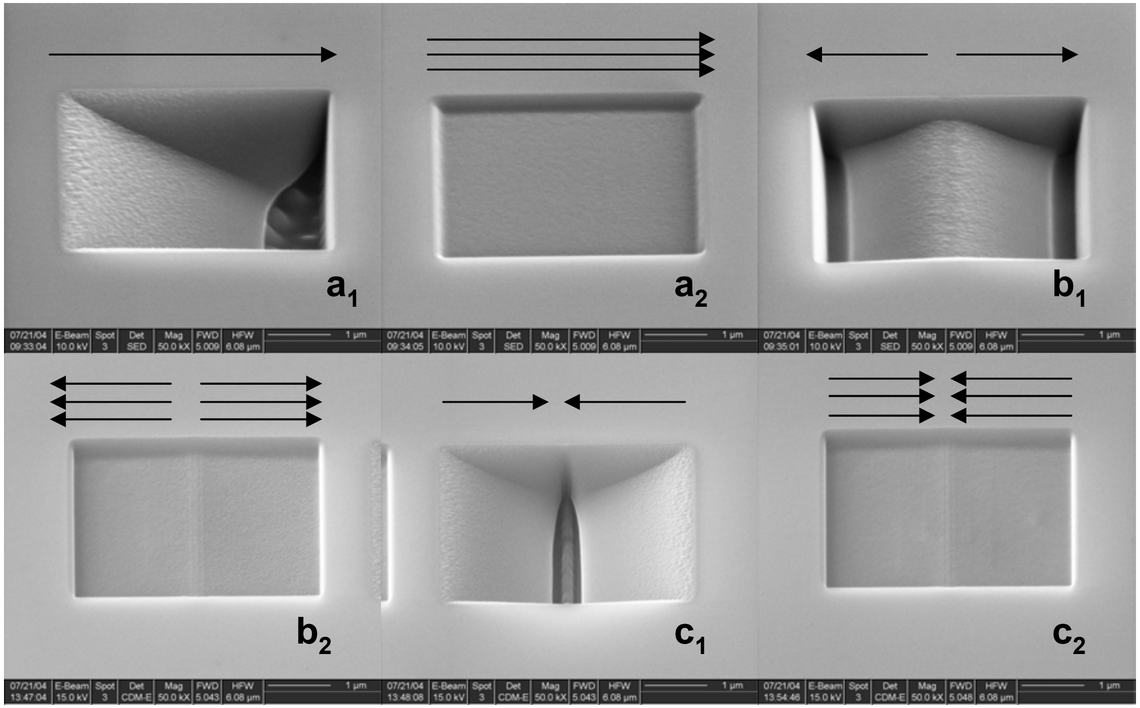
Squares: **(52°-view)**

312x311 dots

distance 12.75 nm

130 pA ion current

total dose per point 0.8 fC/nm²



strategy	**a**	**b**	**c**
1) 1 ms/dot/pass single pass	left to right / single pass	symmetrical: middle to edge / single pass	symmetrical: edge to middle / single pass
2) 0.01 ms/dot/pass 100 passes	left to right / 100 passes	symmetrical: middle to edge / 100 passes	symmetrical: edge to middle / 100 passes

