Thermal Probe Nanolithography

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Contractor at IBM Research Zurich

Euspen, 28.Nov.2013

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Nano / Micro - Manufacturing

SwissLitho AG
Innovative Nanofabrication Tools

nm **µm** **mm**

Particle Beams **Laser** **Mechanical**

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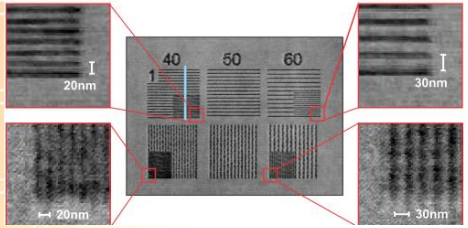
Overview NanoFrazor

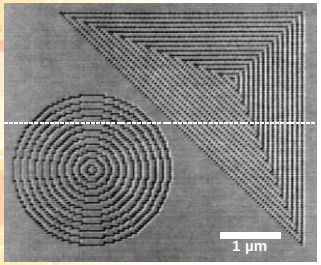
SwissLitho AG
Innovative Nanofabrication Tools

Resolution



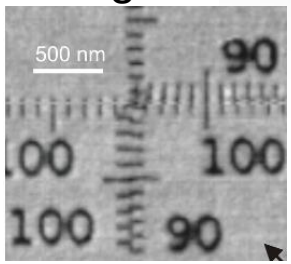
10 nm HP

Speed



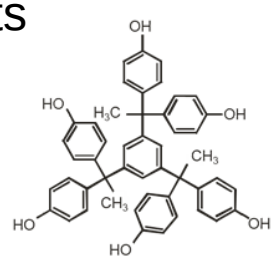
500 kHz, 20mm/s

Stitching & Overlay

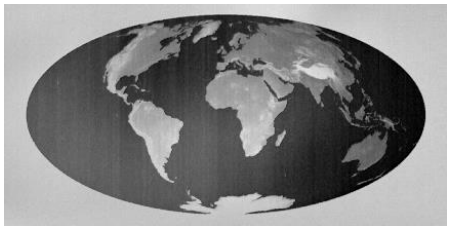


10 nm accuracy

Resists

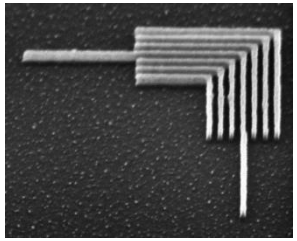


3D direct-write



~1 nm accuracy in Z

Pattern transfer



27 nm hp, LER=1nm
60 nm deep in Si

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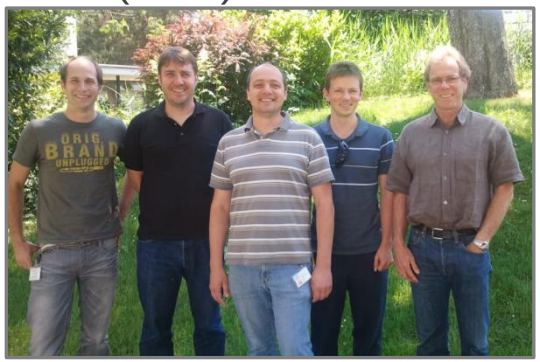
IBM Research in Rüschlikon

Zurich

thermal probe team at IBM (2011)



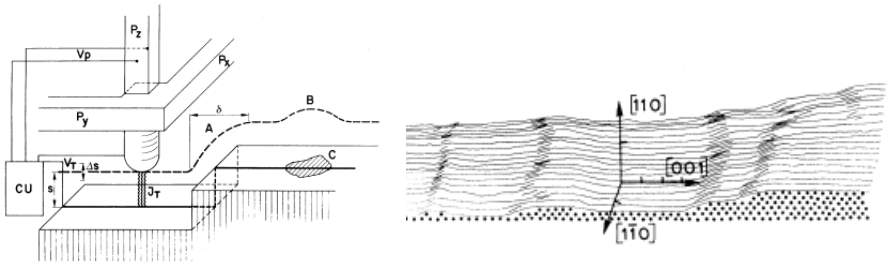
Felix Holzner, Armin Knoll, Michel Despont, Philip Paul, Urs Dürig

- Total: ~300 employees
- ca. 80 researchers in Science & Technology
- mainly basic research in various fields (molecular electronics, spintronics, photonics, microfluidics)
- 4 Nobel prize laureates

Scanning Probe Microscopy

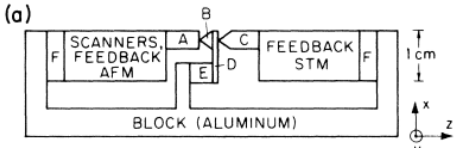
1981: Scanning Tunneling Microscope (STM)

Binnig and Rohrer,
IBM Rüschlikon, Nobel Price 1986



Binnig et al., Phys. Rev. Lett., 49, 57–61, (1982)

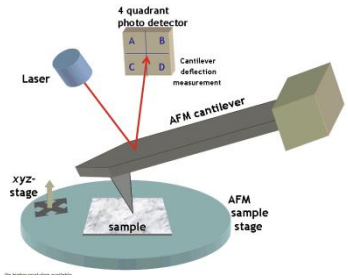
1986: Atomic Force Microscope (AFM)



Binnig et al., Phys. Rev. Lett.,
56, 930–933, (1986)

First AFM: deflection measured with STM

Today: ~50 companies selling Scanning Probe Microscopes



> 20 different imaging methods

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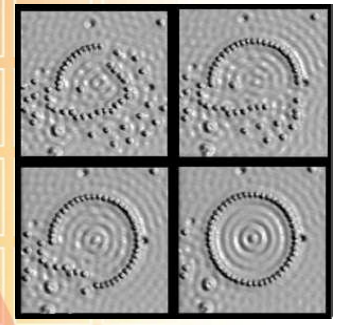
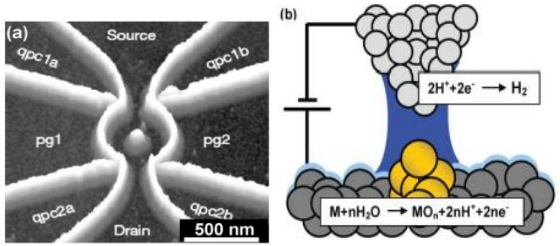
Scanning Probe Lithography (SPL)

STM (Tunneling Microscope)



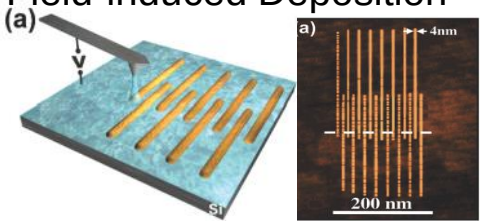
IBM Research Almaden, Don Eigler, 1990

Local Anodic Oxidation



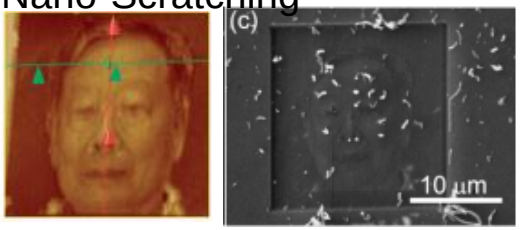
Dagata 1990
A. Fuhrer et al., *Nature* **2001**, *413*, 822.

Field-induced Deposition



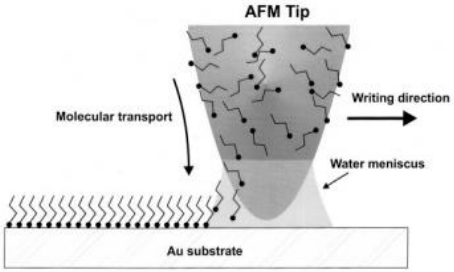
Garcia et al., Nano Lett. 2007, 7, 1846.

