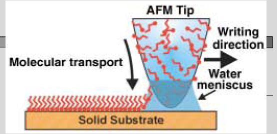
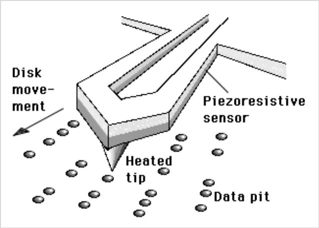
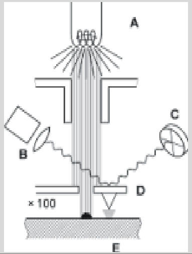
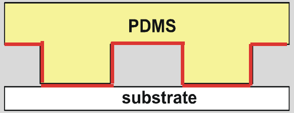
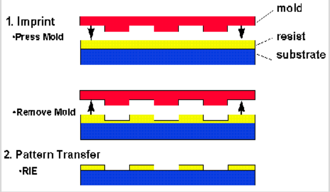
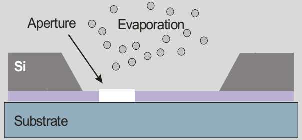
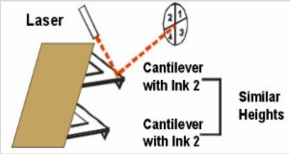
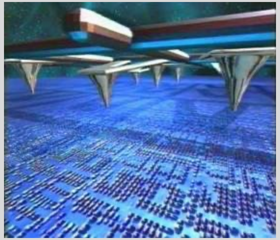
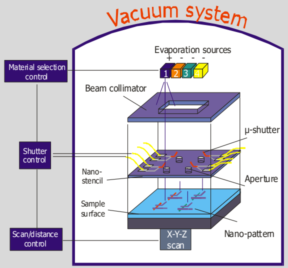
	Molecule Delivery Wet, soft-contact, 100 nm scale		Thermo-mechanical Nano-imprint, embossing, hard contact, 10 nm scale		Local Deposition Stencil, vacuum, no contact 10-100 nm scale	
Single & Scanning *de novo*	**DipPen NADIS**		**Heated AFM**		**AFM Nanostencil**	
Parallel & Static *Replication*	**Soft-litho-graphy**		**NIL**		**Membrane Nano-stencil**	
Parallel & Scanning *Adaptive mass-production*	**Parallel NADIS**		**Millipede**		**Smart Stencil**	

Thermal scanning probe lithography (basics)

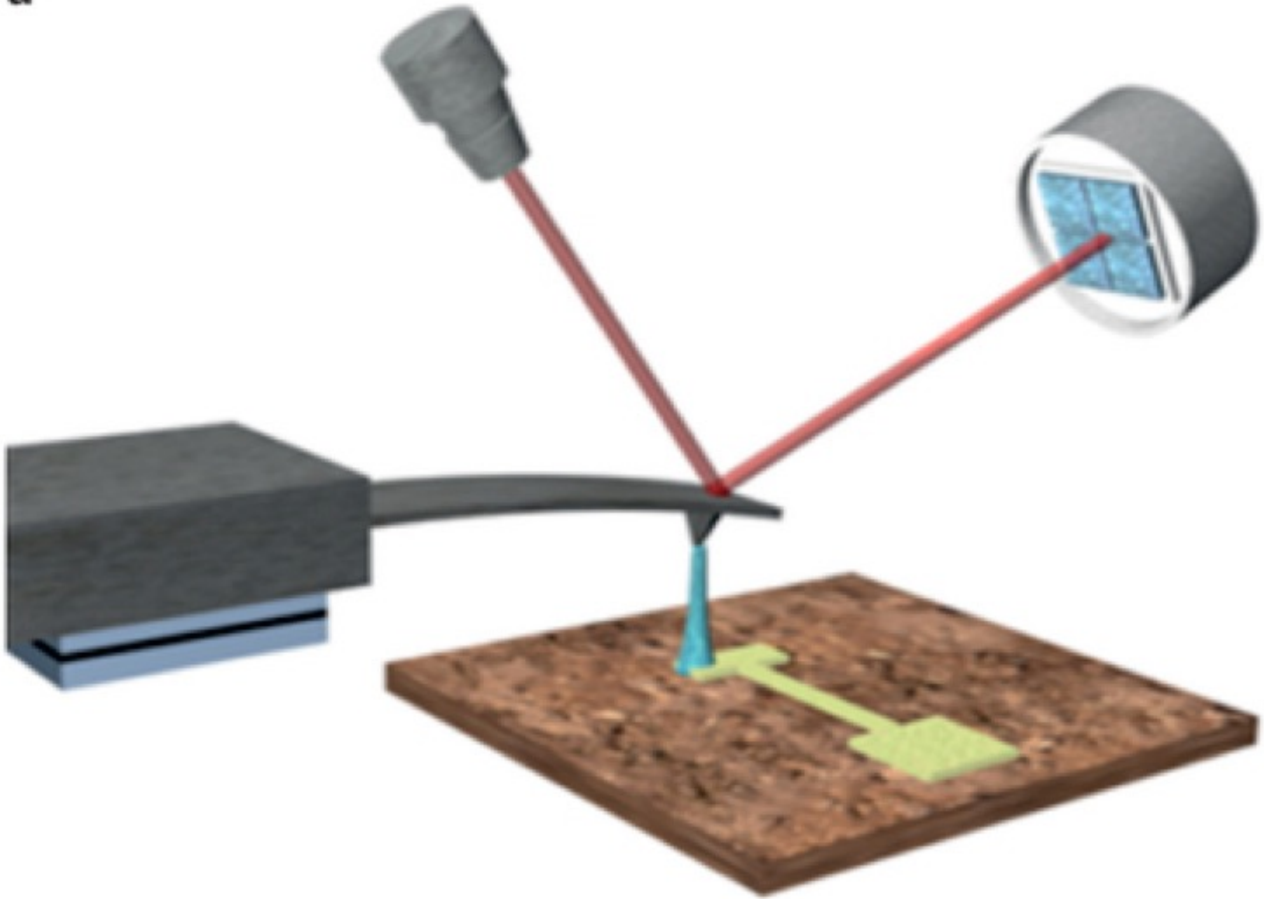
- Scanning probe lithographies (overview)
- SPM based resist exposure
- SPM based local oxidation
- SPM based liquid dispensing
- SPM based 3D printing (electrochemical)
- Thermal probe lithography
- IBM’s millipede project
- Commercial T-SPL tool