Milling strategies

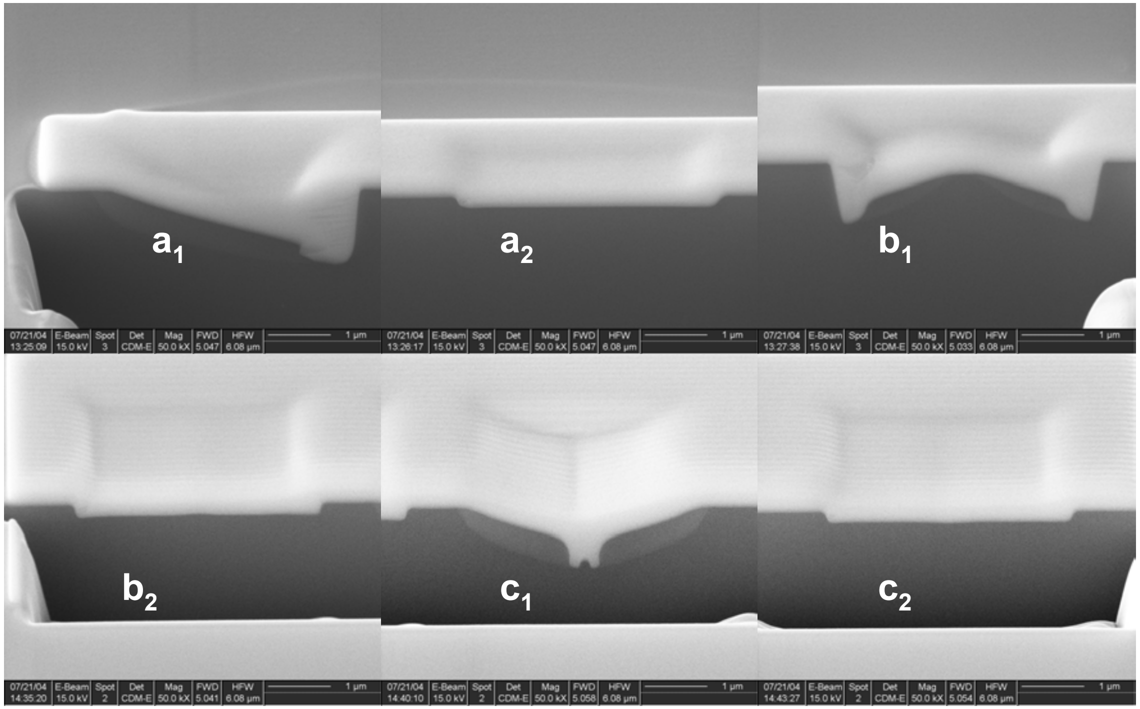
Squares: **(cross sections)**

312x311 dots

distance 12.75 nm

130 pA ion current

total dose per point 0.8 fC/nm²

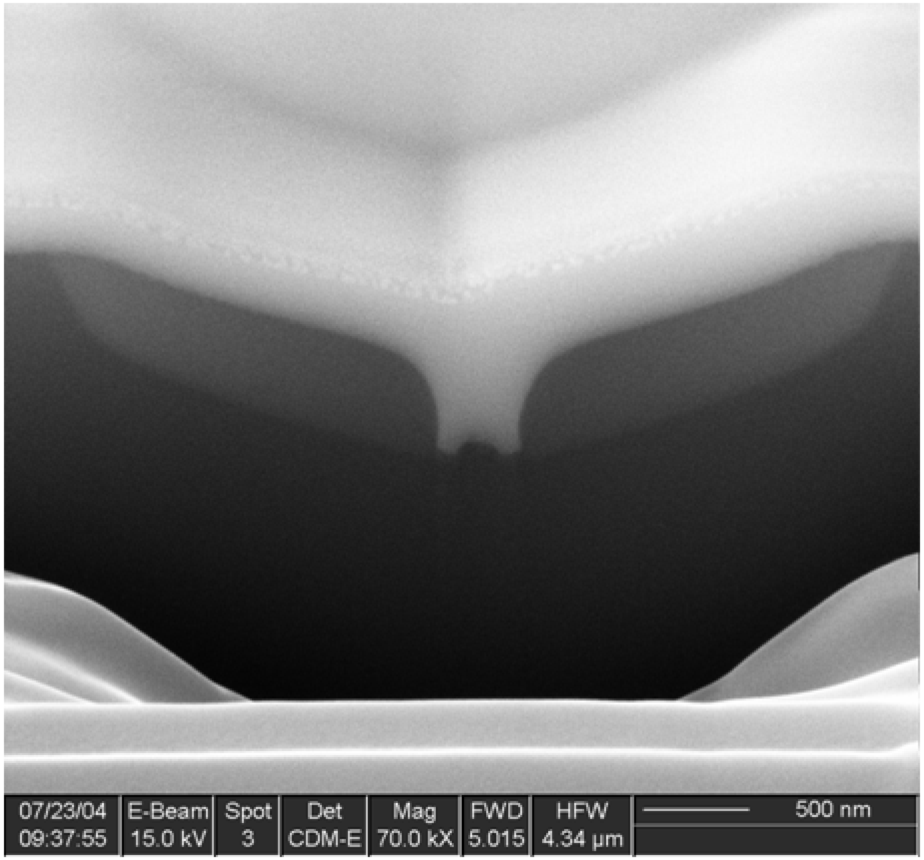


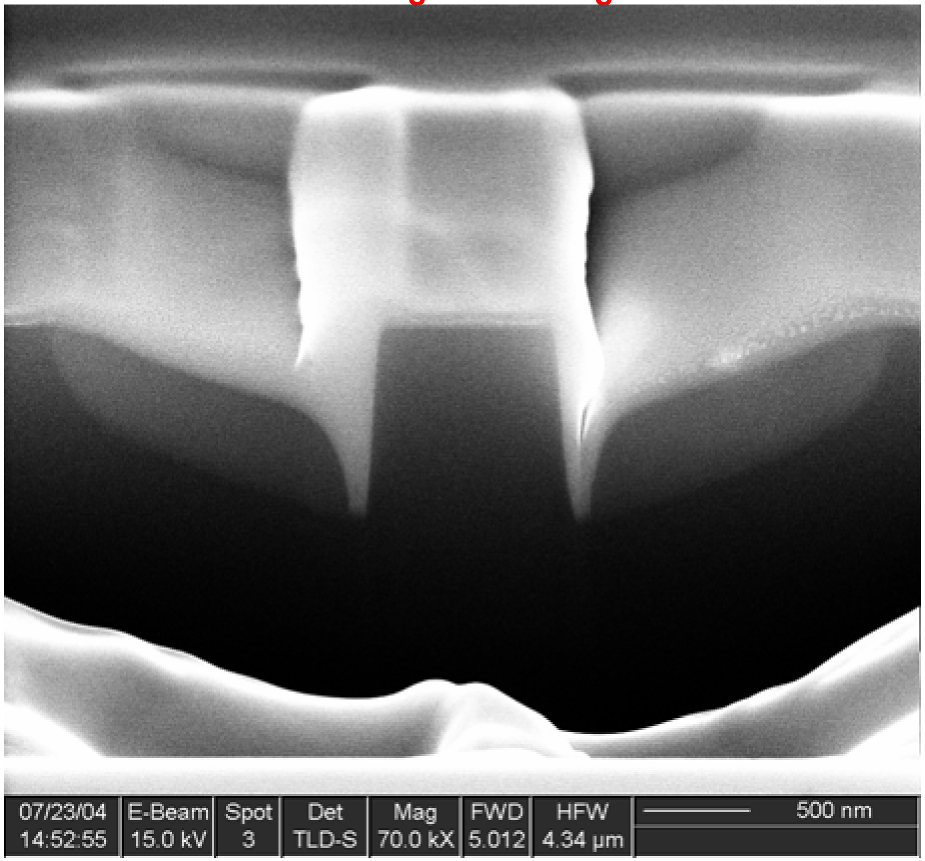
strategy	**a**	**b**	**c**
1) 1 ms/dot/pass **single pass**	left to right / single pass	symmetrical: middle to edge / single pass	symmetrical: edge to middle / single pass
2) 0.01 ms/dot/pass **100 passes**	left to right / 100 passes	symmetrical: middle to edge / 100 passes	symmetrical: edge to middle / 100 passes