Nano-Scratching



Dong et al., small, 2010

Dip-Pen Nanolithography



Mirkin et al., Science 1999, 283, p661

Main issues of SPL:
- only specific applications
- slow
- tip wear

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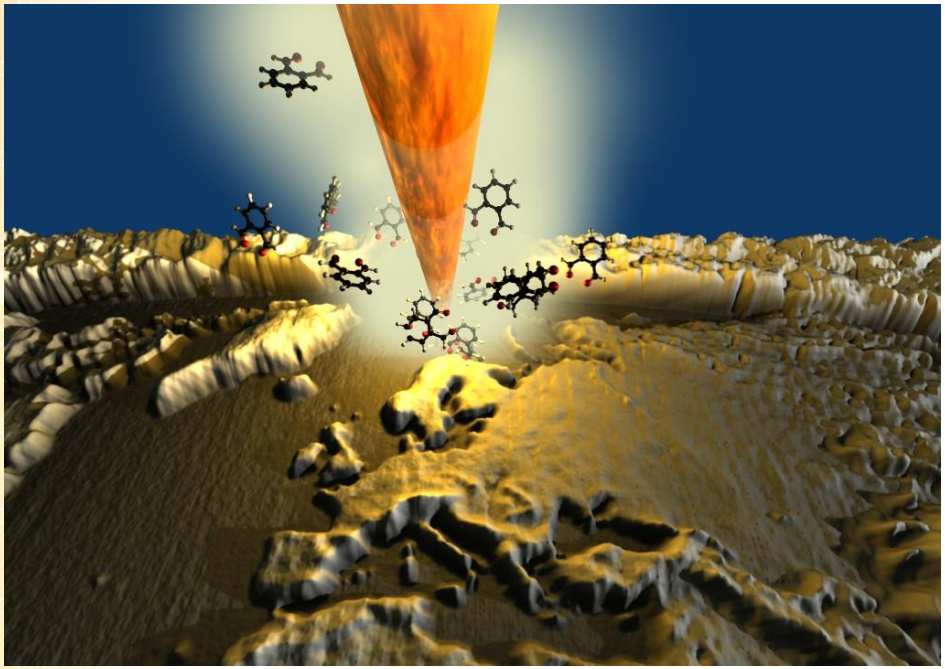
Patterning Prinicple:

Thermal Desorption Scanning Probe Lithography

Heated tip => local evaporation of resist



Advantages:

- versatile
- tip preserving
- compatible to CMOS
- in-situ inspection

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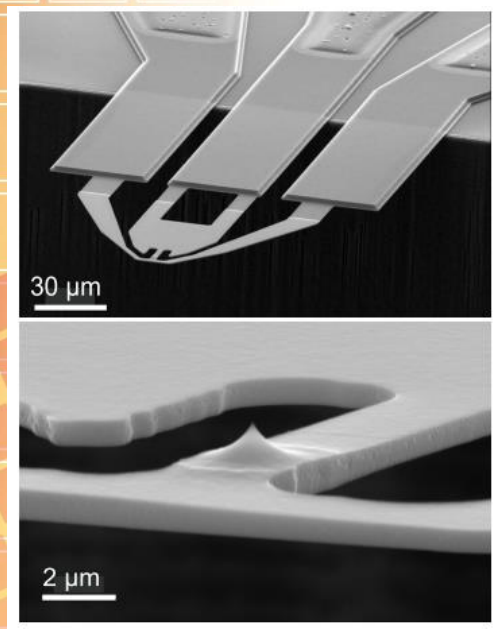
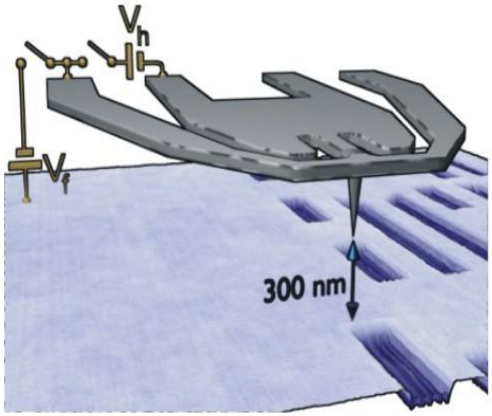
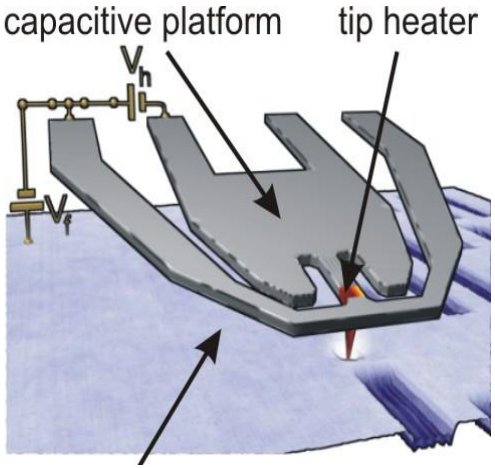
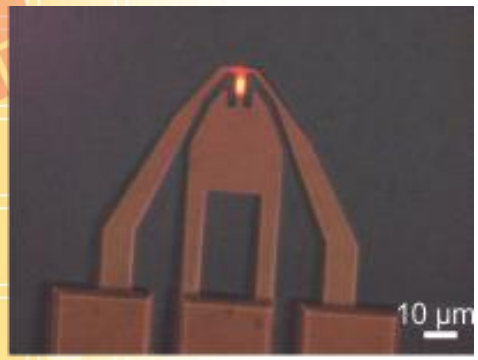
Thermal Cantilevers







Thermal sensor for measuring topography in special AFM imaging mode



Heating of the tip:

- Microheater: 2x2 µm^2 area with higher electric resistivity (lower dopant concentration in Si) heats up to 1000 ºC

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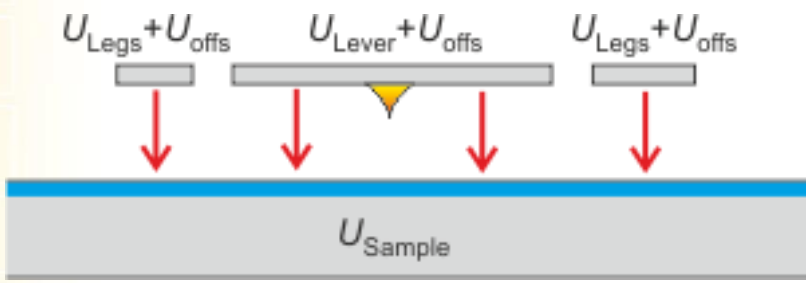
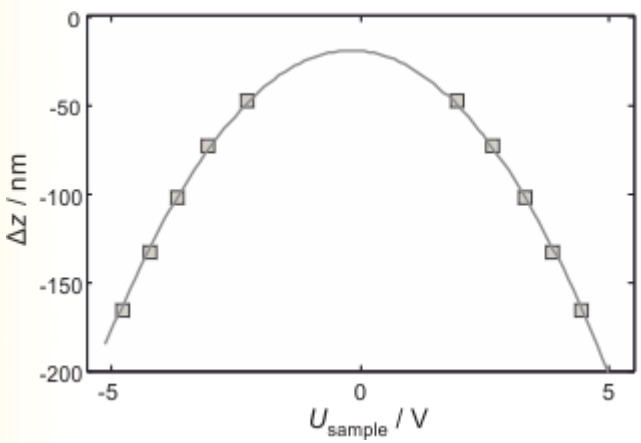
Actuation mechanism

Force control:
- Voltage between cantilever and substrate
=> electrostatic actuation (~1 µs pull-in time)



Fast:	1µs
Accurate:	1nm



Electrostatic force:

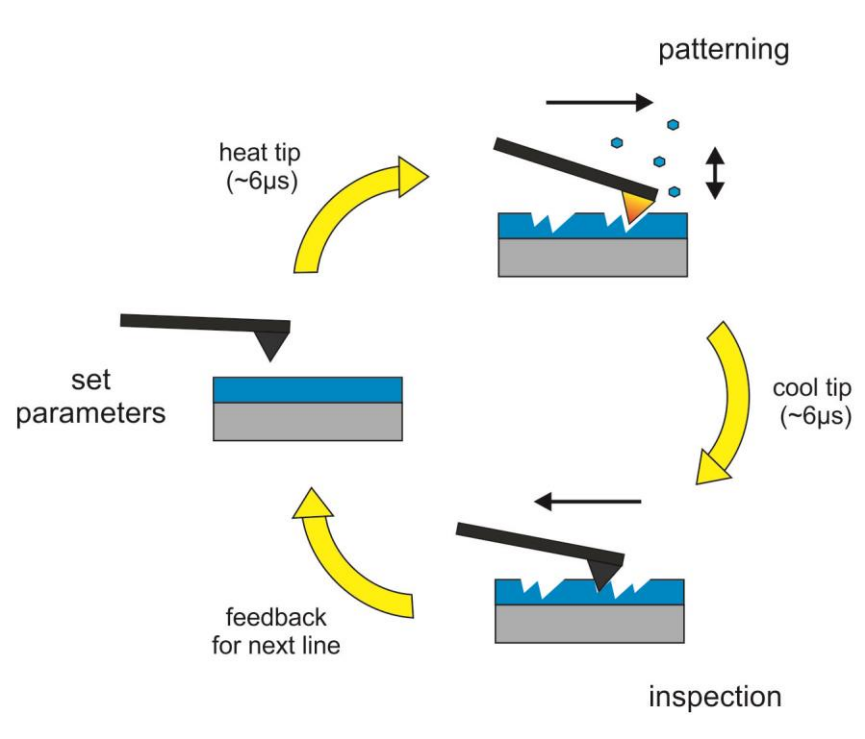
$$F_{\mathrm{el}} \sim \Delta U^2$$

Restoring force:

$$F_k = \Delta z \cdot k_{\mathrm{spring}}$$

$$k_{\mathrm{spring}} \approx 1\ \mathrm{N/m}$$

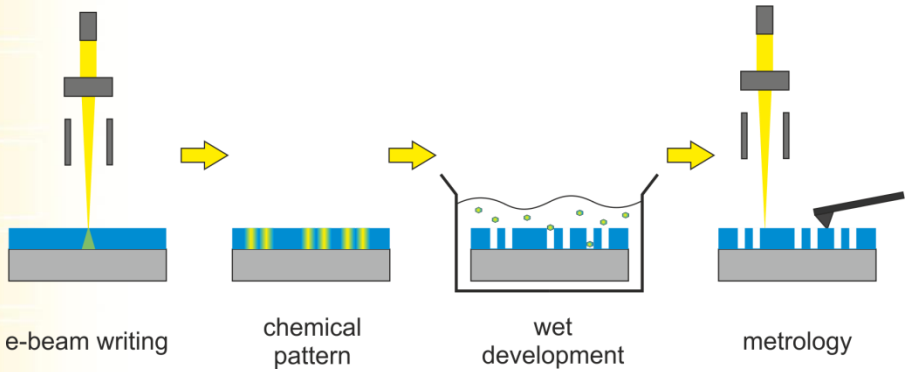
Closed-Loop Lithography



- direct feedback

⇒ automated adaption
⇒ less critical on environment
⇒ turnaround in seconds

E-Beam Lithography:



- Feedback after hours or days

⇒ control over everything
⇒ long turnaround

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Resist strategies

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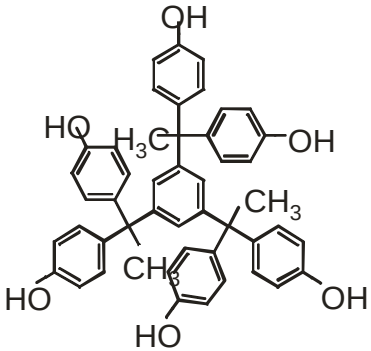
Challenges:

- efficient thermally activated process
- stability (etching + imaging)

Molecular glass

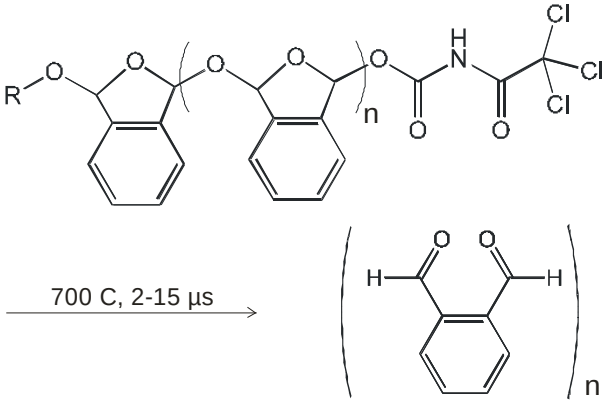


- M_w = 715 g/mol
- physical inter-molecular bonds
- **complete molecules are removed**

- H-bonds: T_g 126 °C

De Silva et al., *Chem. Mater.,* (2008)
Pires et al., Science, (2010)

Unzip polymer



Polyphthalaldehyde (PPA)

- thermodynamically unstable backbone
- synthesis at -78 °C
- **unzips into monomers upon bond breakage**

- $T_g = T_{unzip} \approx 150$ °C

Ito et al., Poly. Eng. & Sc., 1983

Coulembier et al., Macromolecules, 2010

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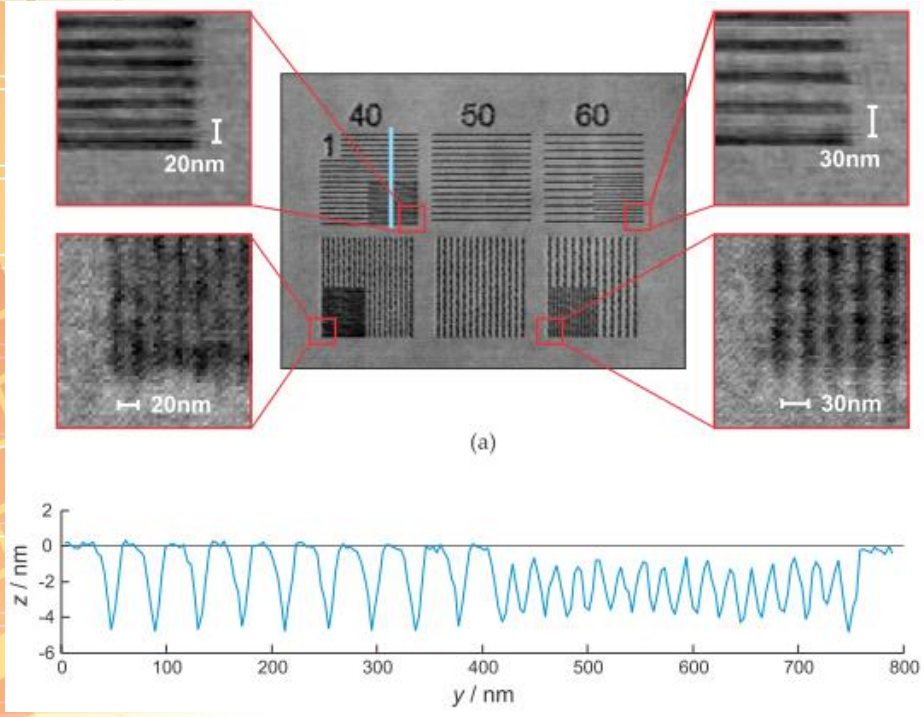
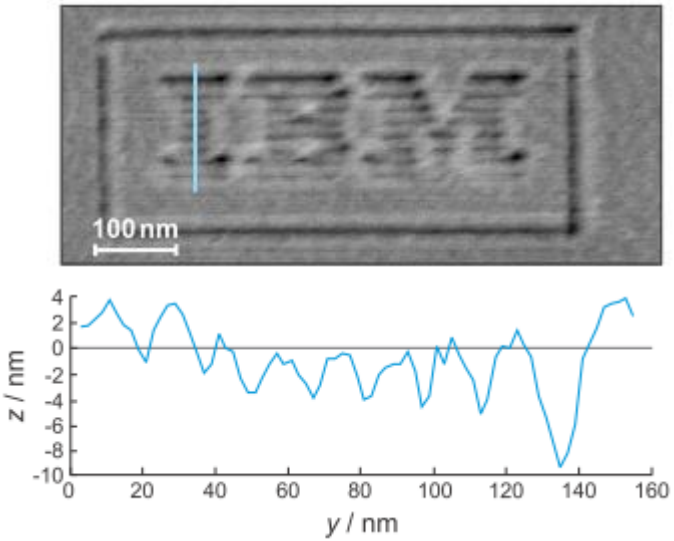
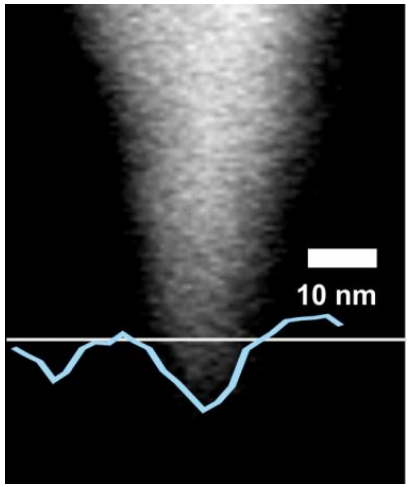
Resolution

10 nm HP



8 nm HP





Limitations:

- tip size
- temperature
- molecular size

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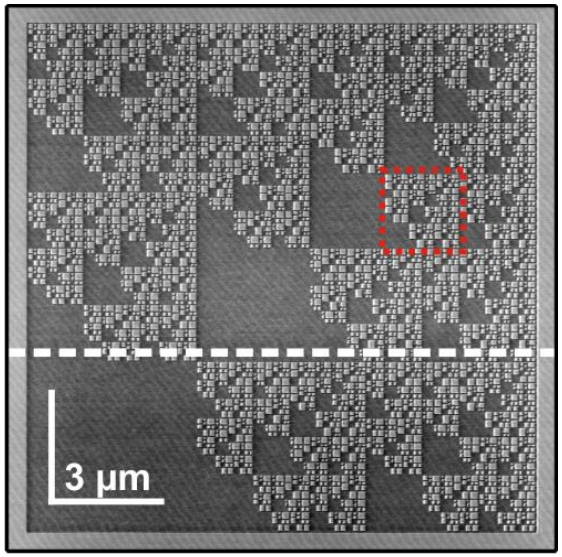
Speed

