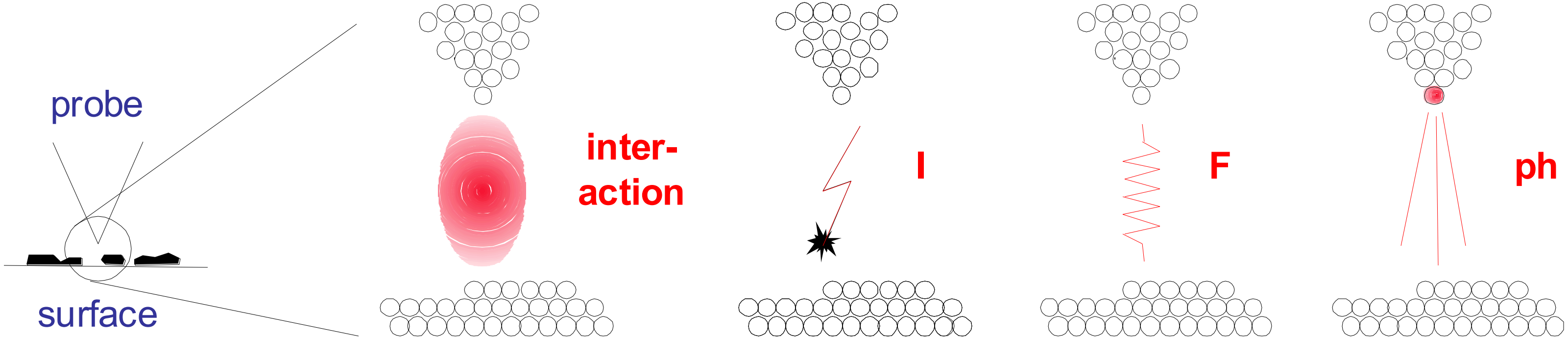
Thermal scanning probe lithography

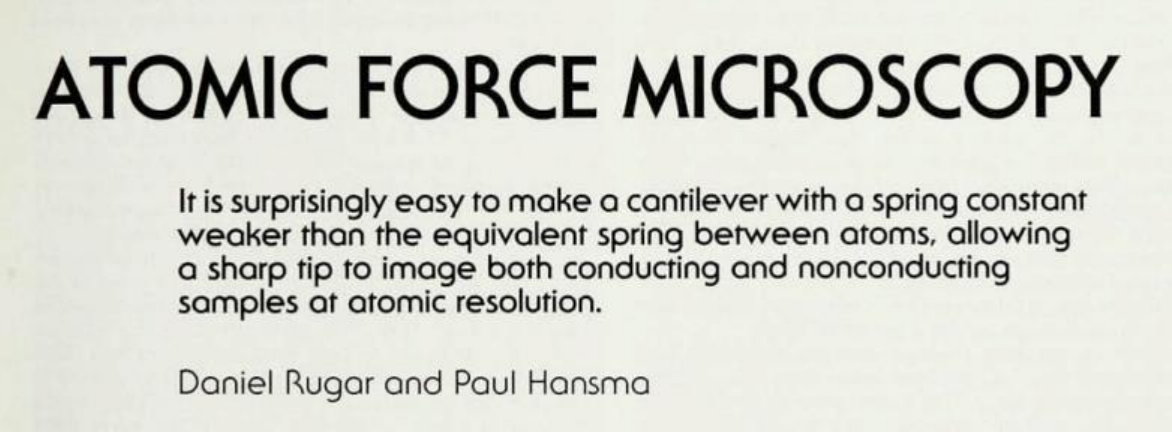
- Scanning probe lithographies (overview)
- Thermal probe lithography
- IBM’s millipede project
- Commercial T-SPL tool
- High aspect ratio grayscale lithography
- 2D material strain engineering

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



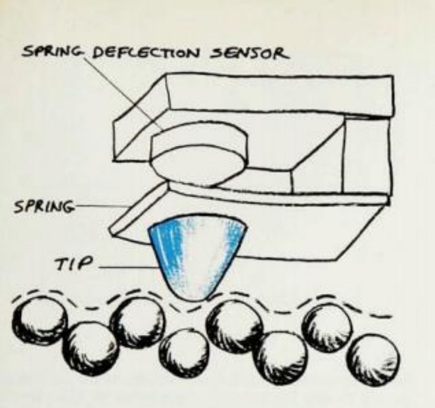


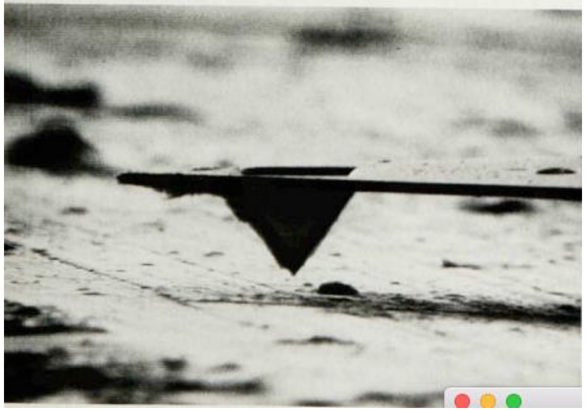
ATOMIC FORCE MICROSCOPY

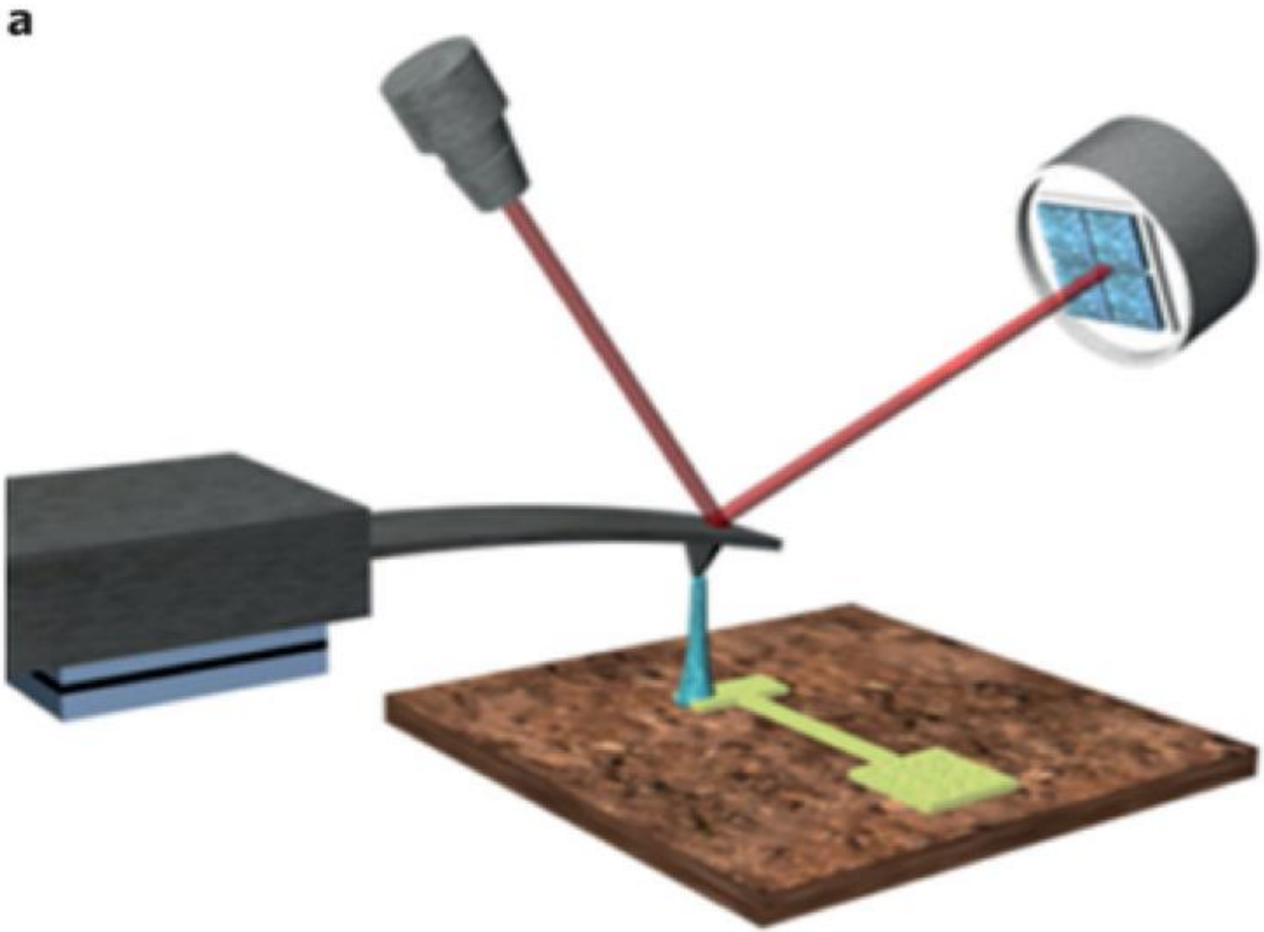
It is surprisingly easy to make a cantilever with a spring constant weaker than the equivalent spring between atoms, allowing a sharp tip to image both conducting and nonconducting samples at atomic resolution.