Milling strategy

Analysis of c1: process

Rechts war eine Bildfolge im Vortrag



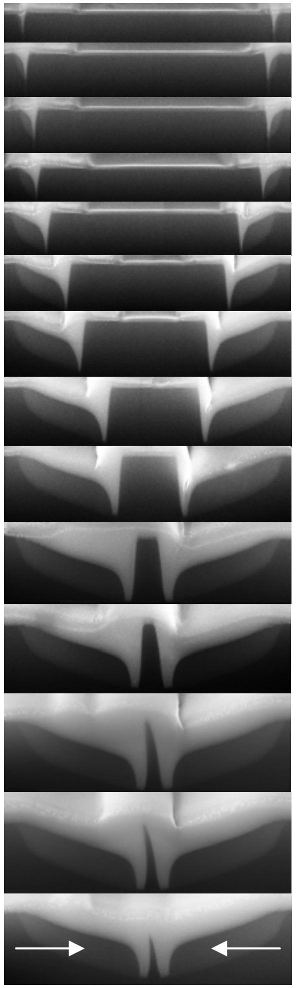


sequence of structures with increasing number of lines from each edge towards the center:
5, 10, 15, 20, 40, …, 140, 145, 150, 152, 154, 156 (completed half of square).

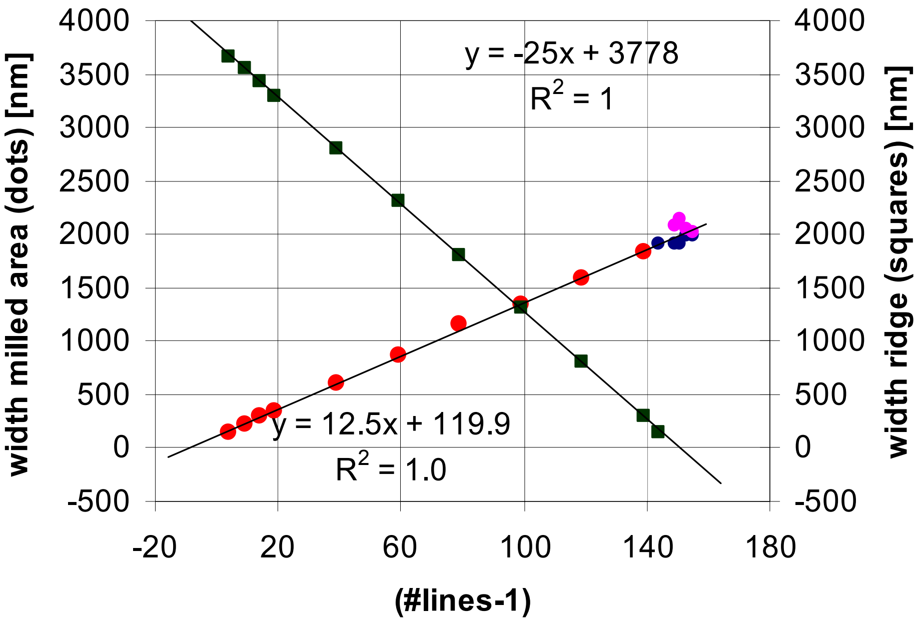
redeposition and self-focusing effect (angle dependent milling and reflected ions)