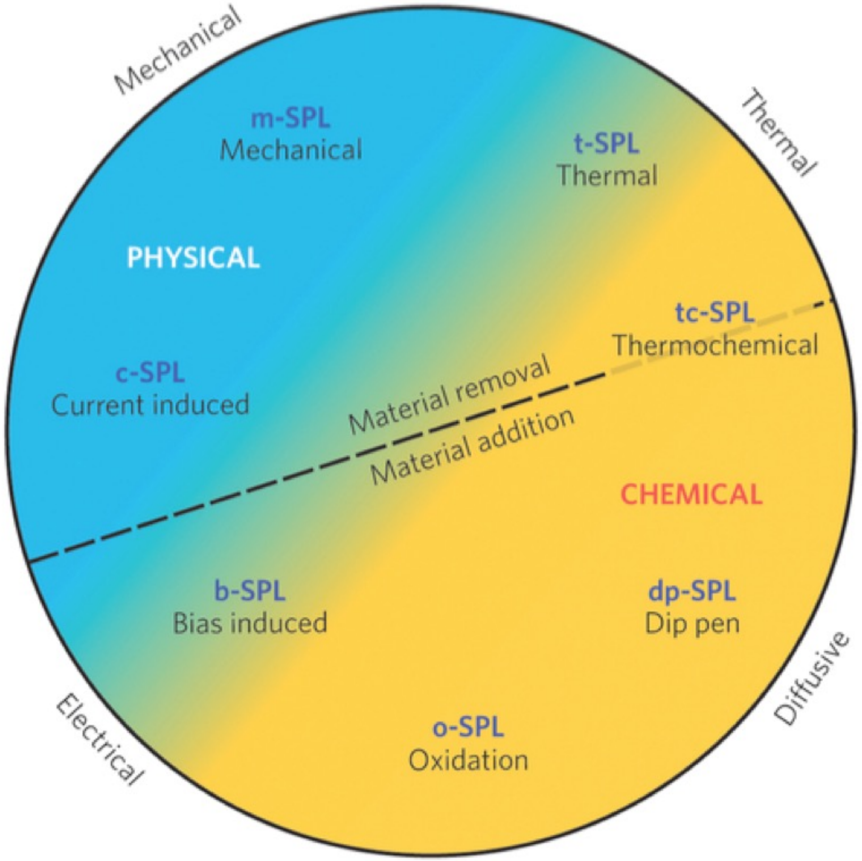
Scanning probe systems

Surface microscopy versus surface modification/patterning

- the nature of the interaction determines the sample property that is observed
- the magnitude of the interaction determines whether we observe or modify: SPM as a microscope or a tool

a



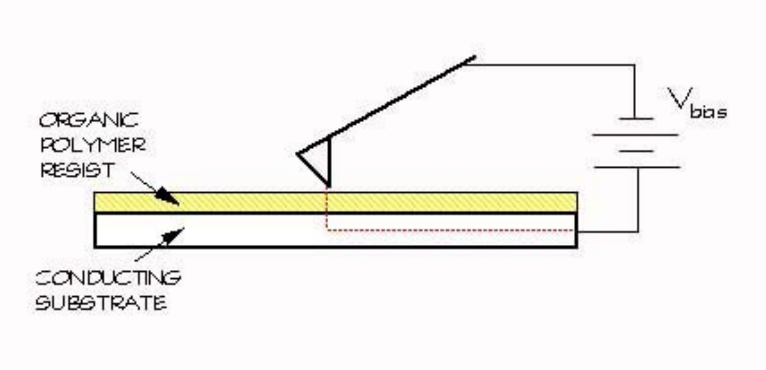

Mechanical
Thermal
Diffusive
Electrical
m-SPL
Mechanical
t-SPL
Thermal
PHYSICAL
tc-SPL
Thermochemical
c-SPL
Current induced
Material removal
Material addition
CHEMICAL
b-SPL
Bias induced
dp-SPL
Dip pen
o-SPL
Oxidation

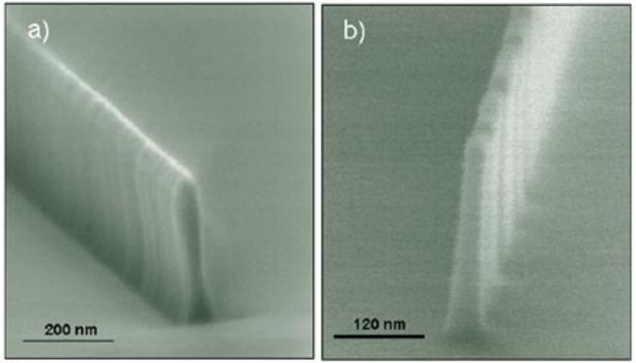
AFM litho

Electron exposure of a resist material, such as an organic polymer or a monolayer resist using field-emission from the tip (induces a chemical changes). This process is in fact very similar to the EBL. Below, the advantages and drawbacks of this technology compared to the EBL are listed.

Advantage: Much cheaper, always in “focus”

Disadvantage: Slower, physical contact between the tip and the surface.

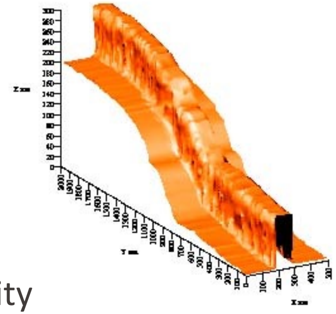


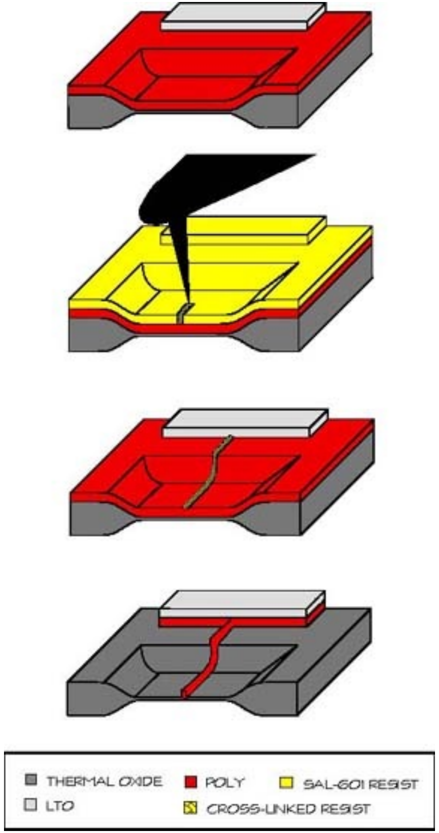


Quate Group, Stanford University

AFM litho

- Exposure of resist (3D capable)
- 100-nm pMOSFET Fabrication Gate Lithography
- Uniform 100-nm Gate Over Topography