Daniel Rugar and Paul Hansma

1990 American Institute of Physics
PHYSICS TODAY OCTOBER 1990



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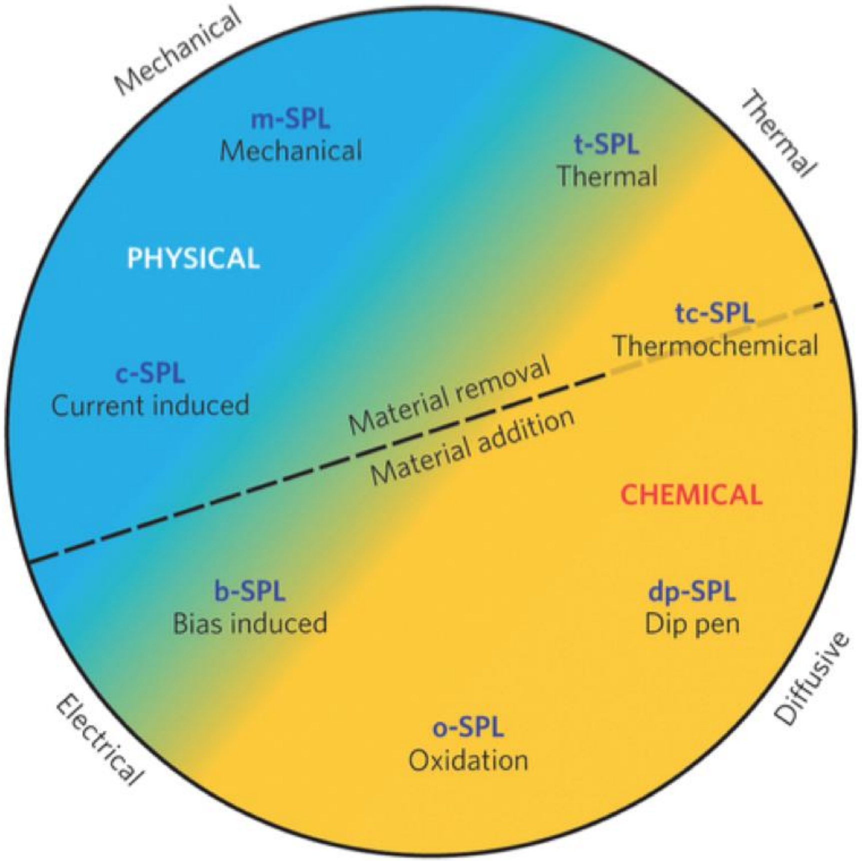
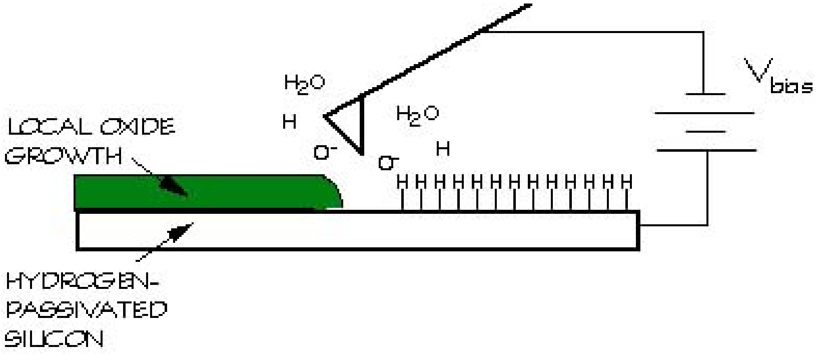

Mechanical
Thermal
Electrical
Diffusive
m-SPL
Mechanical
t-SPL
Thermal
PHYSICAL
tc-SPL
Thermochemical
c-SPL
Current induced
Material removal
Material addition
CHEMICAL
b-SPL
Bias induced
dp-SPL
Dip pen
o-SPL
Oxidation

AFM litho

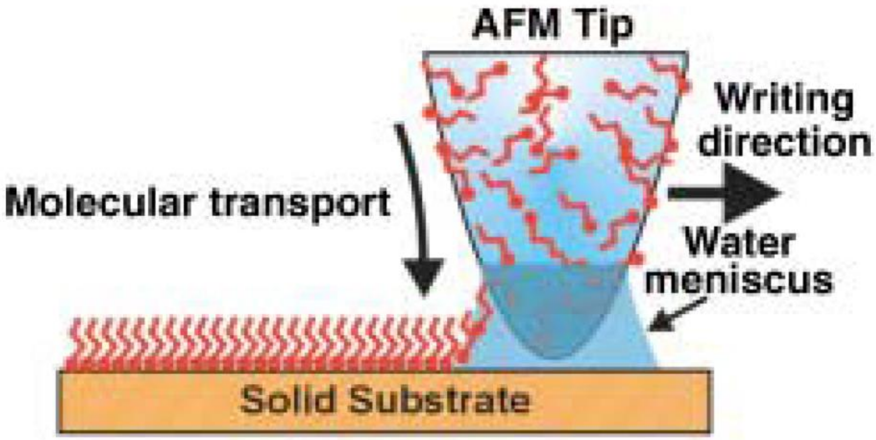
A voltage bias between a sharp probe tip and a sample generates an intense electric field at the tip. The high field can be used to locally oxidize silicon in a process known as electric-field-enhanced oxidation. The high field desorbes the hydrogen passivation on the silicon surface, allowing the exposed 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.

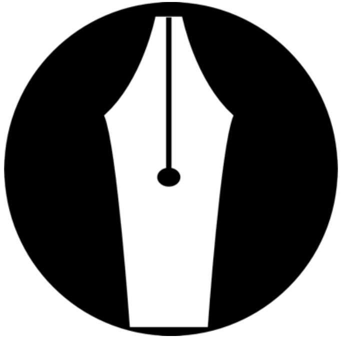
The ink molecules flow from the tip onto the surface as with a fountain pen.