Milling strategy

Analysis of c1: geometry

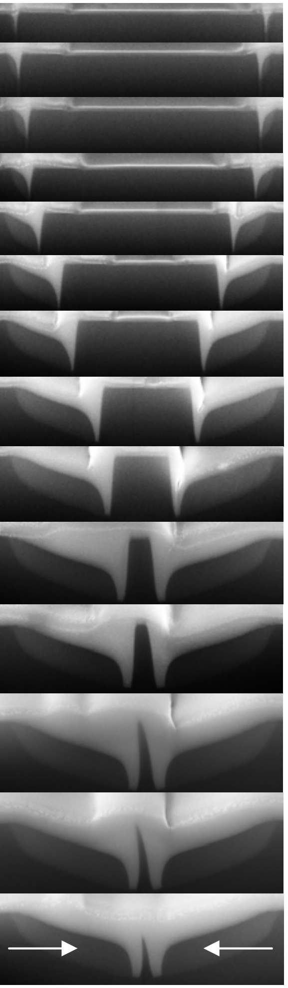


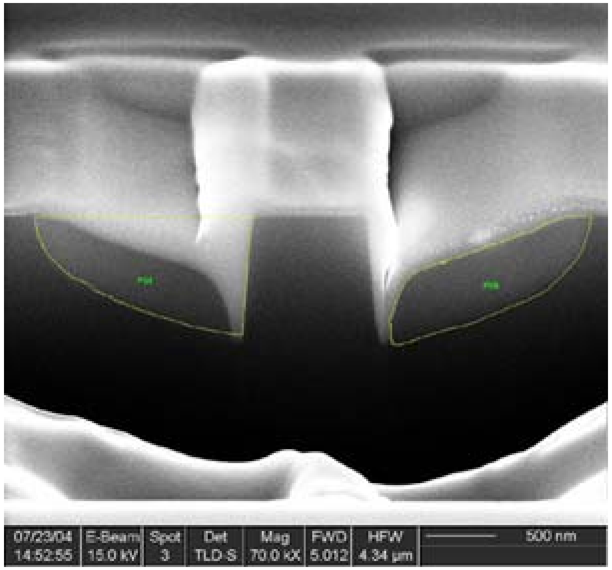
width of milled area and remaining ridge vs. number of lines