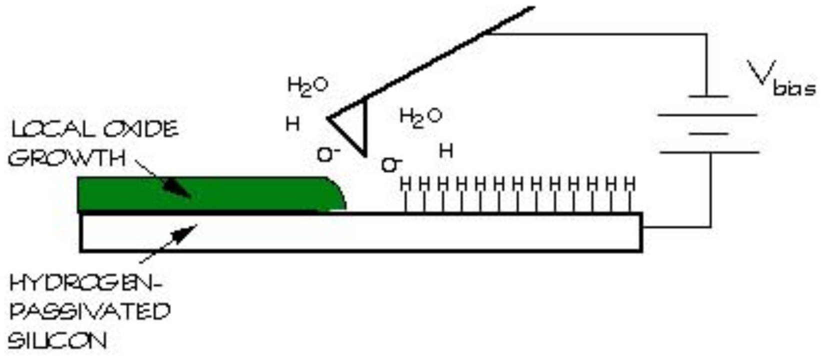




- Quate Group, Stanford University

AFM litho

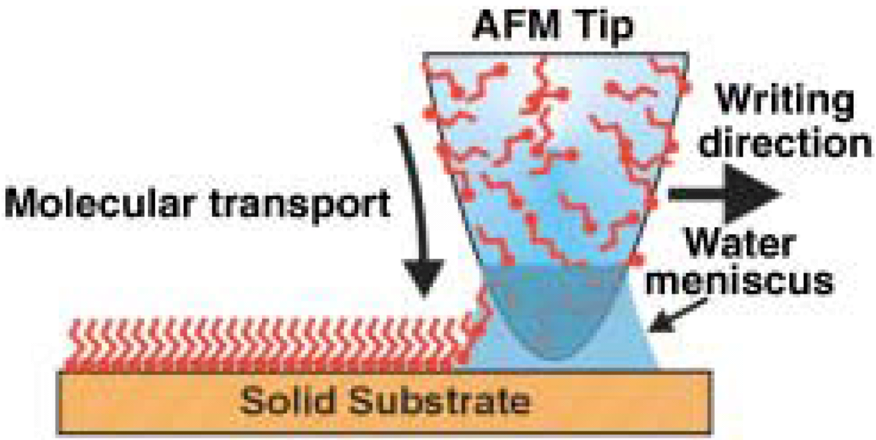
A voltage bias between a sharp probe tip and a sample generates an intense electric field at the tip. The high field can be used to locally oxidize silicon in a process known as electric-field-enhanced oxidation. The high field desorbes the hydrogen passivation on the silicon surface, allowing the exposed silicon to oxidize in air (the oxidation rate is enhanced by the presence of the accelerating field). This local oxidation process is powerful because of its fine resolution (sub-50-nm) and the resistant oxide etch mask that is created.



Use strong mask for transfer etch step

Quate Group, Stanford University

Dip Pen



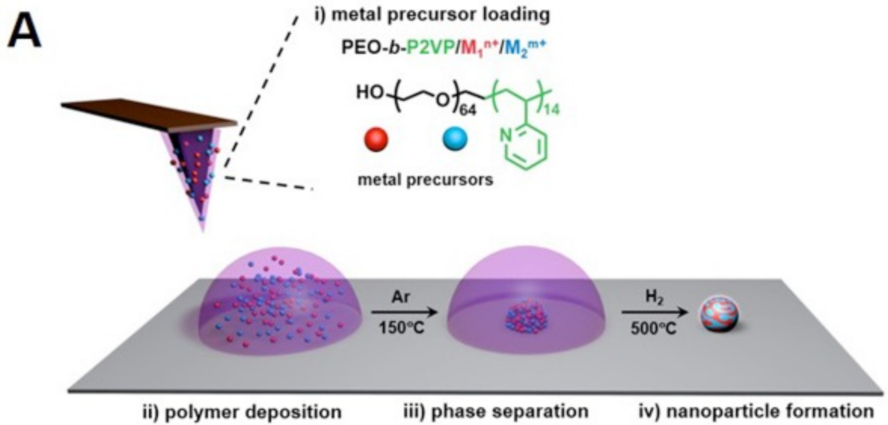
A tip of an AFM operated in air is “inked” with a chemical of interest and brought into contact with a surface.