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

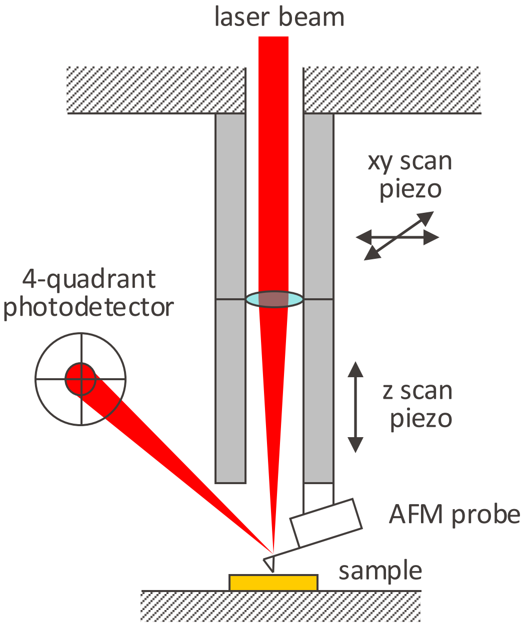
Possible inks: Polymers, Au, DNA, Antibodies

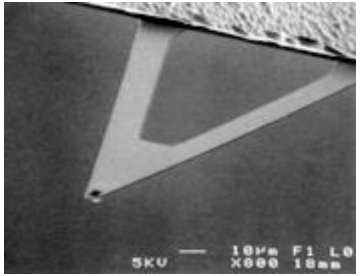
Microfluidics in nanoprobes

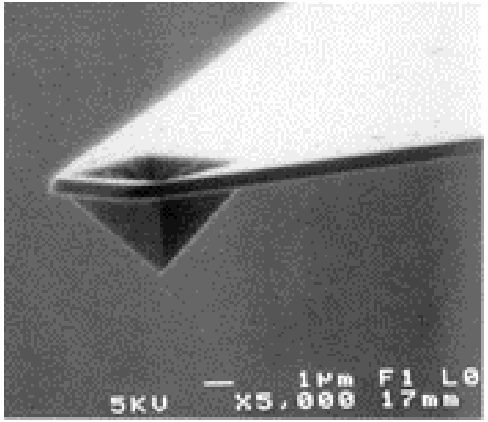
Colourbox

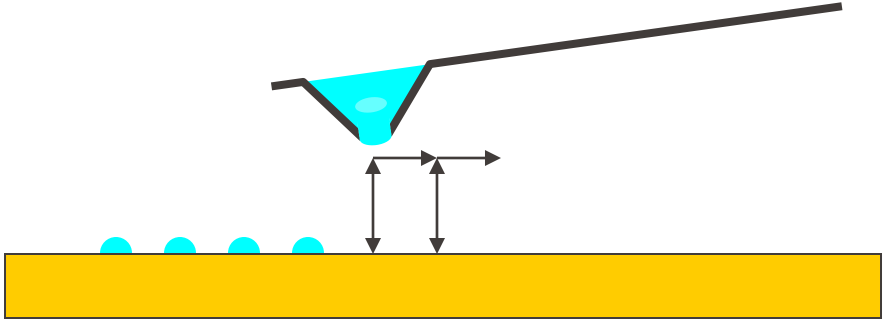


Nanoscale dispenser



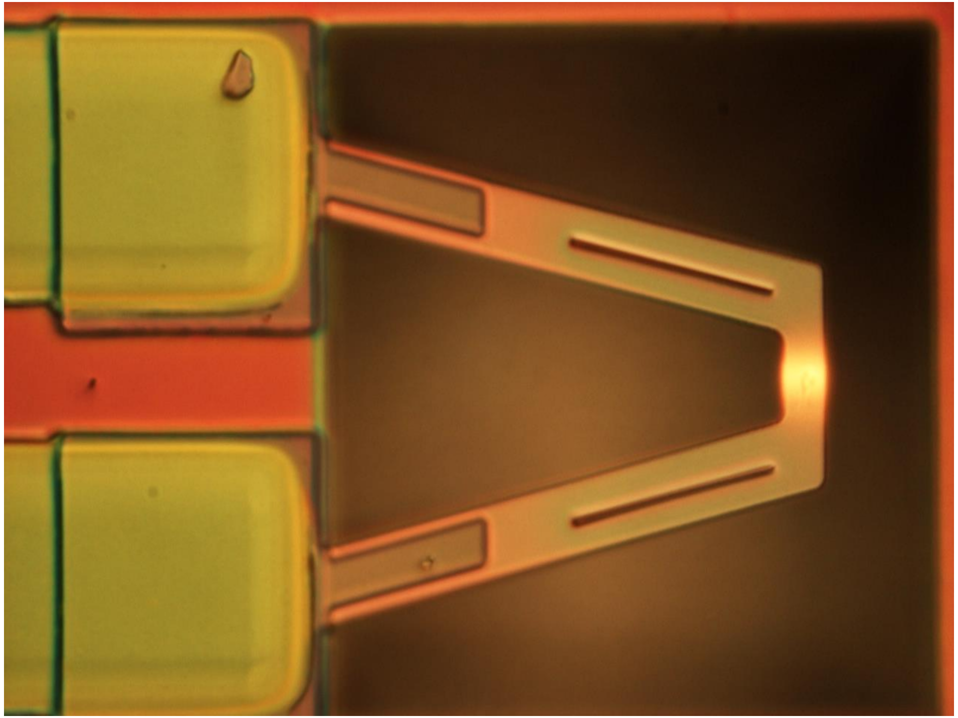




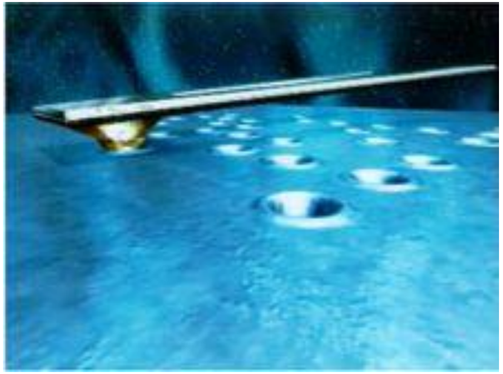


CSEM S.A. Neuchatel

Thermal scanning probe lithography

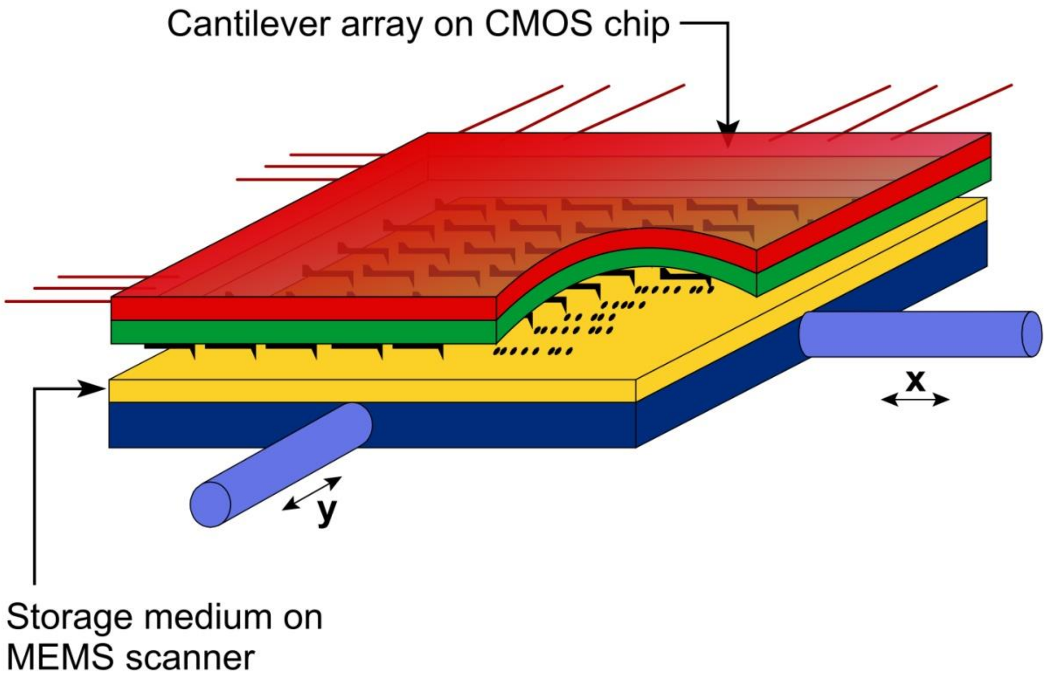


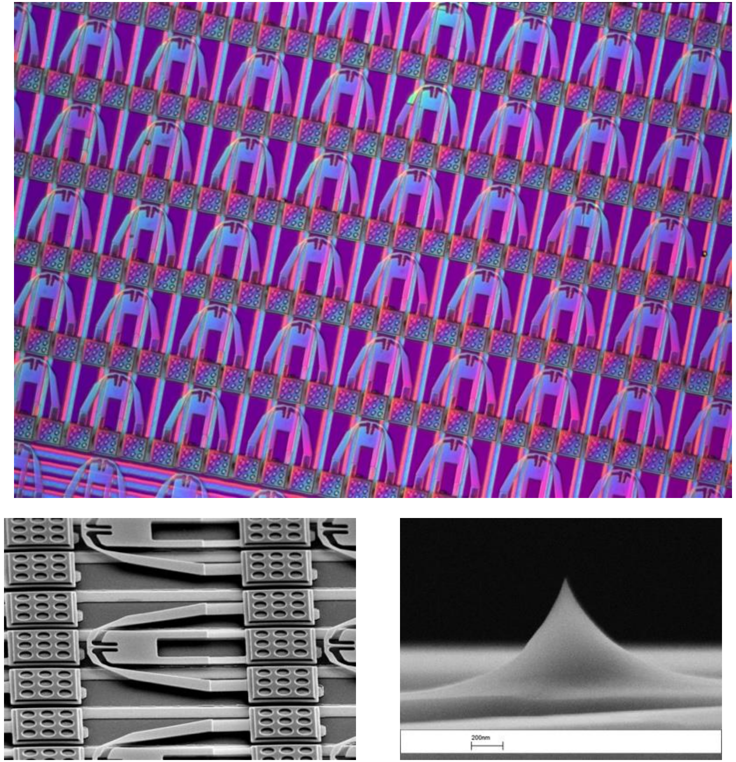
IBM’s millipede data storage project



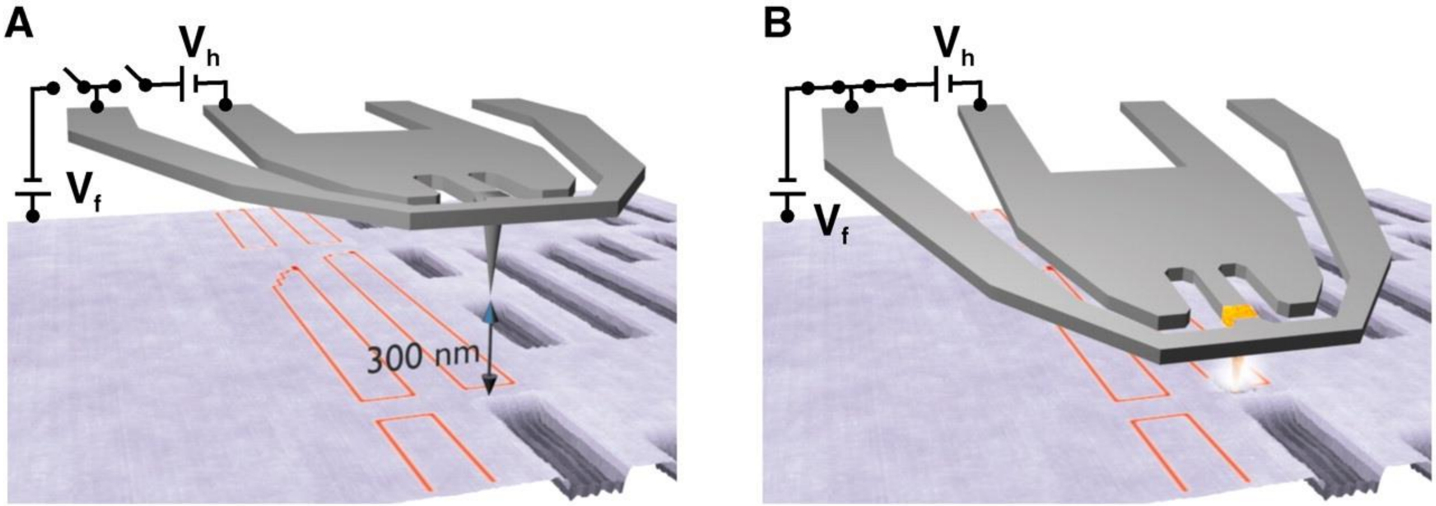
https://www.youtube.com/watch?v=chMFASRIusU