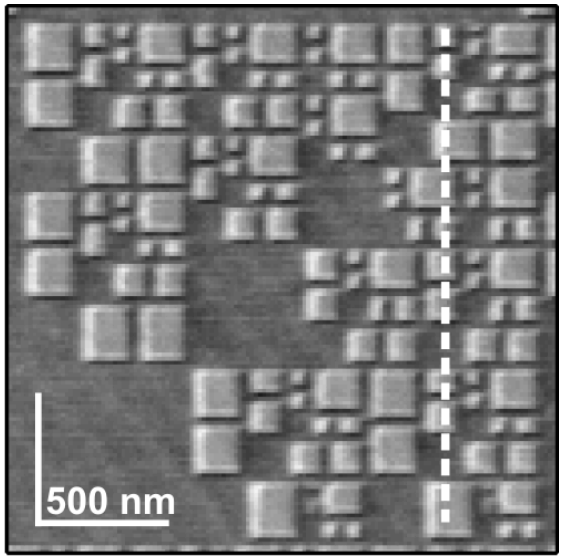
~1 Mpixels

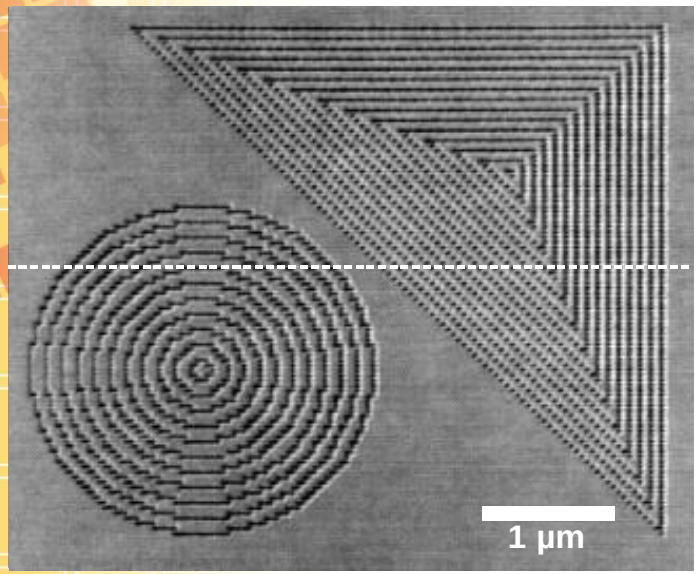
<12s write time

No errors

<1min overall turnaround







< 1 second write time

No influence on neighbouring pixels

Pixel rate: 500 kHz

Scan speed: 20 mm/s

40 nm pixel pitch
125x100 pixels = 5x4 um
4-5 nm deep

Paul et al., Nanotechnology, **23**, 385307, (2012)

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Speed

Challenges & Limitations:

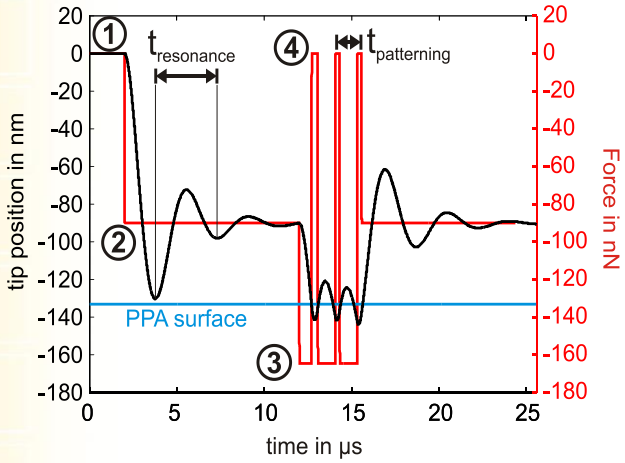
1.) vertical tip movement

2.) precise positioning at high scan speed

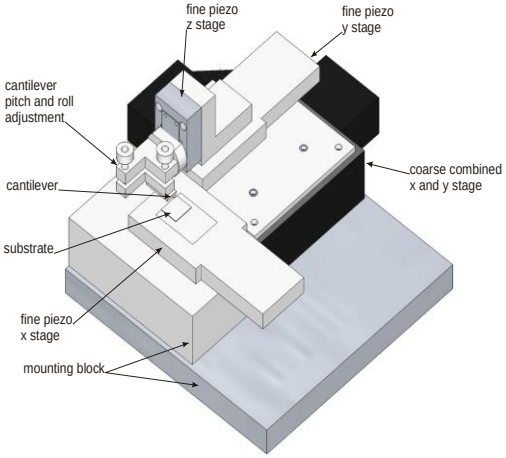
3.) out-of-plane motion at high scan speed

4.) reaction kinetics of thermal decomposition

Actuation above the resonance frequency



Mechanical high-speed setup



Paul et al., Nanotechnology, 22, 275-306, (2011)

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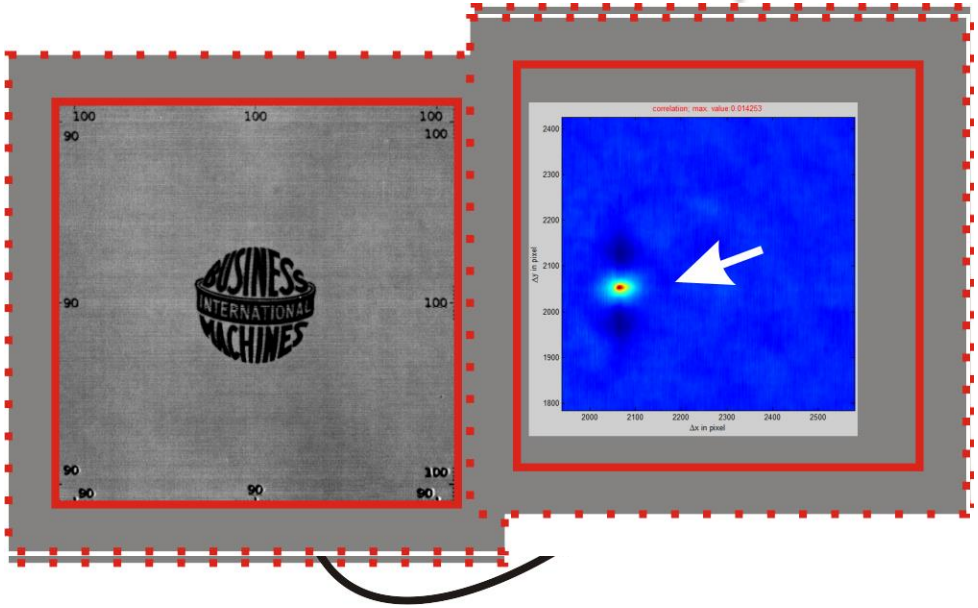
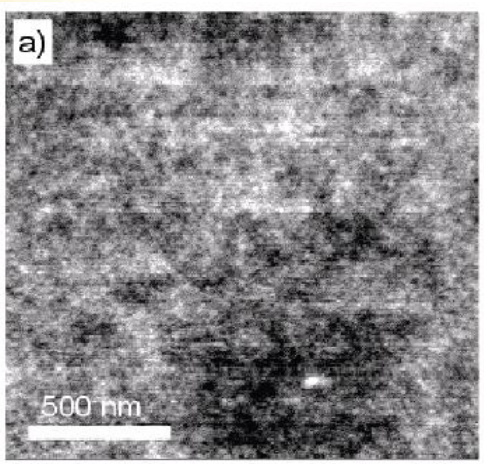
Stitching concept

- Surface roughness after spin coating
- Ca. 1 nm in amplitude
- Randomly distributed

→ Unique in each area





Write first field, and read back with a stitching margin

Move with coarse positioning stage
Read at new position

Correlate the two fields => **Offset determination: ~1nm**

Write second field at correct position

Paul et al., Nanotechnology, **23**, 385307, (2012)