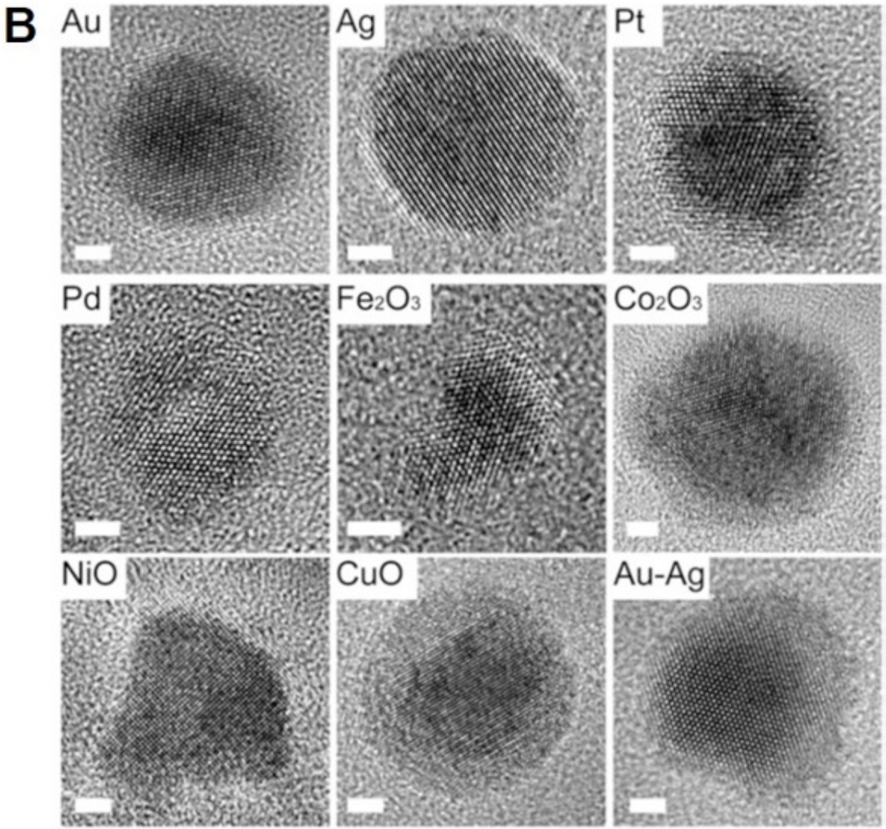
The ink molecules flow from the tip onto the surface as with a fountain pen.

The water meniscus that naturally forms between the tip and the surface enables the diffusion and transport of the molecules.

Possible inks: Polymers, Au, DNA, Antibodies

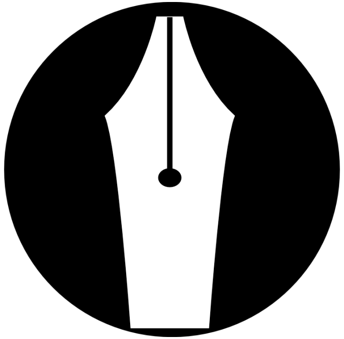
Dip Pen



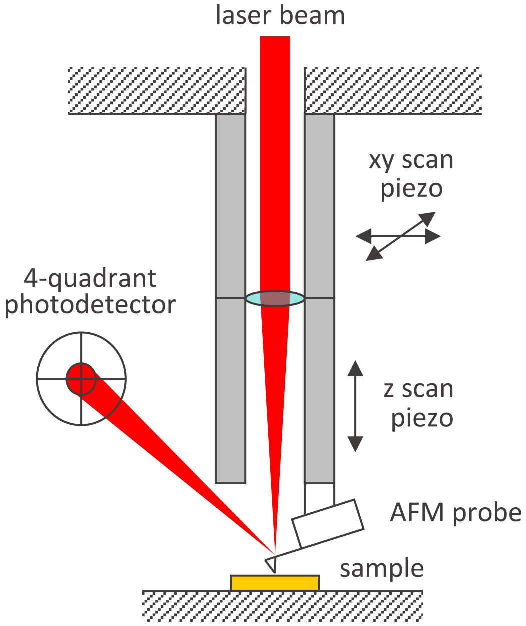


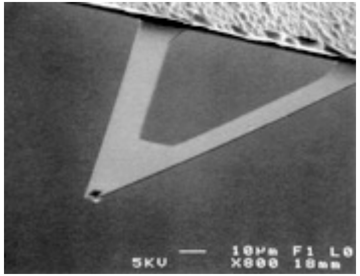
- https://mirkin-group.northwestern.edu/project/dip-pen-nanolithograph/