IBM's millipede data storage project





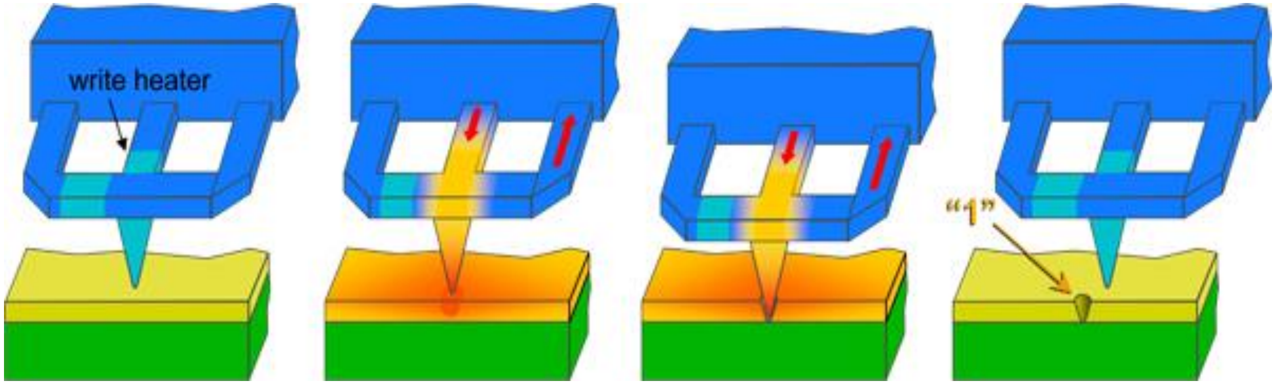
Multifunctional MEMS cantilever



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

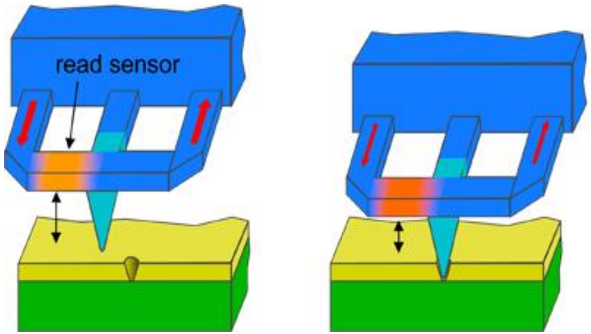
Writing

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

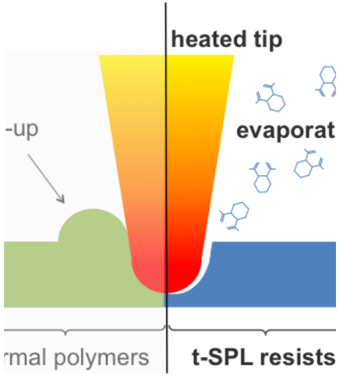
Read-back of the data is performed using a thermo-mechanical sensing technique in which a second resistive heater integrated into the cantilever is heated to a temperature of around 200 °C while the polymer medium is scanned under the tip. The principle of thermal sensing is based on the fact that the 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.