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Stitching results

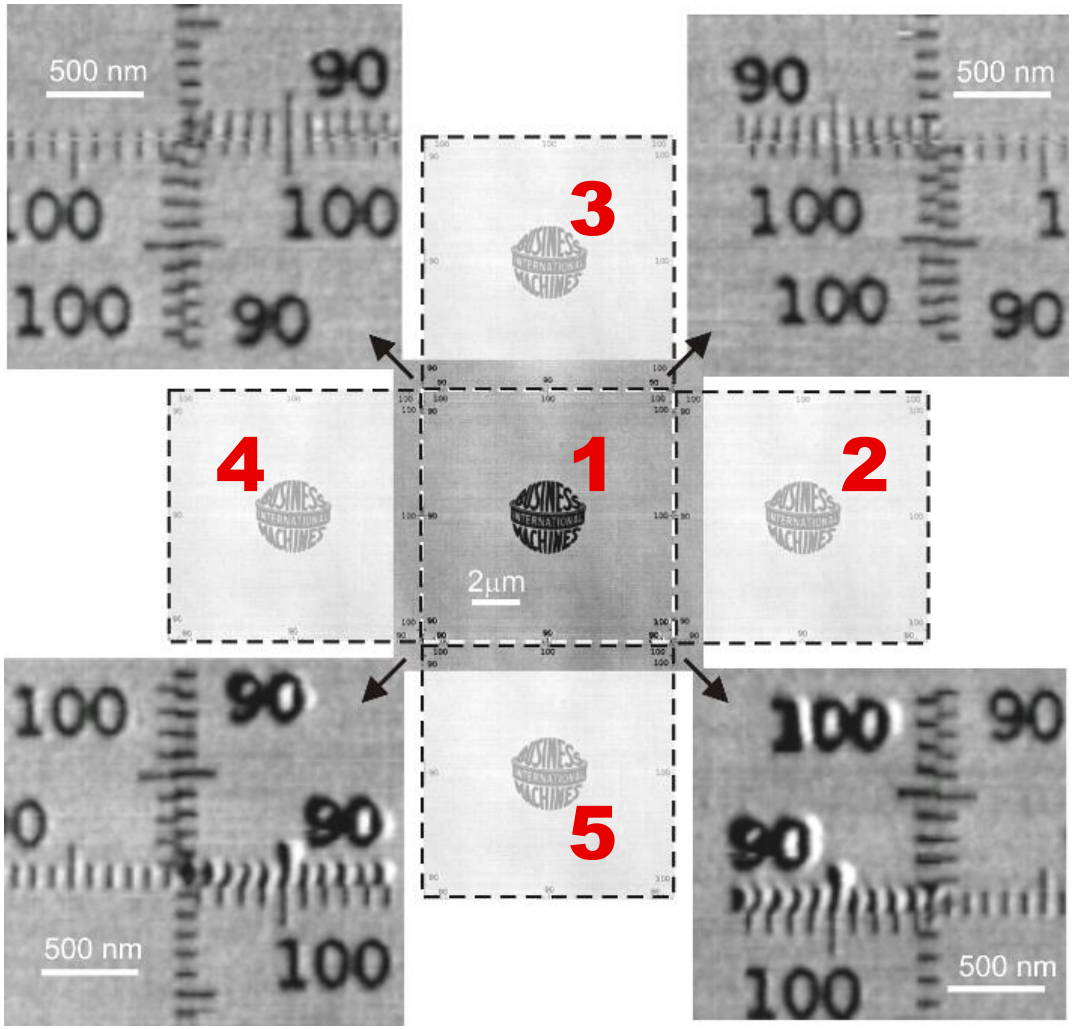
10 nm alignment accuracy

Limited by fine piezo stage

10 µm write field
1100 x 1100 pixels

1 um stitching margin

Vernier dials:
90 nm, 100 nm pitch



Paul *et al., Nanotechnology*, 23, 385307, (2012)

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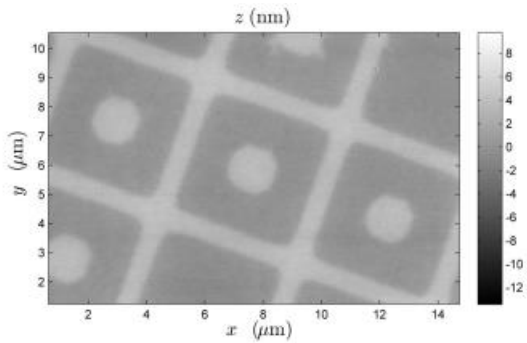
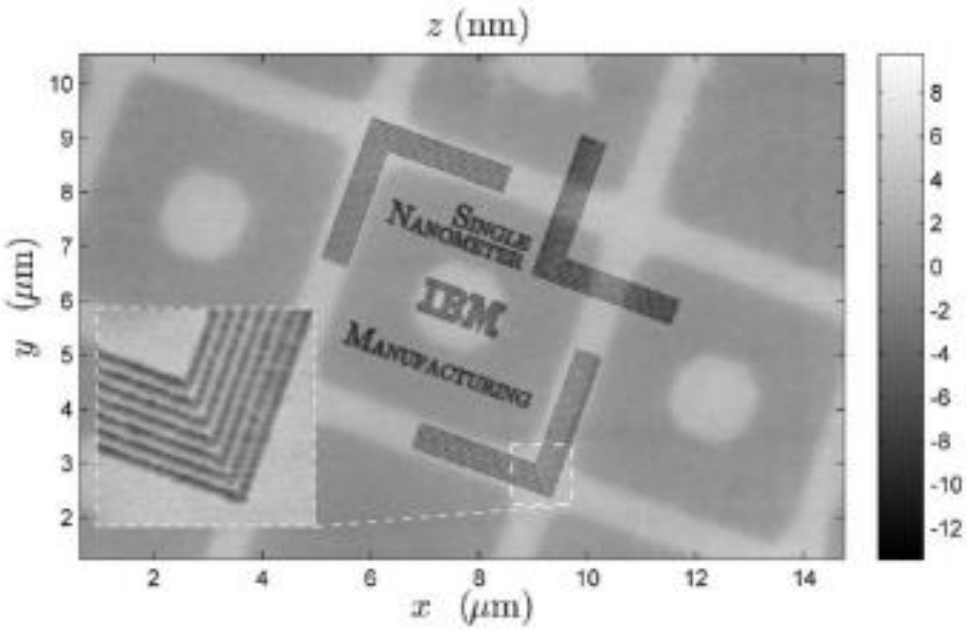
Overlay

PPA spin-coated on top of Si structure:
⇒ part of topography remains
⇒ detect with AFM mode
⇒ Write Overlay





Rawlings et al., (2013)

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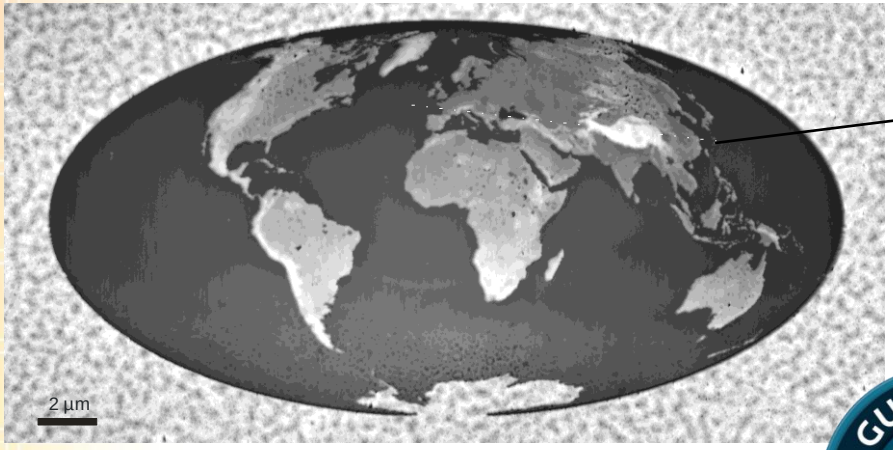
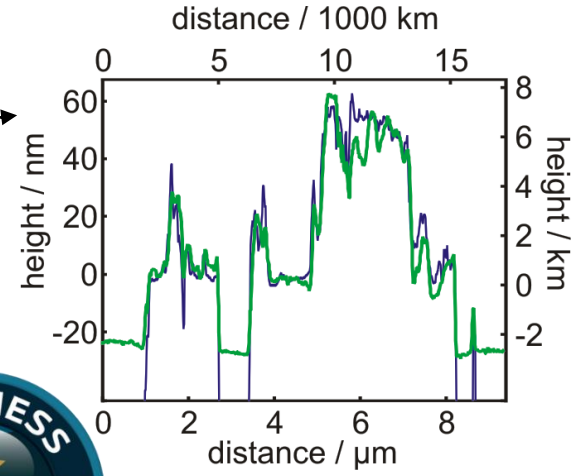
3D patterning