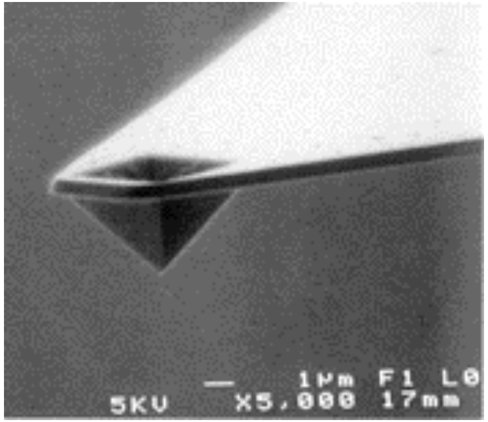
Microfluidics in nanoprobes

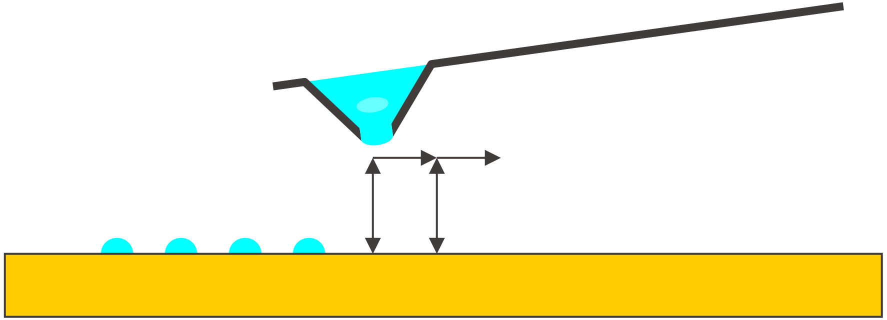


Nanoscale dispenser



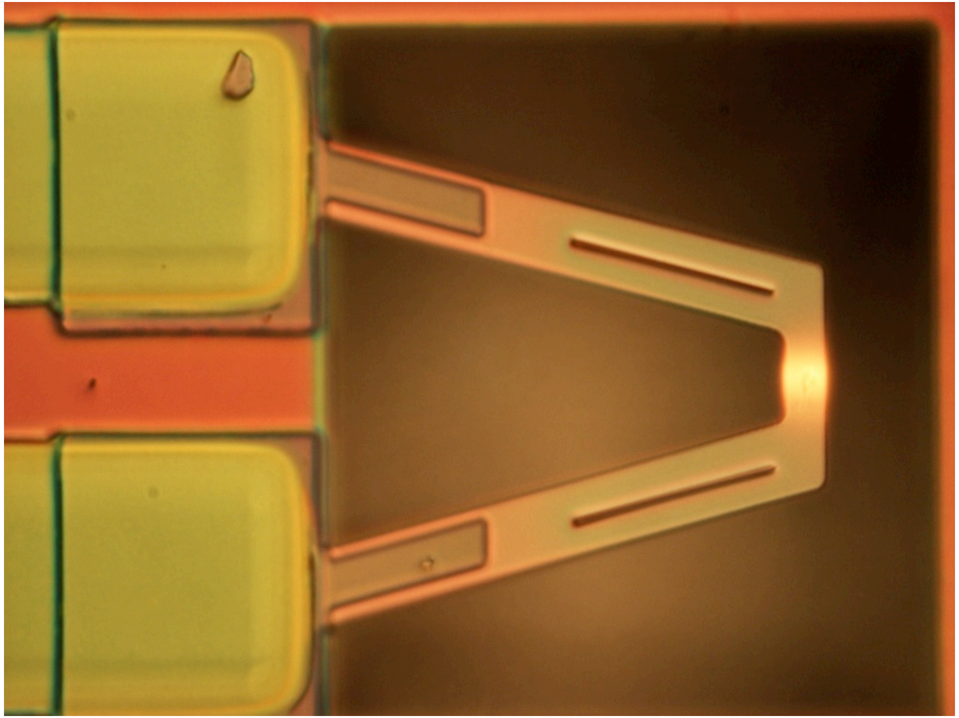




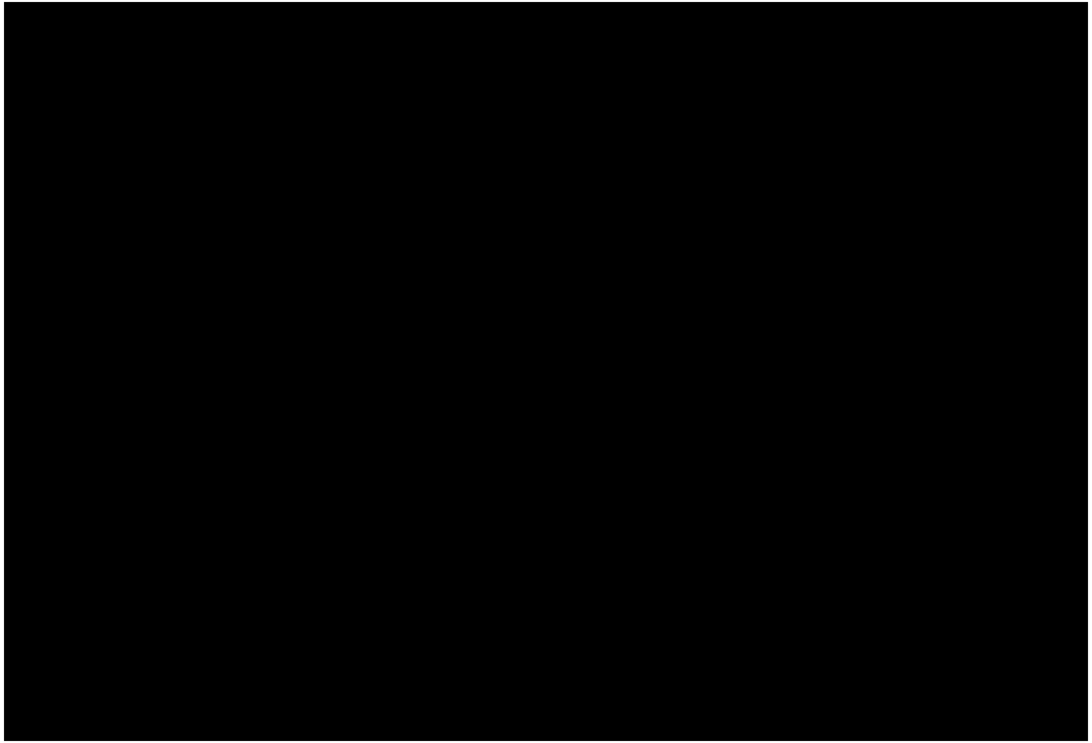


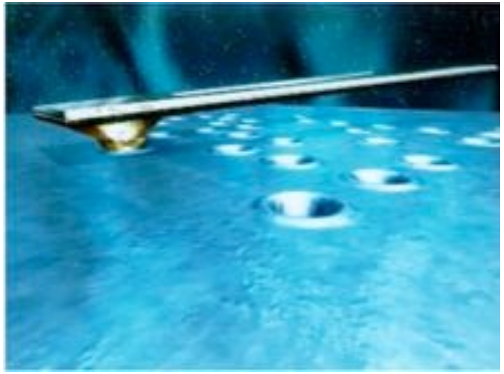
CSEM S.A. Neuchatel