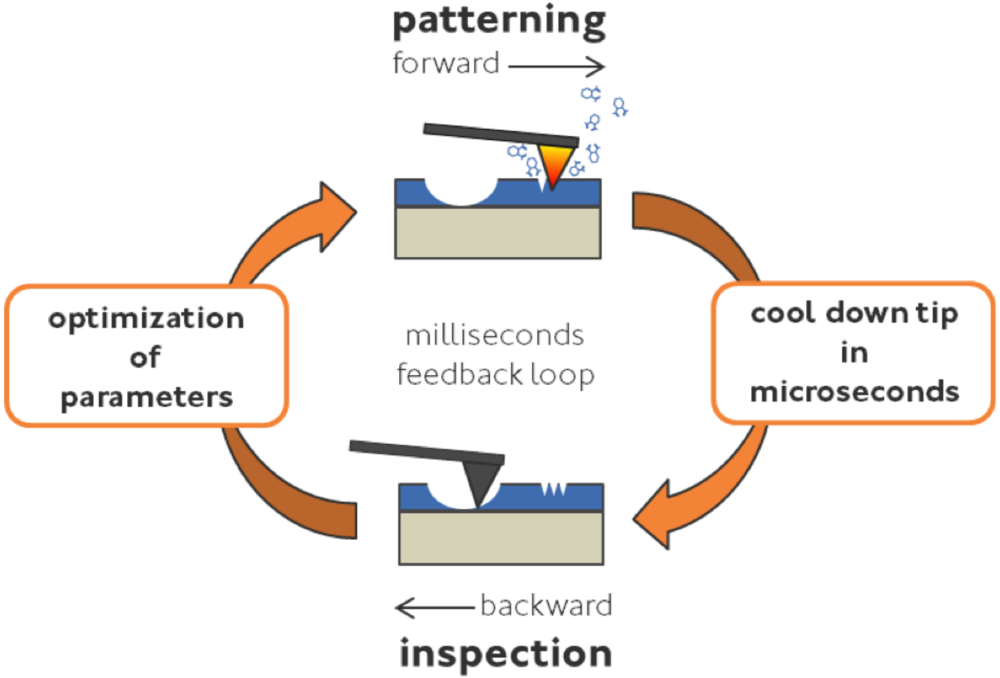


Decreased distance
→ increased cooling
→ decreased temperature
→ increased resistance

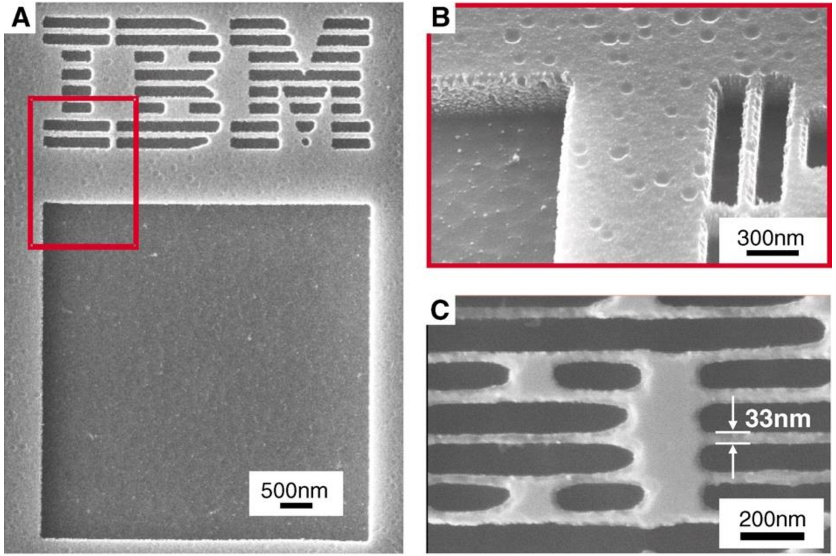
Closed-loop lithography

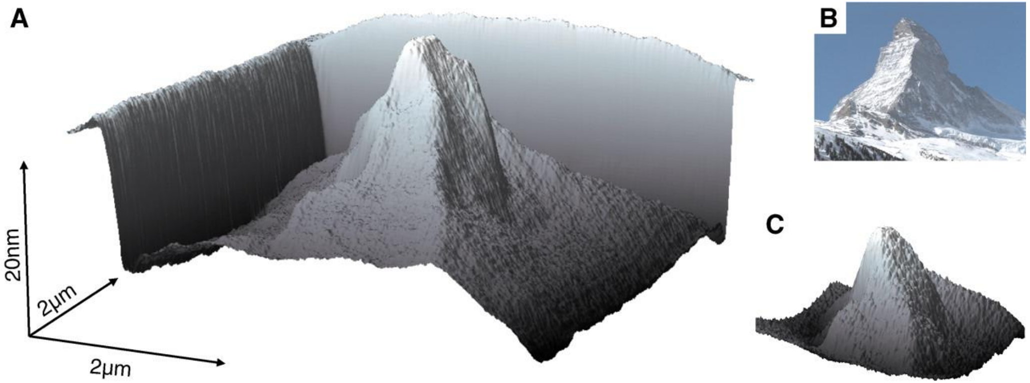
- Resist requirement (when heated):
- Not ‘flowing’ like normal polymer
- Completely removed into vapor phase
- “see what you get”
- In-situ metrology