grayscale bitmap => different voltages => different forces => different depths

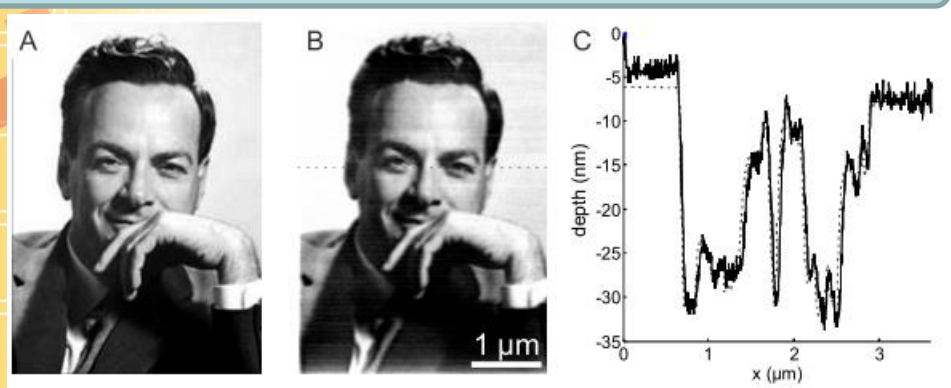




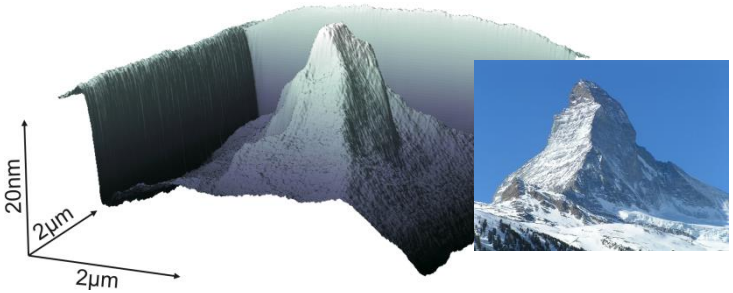
A. Knoll et al., *Advanced Materials*, **22**, 31, (2010)

Replica of the Matterhorn

Closed-Loop Lithography => 1nm accuracy



Zientek et al., (2013)



Pires et al., *Science*, (2010)

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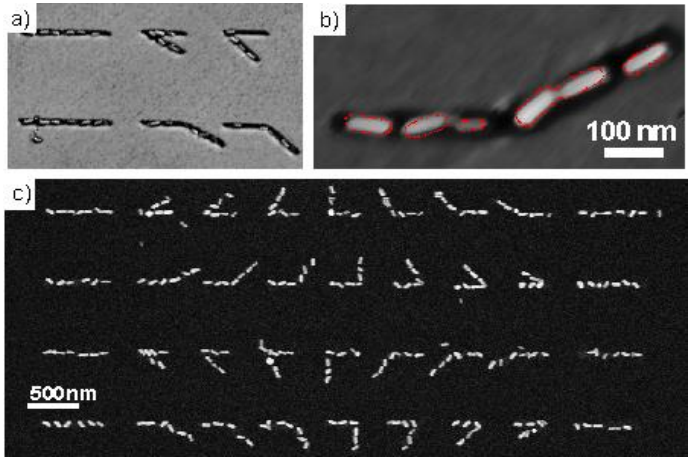
3D Applications I + II

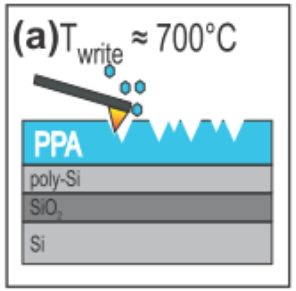
Positioning and placement of nanoparticles

- Shape matching traps written in PPA by tSPL
- Au nanorods trapped using Capillary Assembly
- Au nanorods transferred to substrate by evaporation of the PPA layer

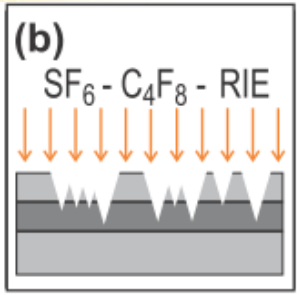


Holzner et al., *Nano Letters*,11, 3957–3962, (2011)

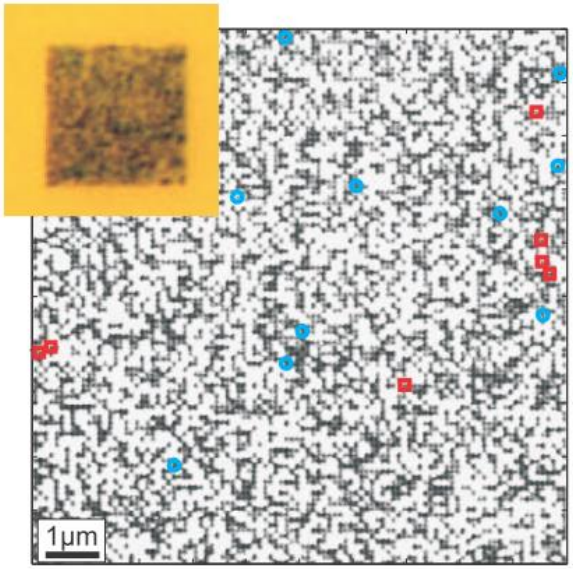
Multi-Level Archival Data storage



tSPL in PPA:
3 level logic + 100 nm pitch
⇒ 99 Gbit/in^2



Etch transfer:
29 s reactive ion etching
⇒ Indents transferred in SiO_2
⇒ Data preservation



Holzner *et al.,* Appl. Phys. Lett., 99, 023110, (2011)

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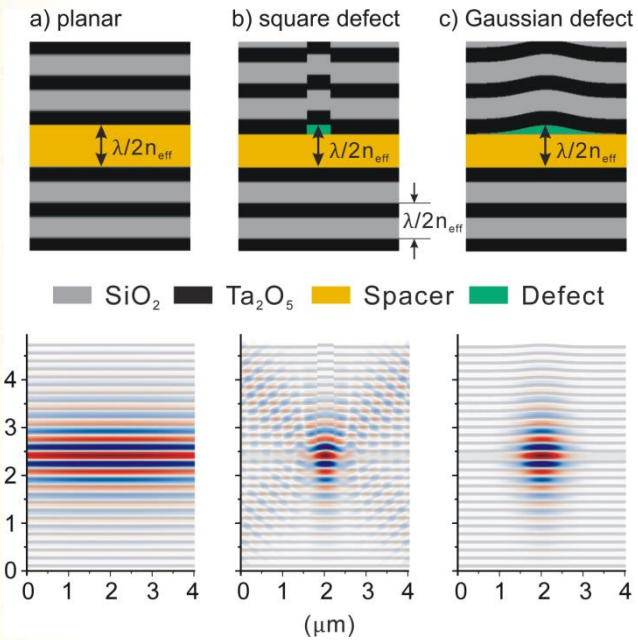
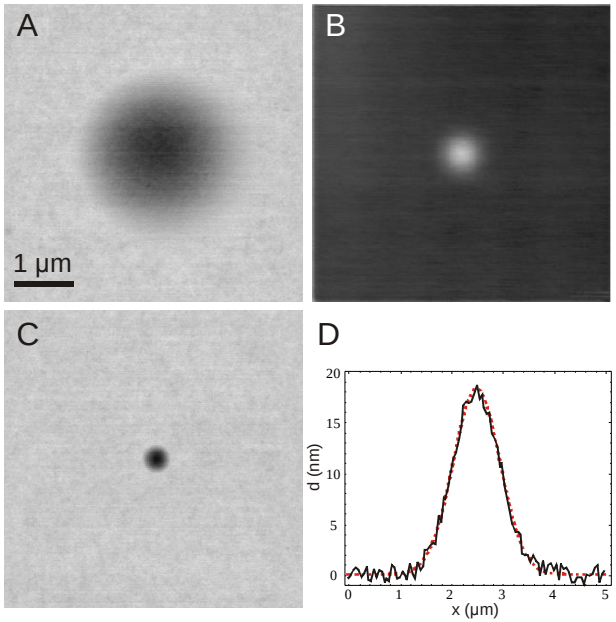
3D Application III:
High Performance Optical Micro-Cavities

Simulation: >100 x improvement



Gaussian structures by tSPL:



Coupling of light and matter

Figure of merit: Q/V, (Q: quality factor of cavity, V: optical mode volume)

High Q/V enables strong coupling of the light-field in the cavity with an optically active material