Thermal scanning probe lithography



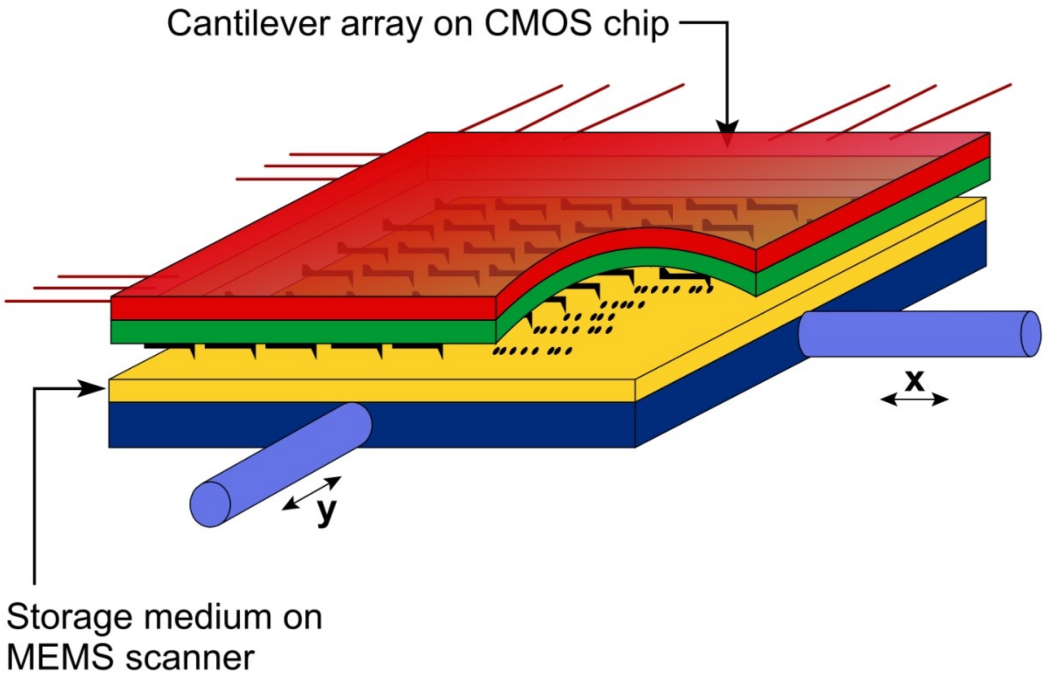
IBM’s millipede data storage project

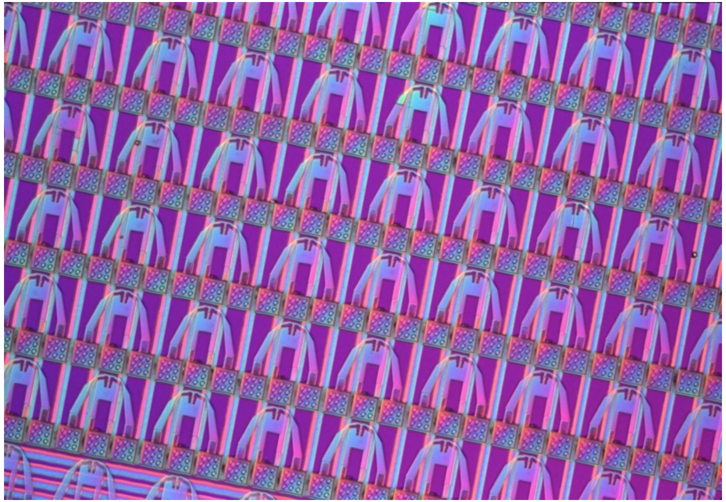


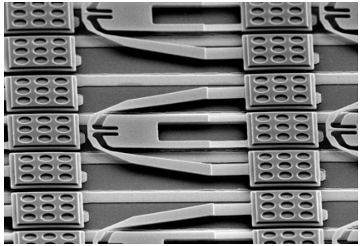


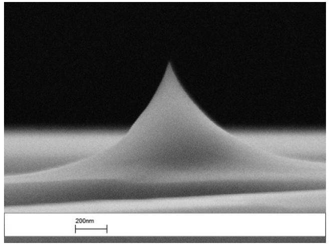
- https://www.youtube.com/watch?v=chMFASRIusU