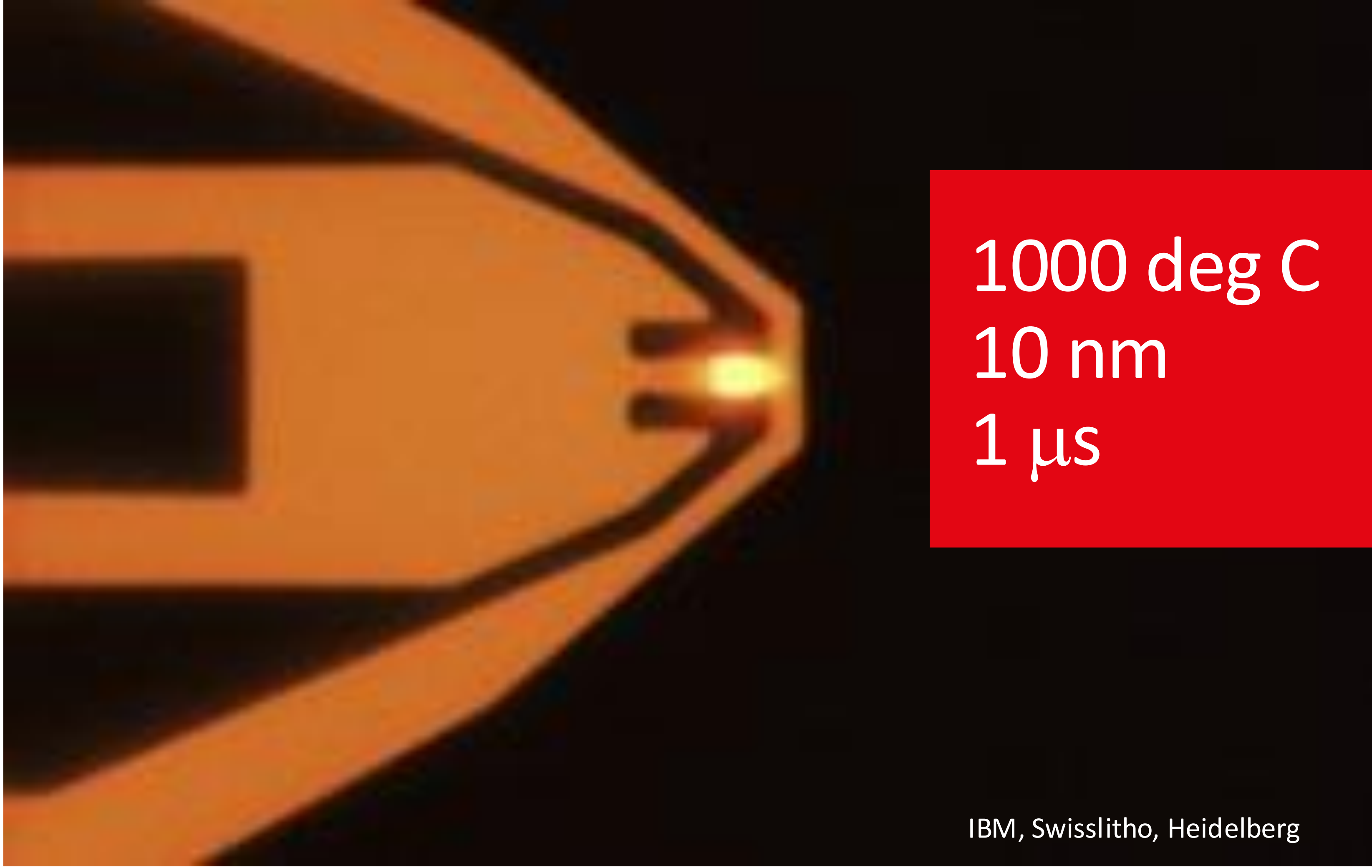


Early T-SPL demonstrations





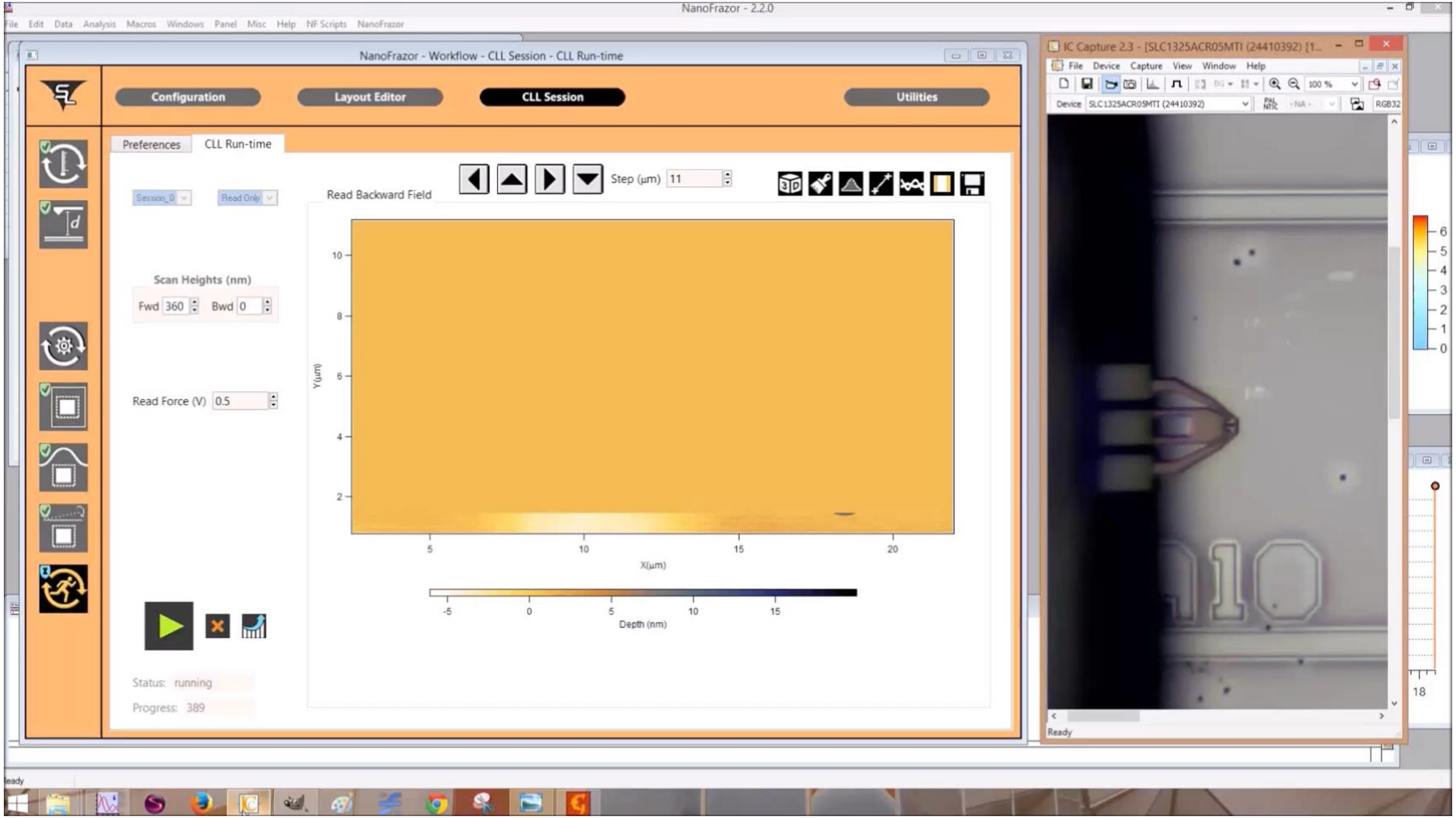
D. Pires et al., Science 328, 732-735 (2010)



1000 deg C
10 nm
1 µs

IBM, Swisslitho, Heidelberg

Modern t-SPL system (closed loop)



Step (µm) 11

Scan Heights (nm)

Fwd 360 Bwd 0

Read Force (V) 0.5

Status: running

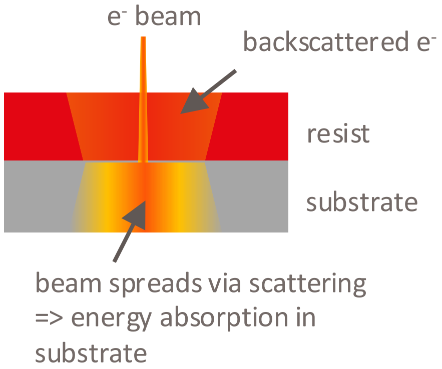
Progress: 389

Device SLC1325ACR05MTI (24410392)

Courtesy Swisslitho

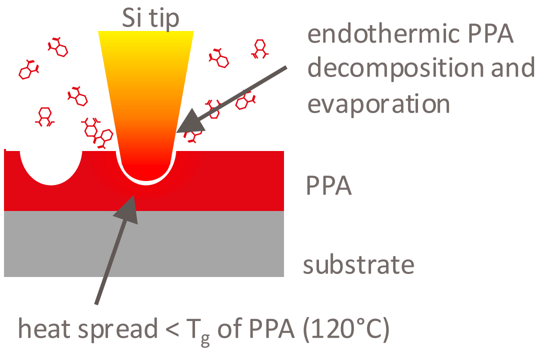
What makes t-SPL unique, specific w/r to EBL ?

Electron Beam Lithography



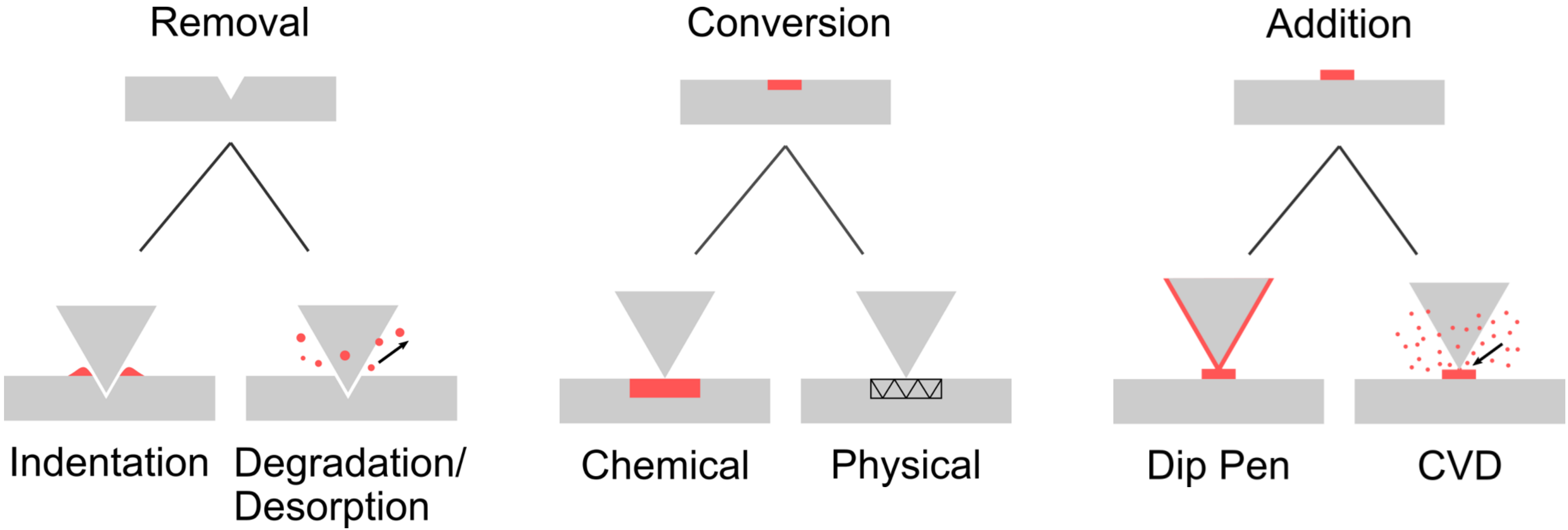
Possible damage of the substrate by lattice defects, vacancies or trapped charges
2D materials, organic molecules, dielectrics