Applications:
- single photon emitters
- thresholdless lasing

Ding et al., Phys. Rev. B, 2013

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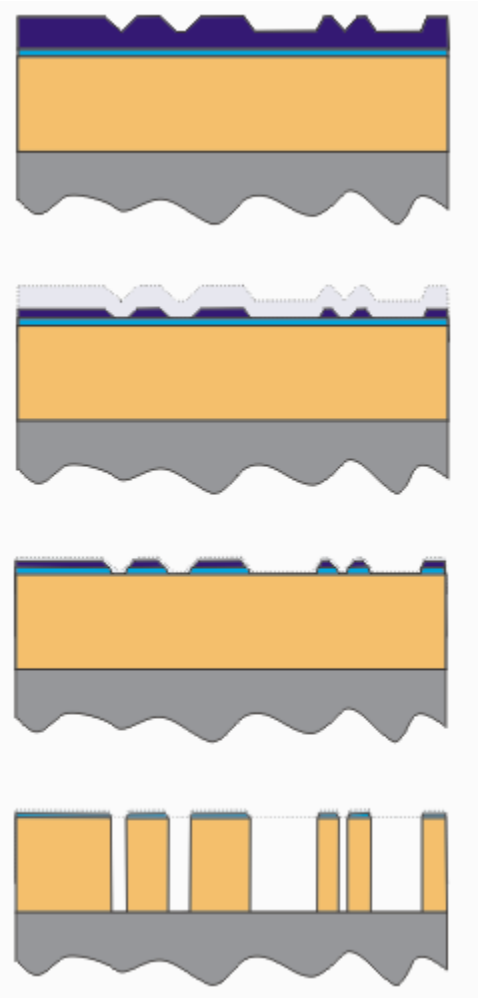
Pattern transfer

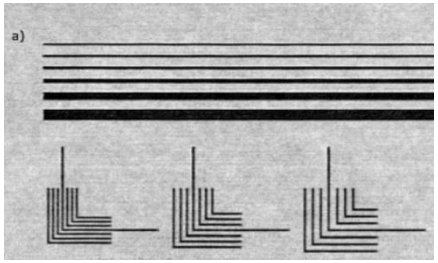
20nm PPA
4nm SiO_2
50nm HM

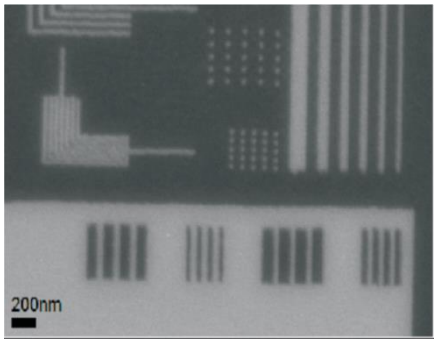
Step 1:
N_2/O_2 RIE thinning

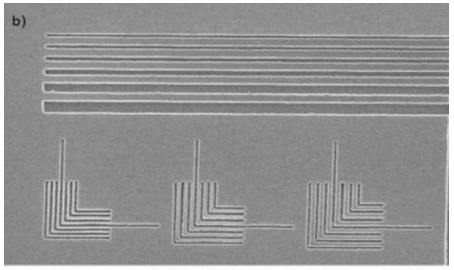
Step2:
CHF_3 RIE into SiO_2

Step3:
O_2 RIE into HM8006









Cheong et al., Nano Letters, **13(9)**, 4485-4491, (2013)

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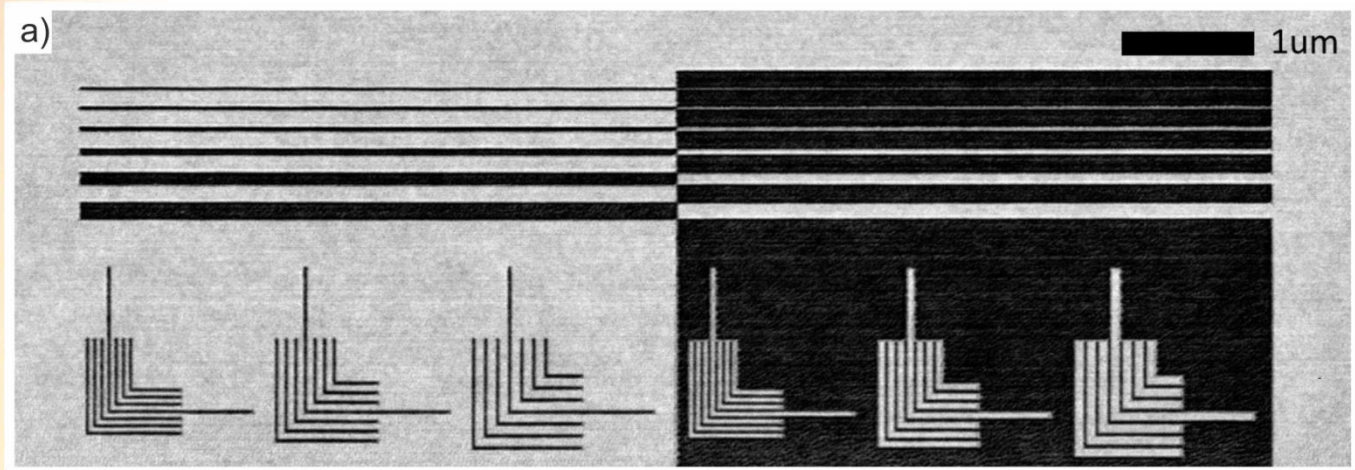
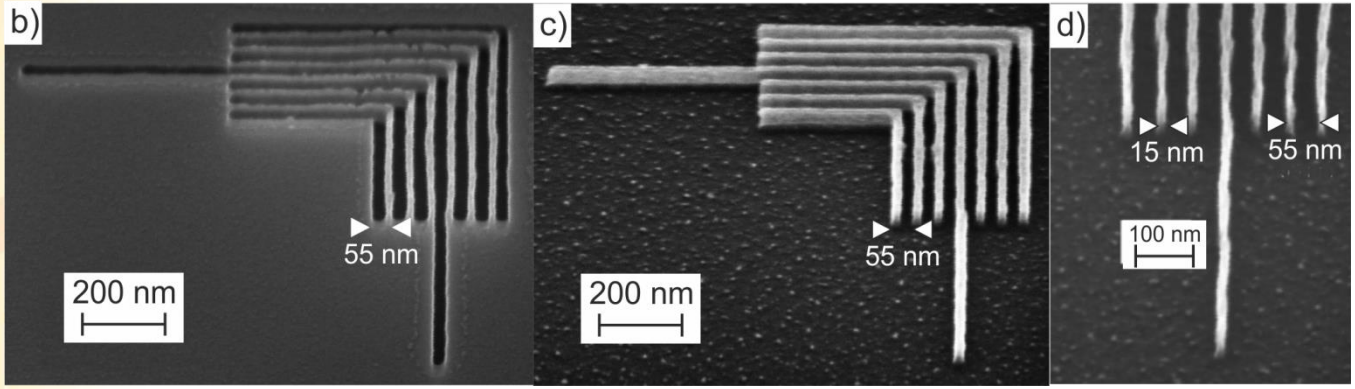
Pattern Transfer



Pattern in PPA



Pattern in Si

Line Edge Roughness in HM8006 layer:

0.65 nm_{rms} – 0.9 nm_{rms}

(3σ: 1.95 nm – 2.7 nm)

Cheong et al., Nano Letters, **13(9)**, 4485-4491, (2013)

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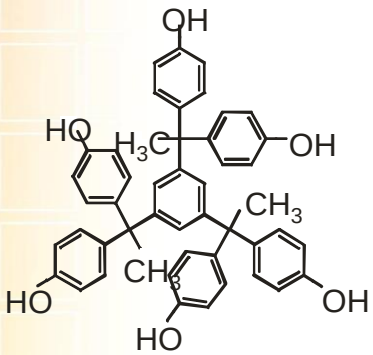
Outlook

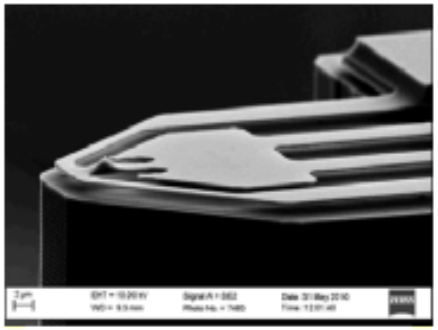
new resists

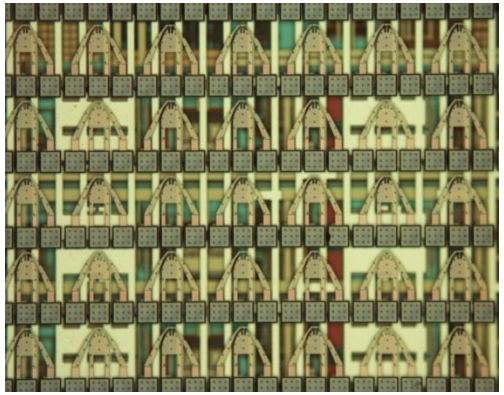


EU project SNM

- Single Nanometer Manufacturing
- 15 partners

new cantilevers + arrays





IBM Millipede

large stroke system

Swiss project (CTI)

- Nanobridge

inspire
AG für mechatronische Produktions-systeme und Fertigungstechnik

SCHNEEBERGER
LINEAR TECHNOLOGY

other applications

- Chemical patterning
- Biological studies
- Material characterization

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SwissLitho AG

Founders:

- Dr. Felix Holzner, CEO, physicist
- Dr. Philip Paul, CTO, engineer

winner ZKB Pionierpreis

Software:
Dr. Nicolae Suditu

Hardware:
Dr. Simon Bonanni

Controller:
Kartik Buddha

Simulation:
Simon Züst

Advisory board

Dr. Peter Vettiger

- Incorporation: 2012
- 6 people, 6 nationalities
- Location: Technopark, Zurich

SwissLitho AG
Innovative Nanofabrication Tools

Thank you for your attention!