IBM’s millipede data storage project

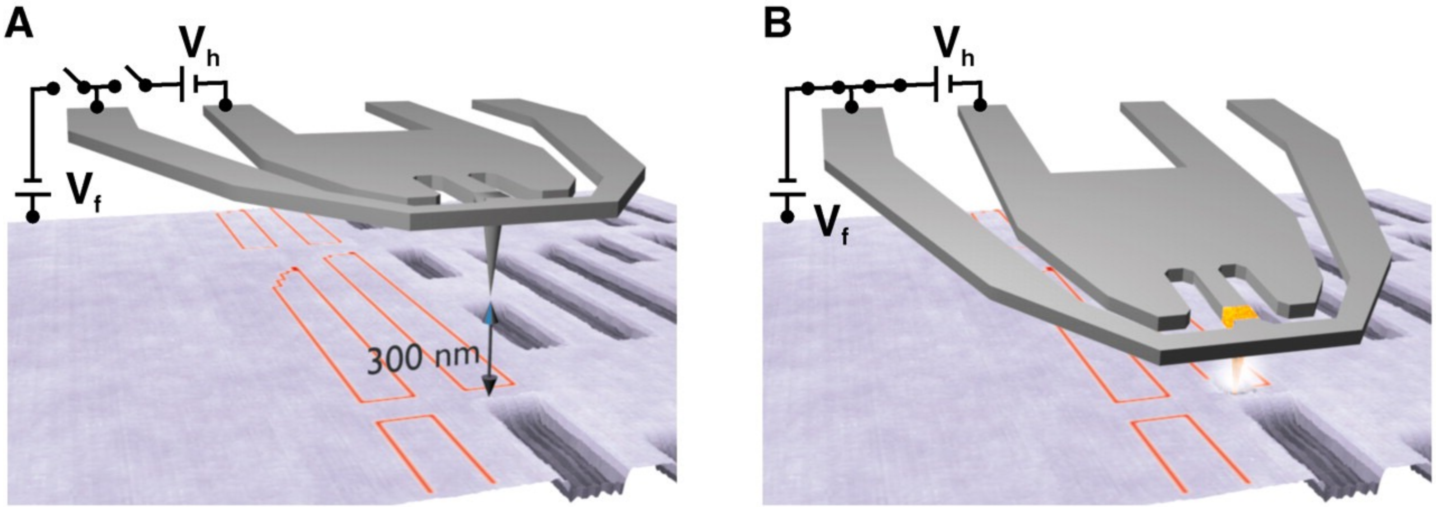








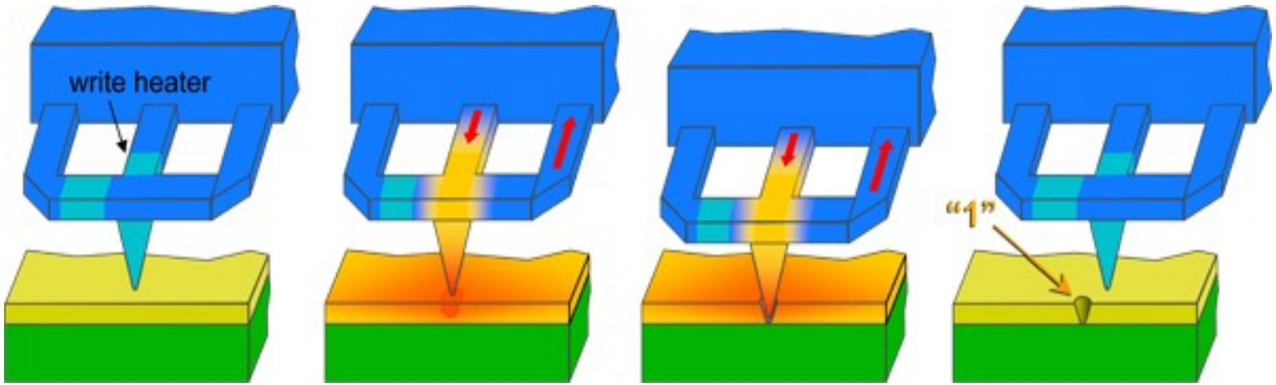
Multifunctional MEMS cantilever



D. Pires et al., Science 328, 732-735 (2010)

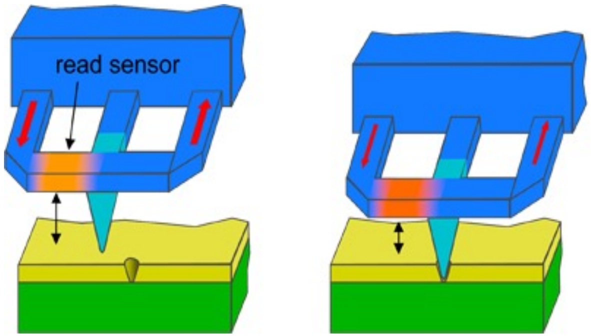
Writing

Thermo-mechanical writing is performed by locally softening the polymer media using the heated tip of a cantilever and simultaneously applying a force to create a nano-scale indentation in the polymer film. The tip is heated by applying a current pulse to a resistive heater integrated into the cantilever, directly behind the tip. During writing, the tip is heated to a temperature above the glass transition temperature of the polymer and forces on the order of a few hundred nanonewtons are applied to the tip for a few microseconds.



Reading

Read-back of the data is performed using a thermo-mechanical sensing technique in which a second resistive heater integrated into the cantilever is heated to a temperature of around 200 °C while the polymer medium is scanned under the tip. The principle of thermal sensing is based on the fact that the rate of cooling of this heater increases as the distance between it and the substrate carrying the polymer medium is reduced. Thus, when the tip moves into an indentation, the distance between the heater and substrate is reduced, resulting in an increase in cooling and hence a decrease in the temperature of the heater. This change in temperature results in an increase in resistance of the heater, which is easily detected by monitoring the current flowing through it.

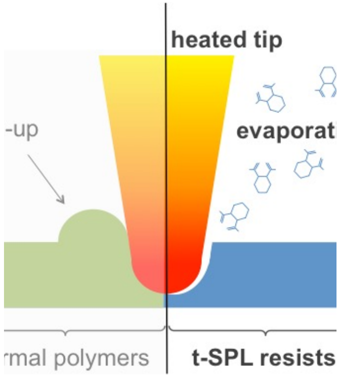


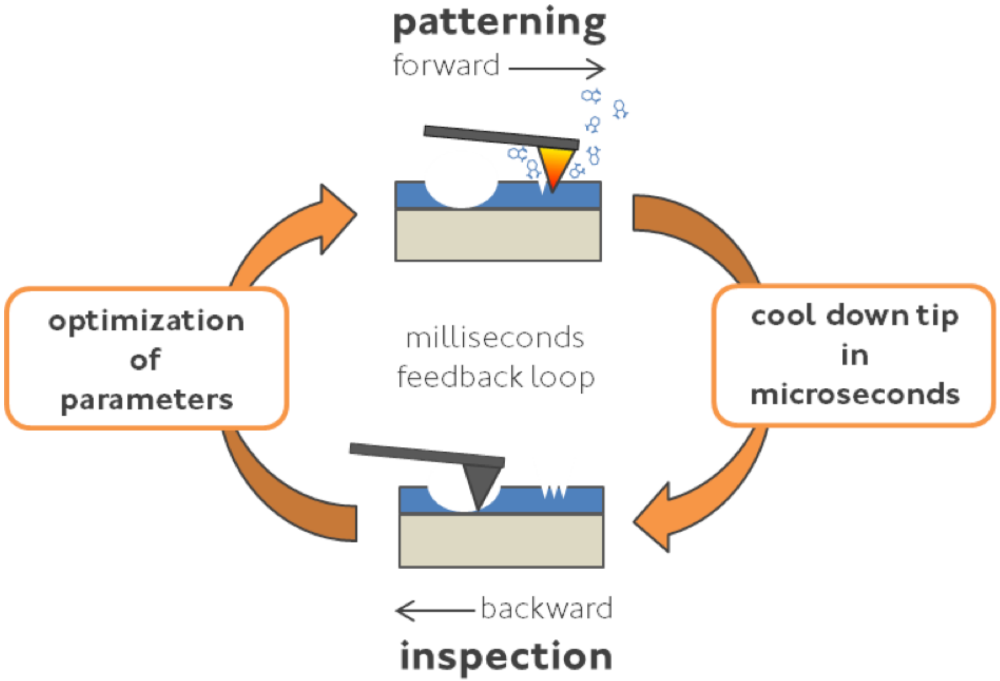
Decreased distance
→ increased cooling
→ decreased temperature
→ increased resistance