T-SPL



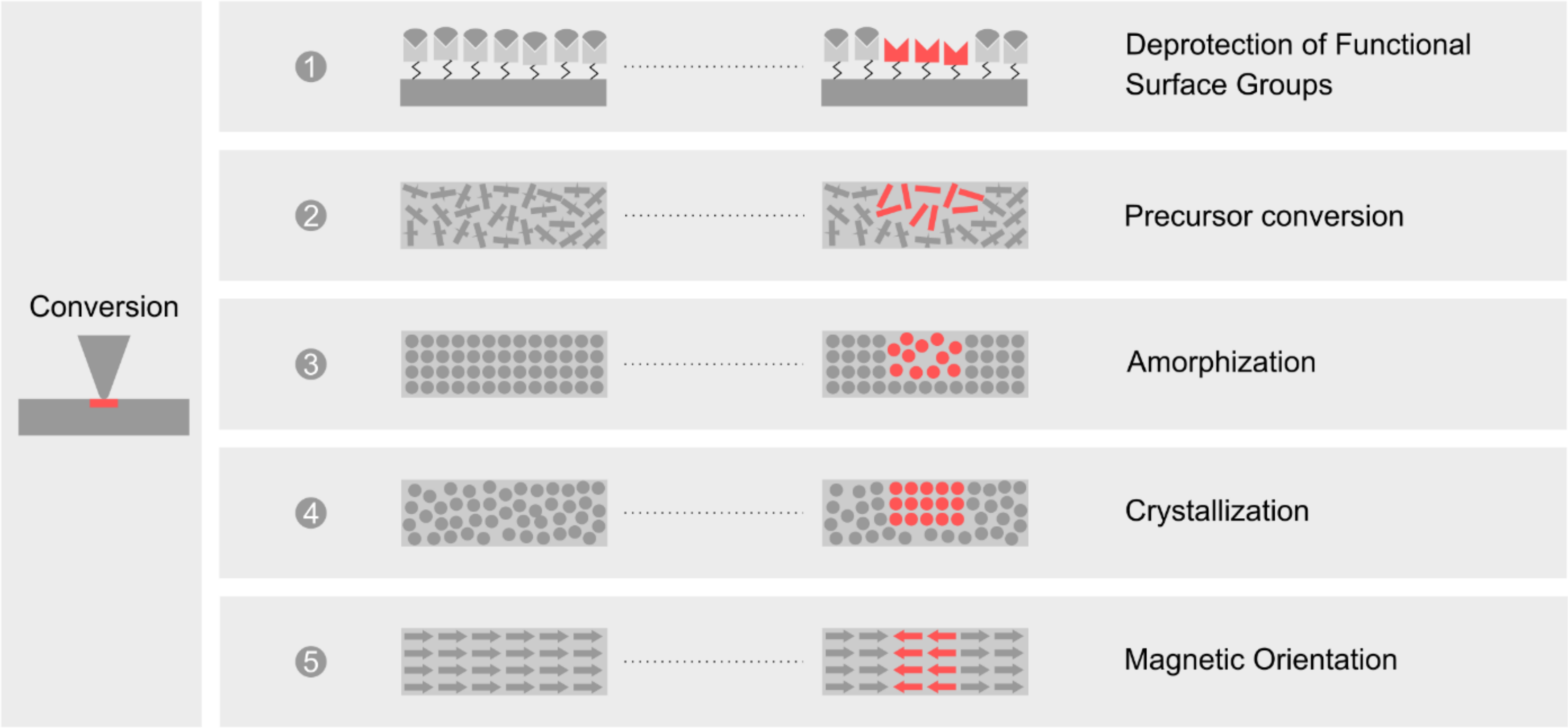
The substrate is hardly heated (in particular for substrates with a high heat conductivity or when a hard mask is applied under the PPA) and hence not damaged

T-SPL surface patterning



Thermal scanning probe lithography—a review
Samuel Tobias Howell, Anya Grushina, Felix Holzner & Juergen Brugger
Microsystems & Nanoengineering volume 6, Article number: 21 (2020)

Conversion



Conversion

① Deprotection of Functional Surface Groups

② Precursor conversion

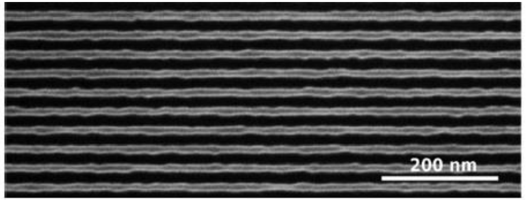
③ Amorphization

④ Crystallization

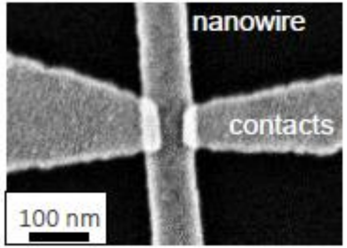
⑤ Magnetic Orientation

ST Howell et al. Microsystems & Nanoengineering, 2020

Typical t-SPL device fabrication

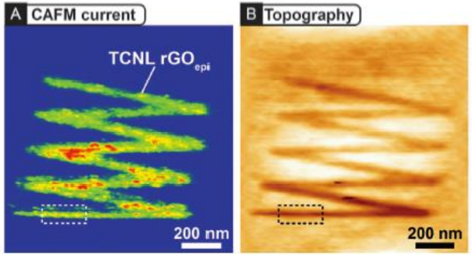


10-20 nm half-pitch into Si
Cho et al. ACS Nano 2017

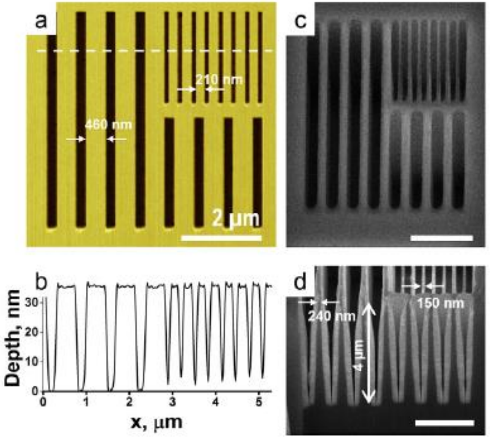


Side gates, contacts on nanowire

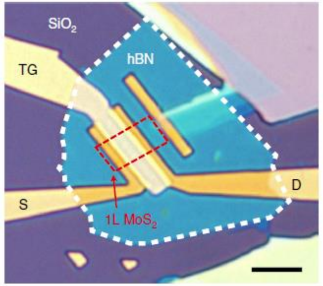
Lift-off
Wolf et al. J. Vac. Sci. Tech. B 2015,