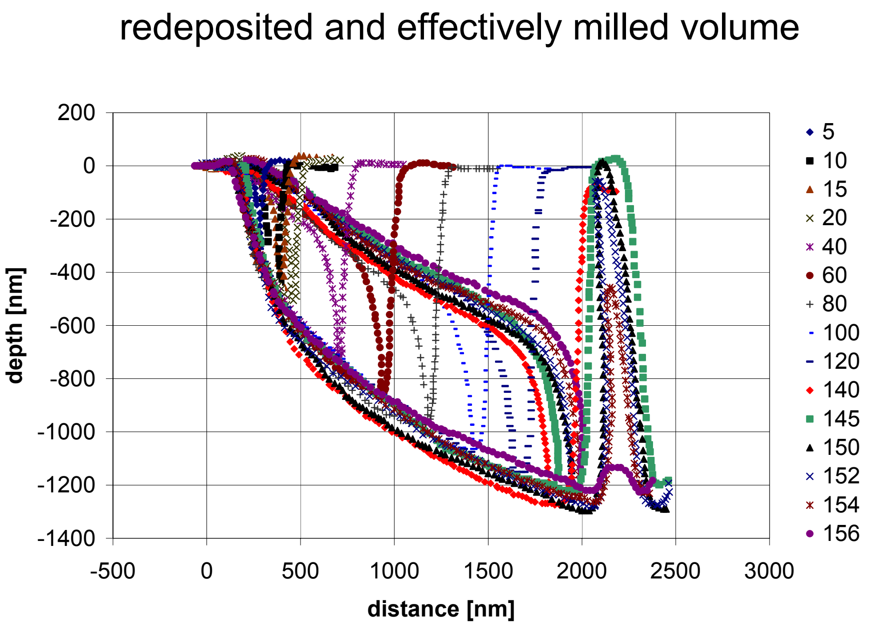


Milling strategy

Analysis of c1: geometry

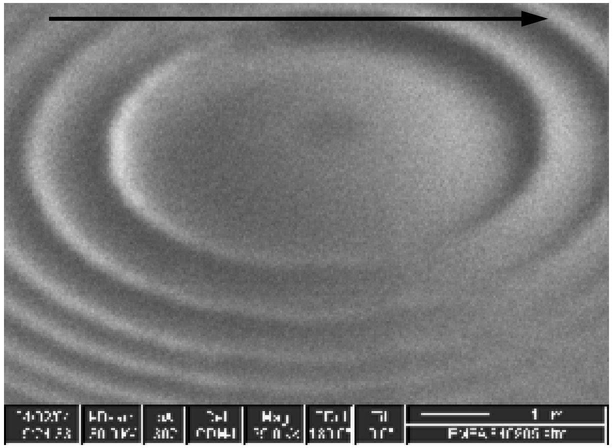


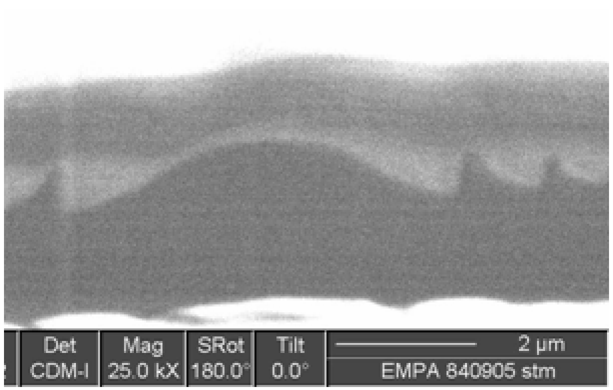



redeposited and effectively milled volume

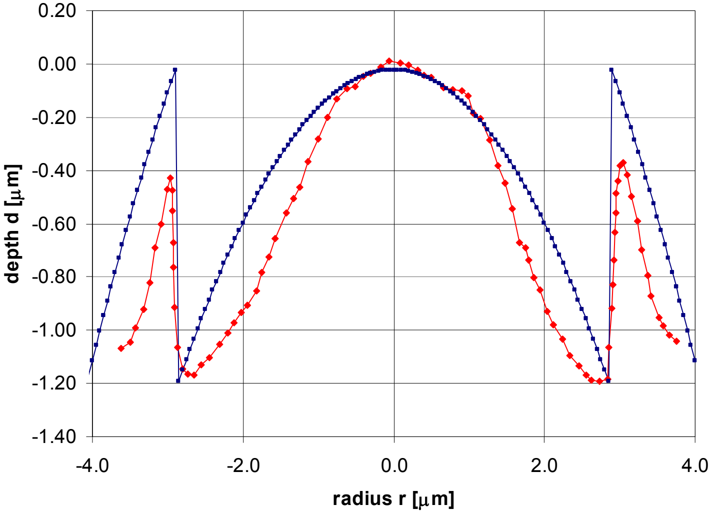
redeposition and self-focusing effect (angle dependent milling and reflected ions)

Microlens structure 1 (on glass)





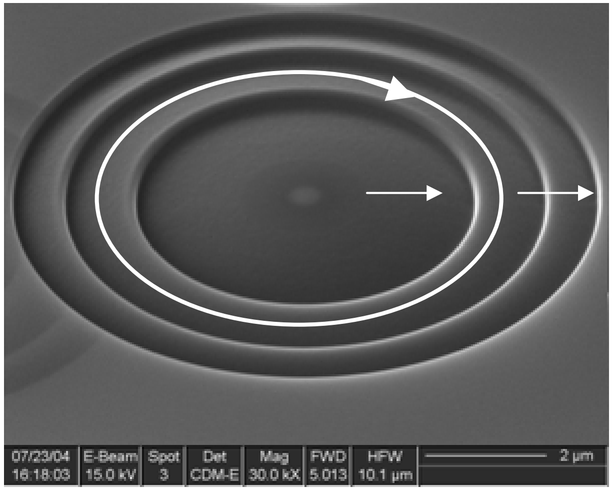
- milling along cartesian coordinates (line by line)
- 1000 pA ion current (electron charge neutralizer)
- dwell times proportional to Fresnel pattern, maximum dwell time 40 µs
- sharp edges blurred (overlapping of wings of ion beam)
- curvature slightly concave instead of convex
- depth of pattern is a factor of 3.1 smaller than required (the theoretical curve scaled down)