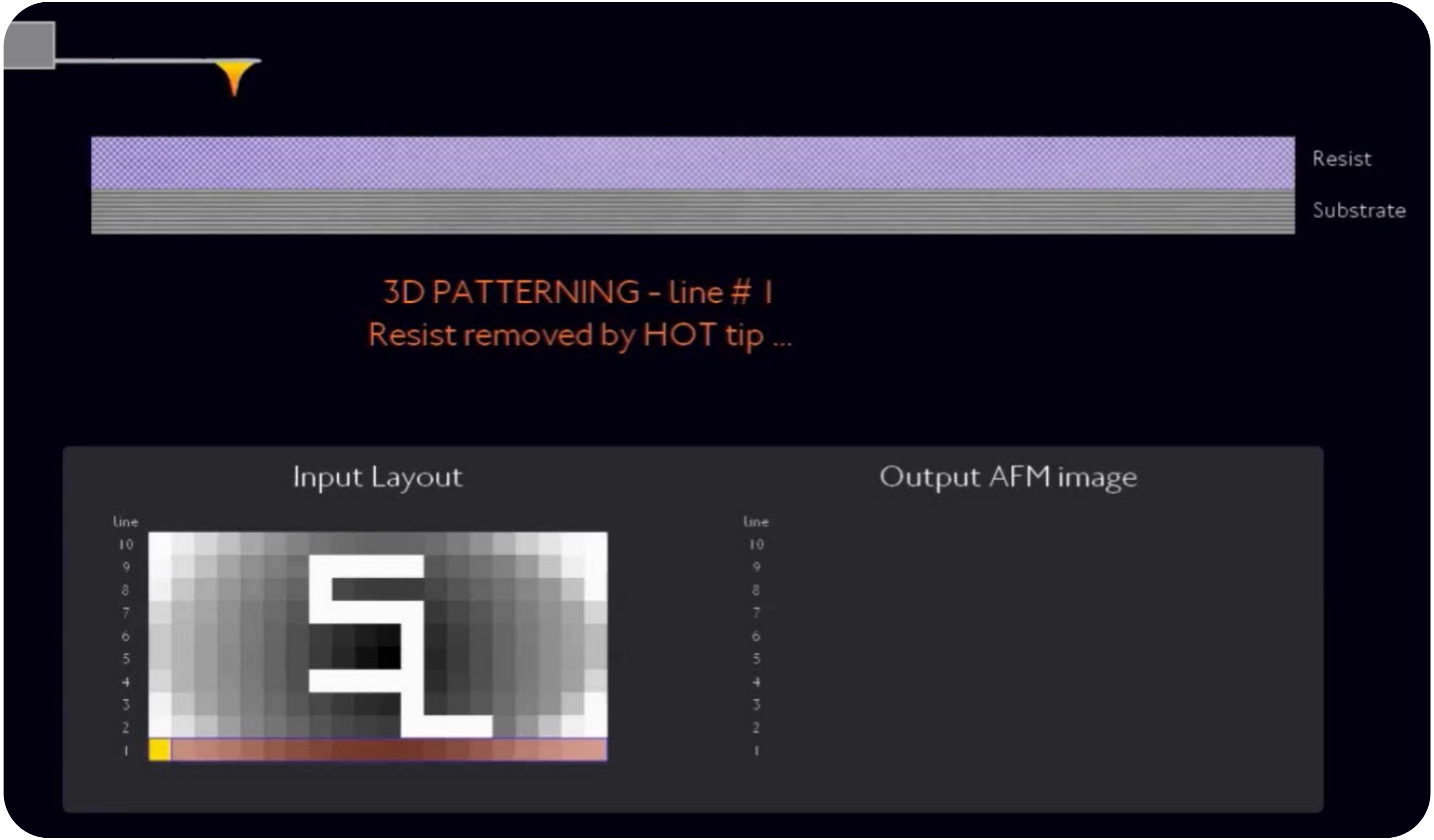
Writing and reading using 1 probe

Closed-loop lithography

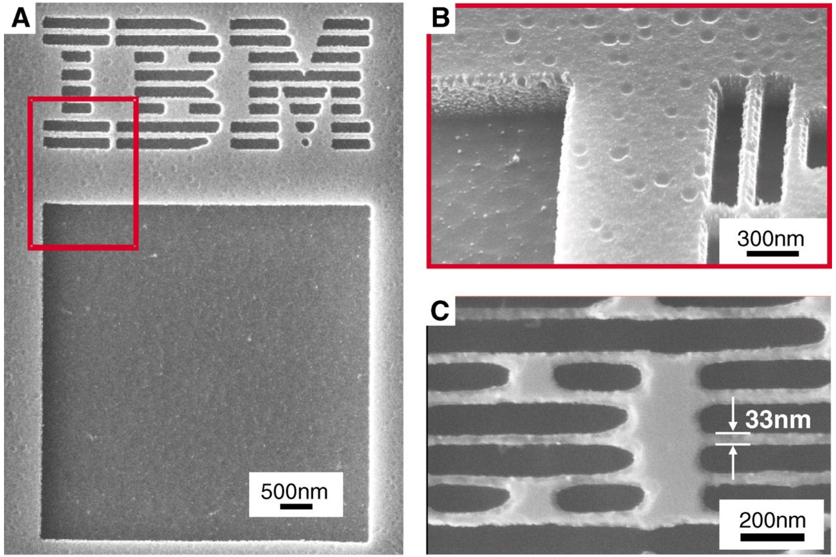
- Resist requirement (when heated):
- Not ‘flowing’ like normal polymer
- Completely removed into vapor phase
- “see what you get”
- In-situ metrology

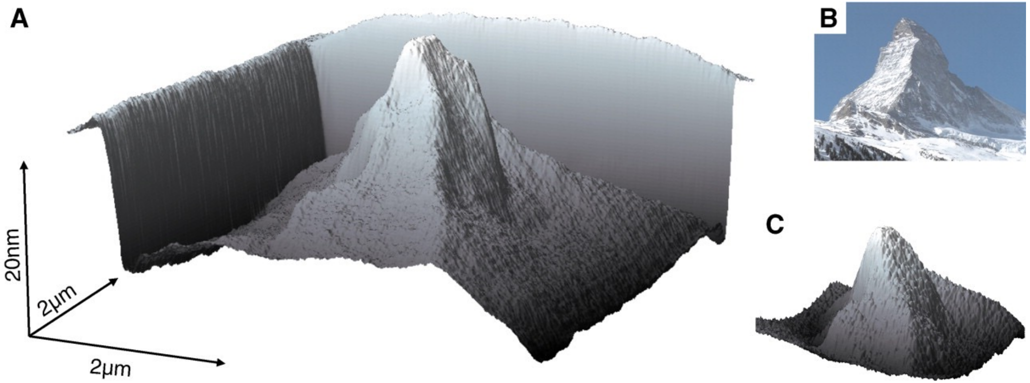





Resist
Substrate
3D PATTERNING - line # 1
Resist removed by HOT tip ...
Input Layout
line
10
9
8
7
6
5
4
3
2
1
Output AFM image
line
10
9
8
7
6
5
4
3
2
1

Early T-SPL demonstrations





D. Pires et al., Science 328, 732-735 (2010)

Thermal scanning probe lithography: take away message

- Nanoscale writing tool
- Various tip-surface interactions
- High resolution (10nm scale)
- Gentle surface contact
- No charged particles damage (with exception of conducting SPM)
- Closed-loop feedback (writing and reading)

- But slow
- Tips are consumables