Product launch at MNE
September 2013 in London

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Pattern Transfer:
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Cyrill Kuemin, Heiko Wolf

Collaboration ETH Zurich**:**
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Microfabrication at IBM Research Zurich:
Ute Drechsler

Optical Microcavities at IBM Research Zurich:
Fei Ding, Lijian Mai, Thilo Stoeffele, Rainer Mahrt

Various at IBM Research Zurich:
Abu Sebastian, Evangelos Eleftheriou, Walter Riess

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A. Knoll et al., *Advanced Materials*, **22**, 31, (2010)
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F. Holzner et al., *Appl. Phys. Lett.*, **99**, 023110, (2011)
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P. Paul et al., Nanotechnology, **23**, 385307, (2012)
Cheong et al., Nano Letters, **13(9)**, 4485-4491, (2013)

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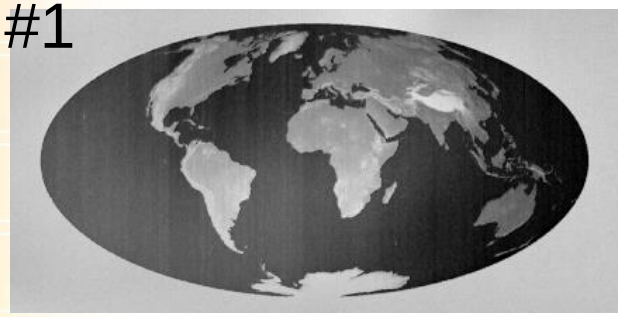
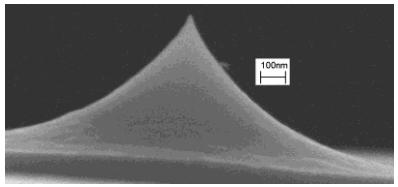
Tip Endurance

World

#1

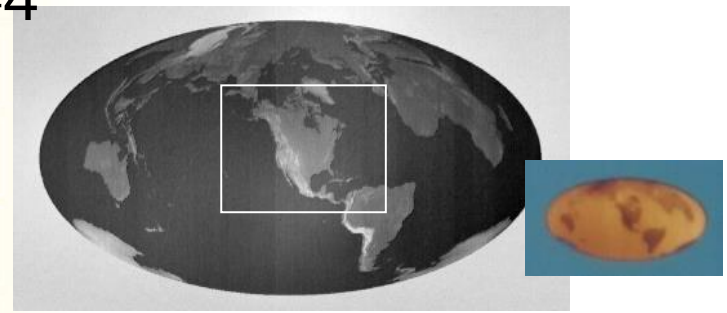


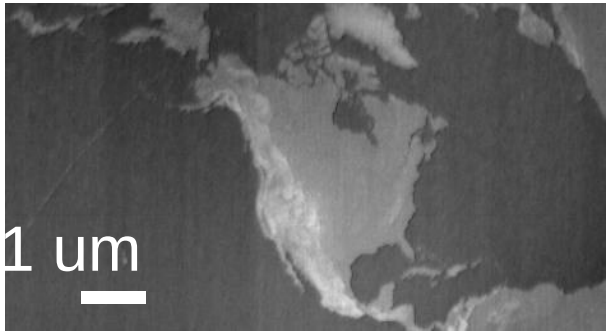
3×10^6 written pixels = 40 μm^3



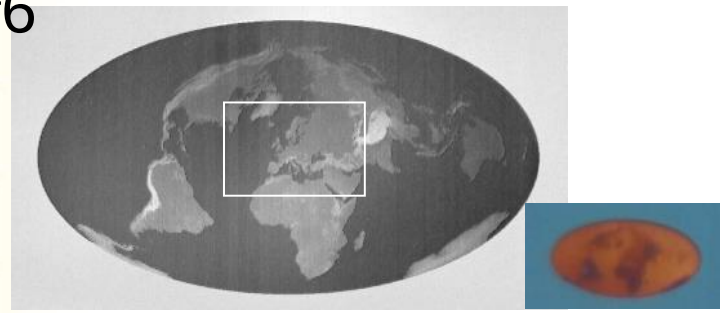
Comparison:
V(tip cone) ≈ 0.13 μm^3
(factor 300)

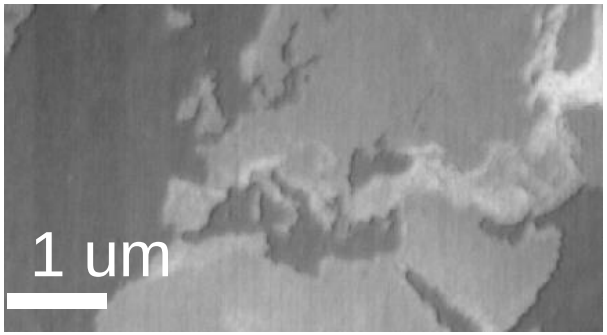
#4





#6





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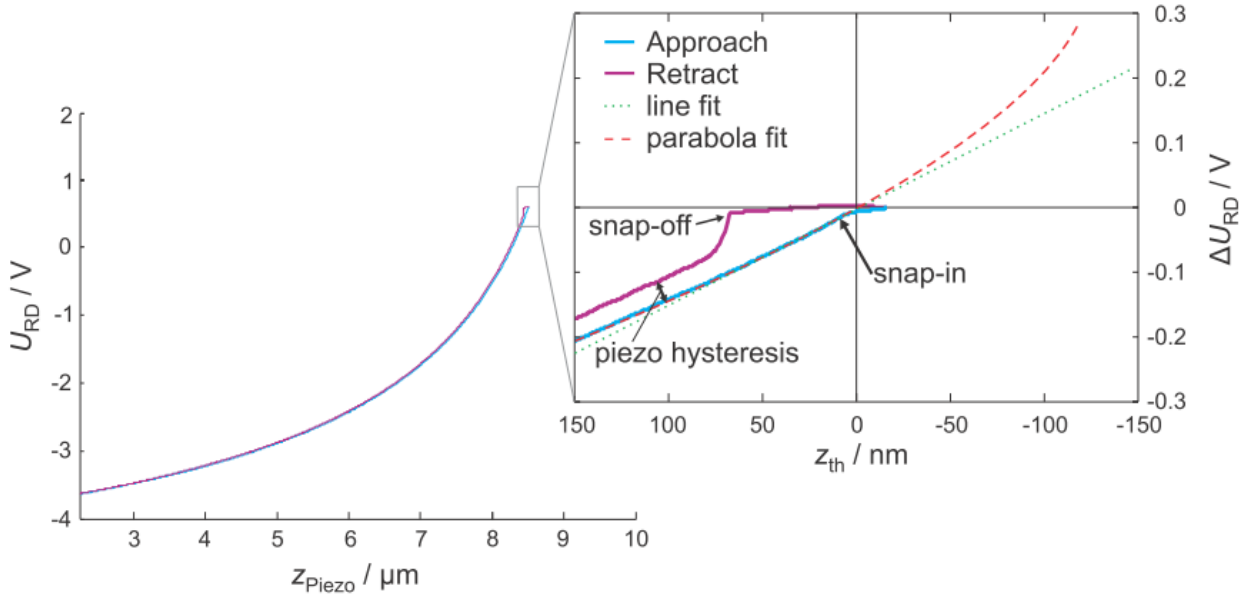
Thermal sensing and imaging

Approach of the thermal sensor



AFM read-out

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