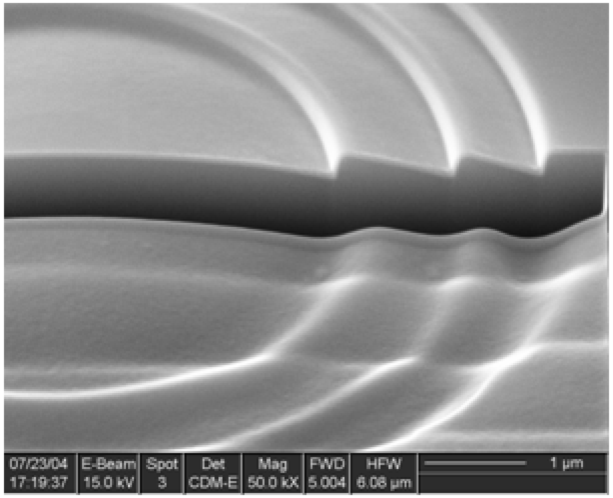


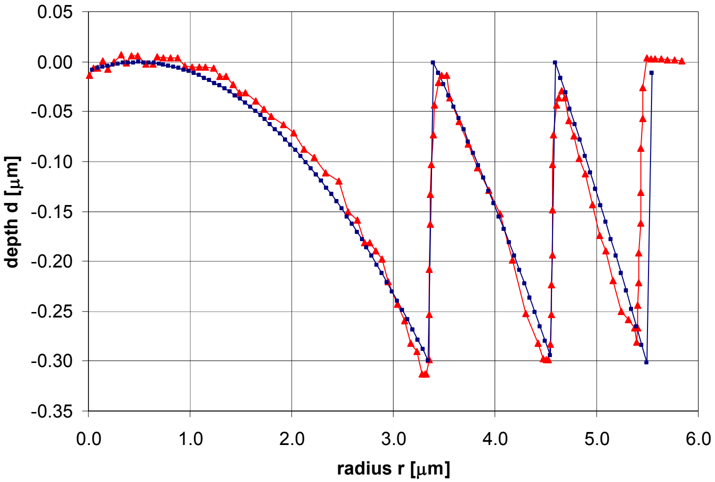
Fresnel structure 1 on glass: overview, cross section, comparison with calculations

Microlens structure 2 (on Si)

- milling along polar coordinates (circle by circle from inside out)
- 134 pA ion current
- dwell times proportional to Fresnel pattern, max dwell time 36.2 µs
- pattern was repetitively milled 120 times
- form much better preserved (sharper, better correspondance)
- depth of pattern is a factor of 6.3 smaller than required (the theoretical curve scaled down)



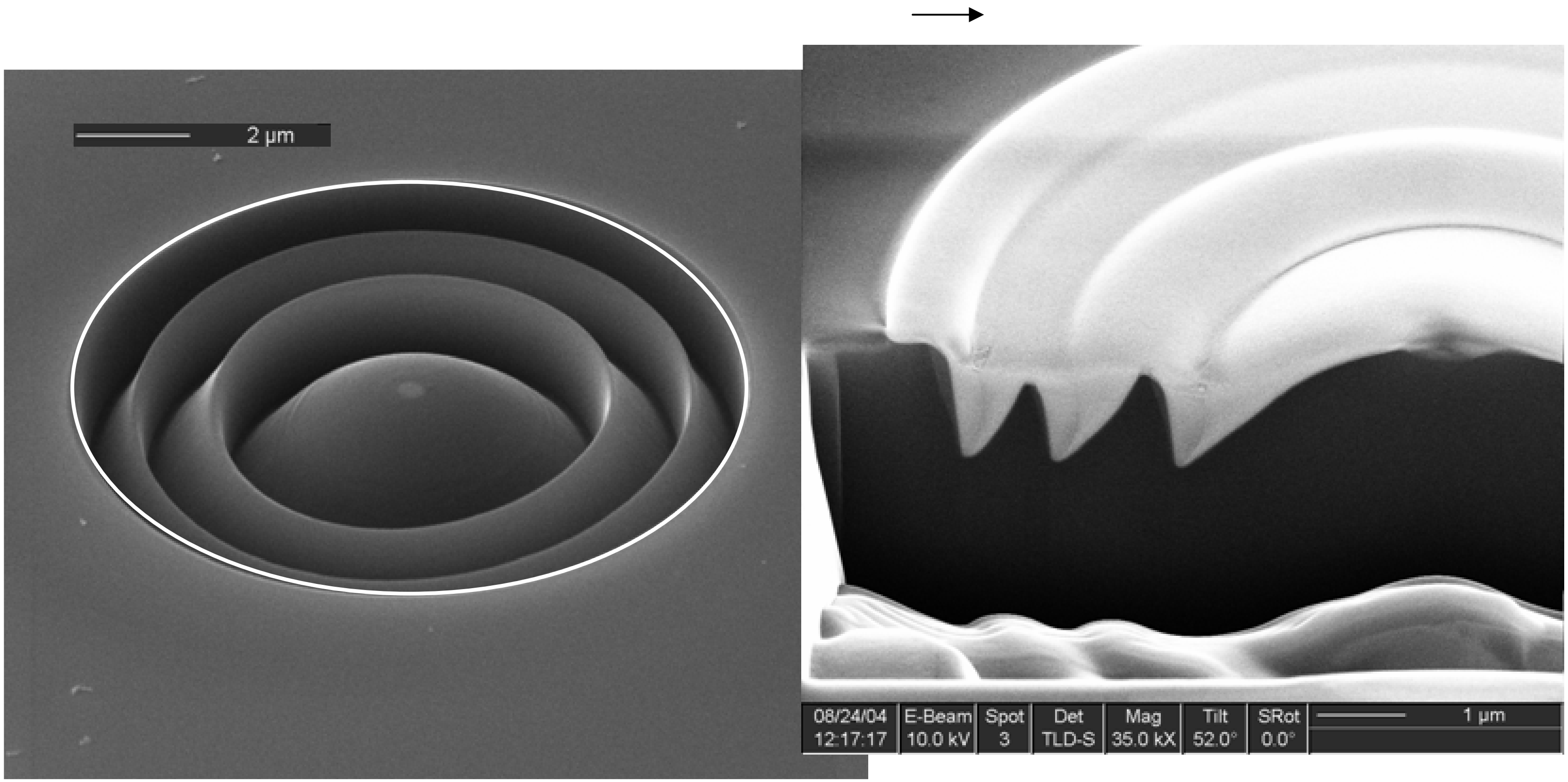




Fresnel structure 2: overview, cross section, comparison with calculations.

Microlens structure

(on Si)



- milling along polar coordinates (circle by circle from inside out)
- 140 pA ion current
- dwell times proportional to Fresnel pattern, max dwell time 36.2 µs
- pattern was repetitively milled 1440*0.6 times
- switching from concave to convex observable
- depth of pattern is nearly correct

Conclusions and Outlook

Useful tool for microstructuring

Steep slopes / large aspect ratio reduce accuracy

Writing strategy improves structuring

Basic experiments: single line milling and milling strategy

Input for modeling of sputtering and redeposition

With improved predictability of microstructuring with FIB new applications can be envisaged:

MEMS device prototyping and modification
scanning probe microscope tips fabrication
micromedical devices
sensor structuring
micro- and nano-print master fabrication
(e.g. diffractive optical elements), and others