Graphene, oxidation
Wei et al. *Science 2010, 328, 1373*



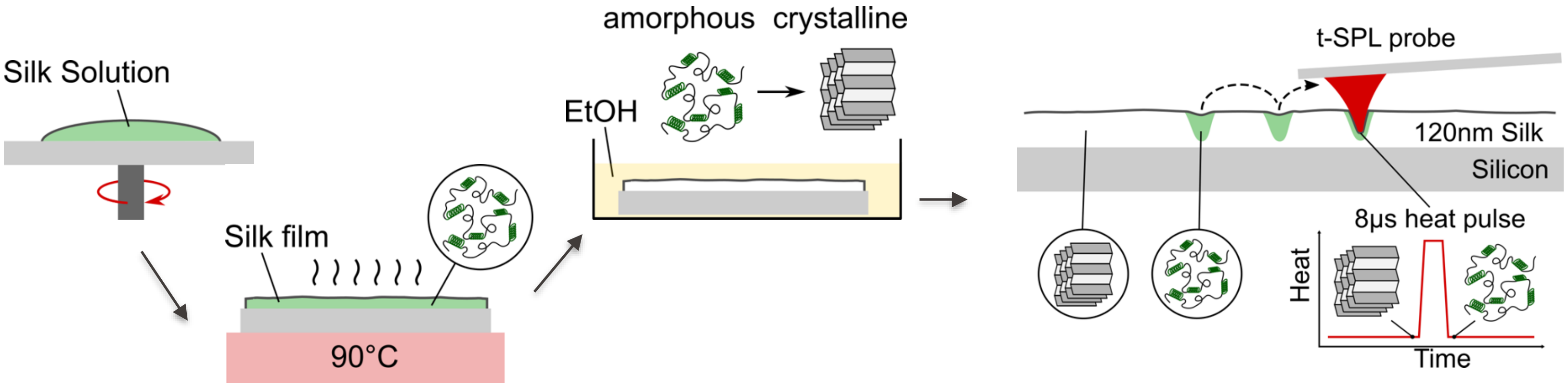
Dry Etching amplification, high aspect ratio
Lisunova et al. MEE 2017

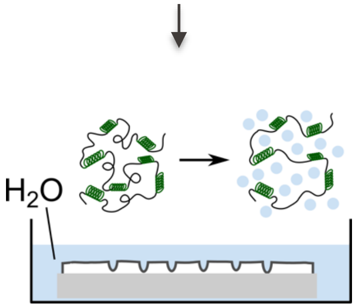


2D material electronics
Zheng et al. Nature Electronics 2019

Nanopatterning in silk using T-SPL

E_{silk} = 1-8 GPa ; 90% transparent

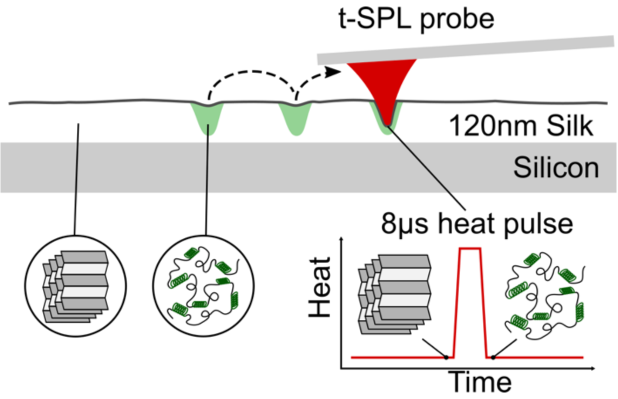


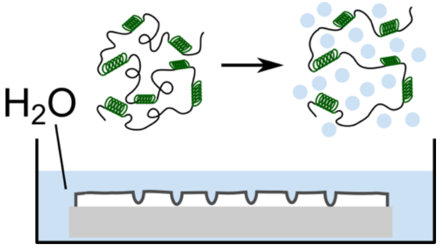


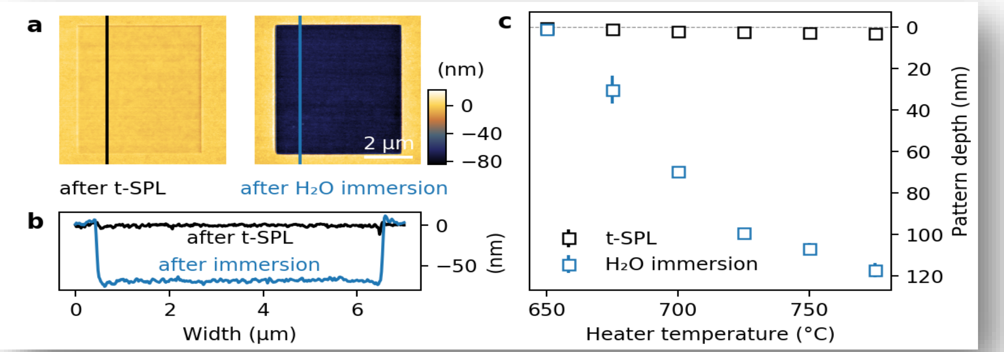
- Silk fibroin extracted from bombyx mori cocoons
- Spin-coating 4% solution (4000 RPM) → ~150 nm thin film
- Soft-baking at 90 °C to remove residual water
- Annealing by immersion in EtOH, MeOH or water steam
- Local heating with a t-SPL probe (400-500 °C for 8 µs)
- Development in water (10 sec)

S. Howell et al.,

Nanopatterning in silk using T-SPL



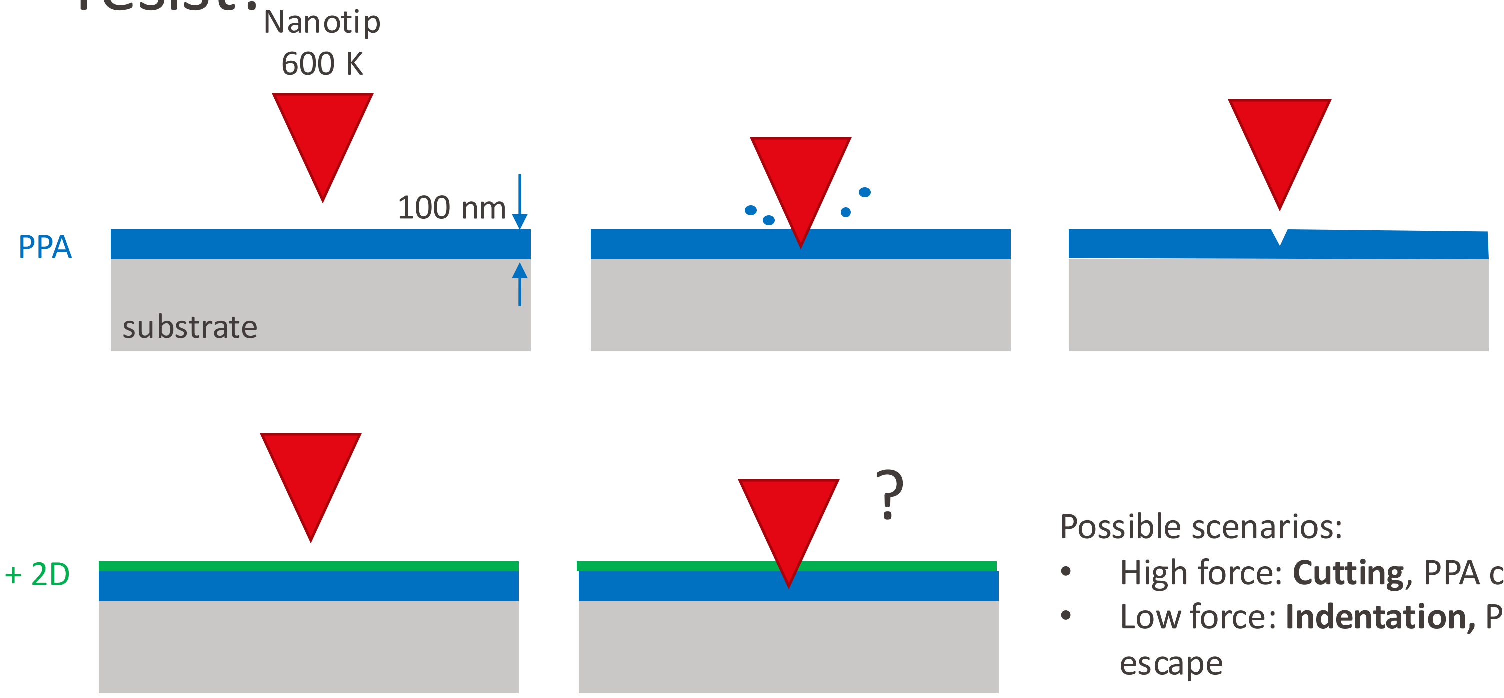




Silk as biomaterial has excellent properties for functional devices, sensors, actuators, medical implants.

S. Howell et al.,

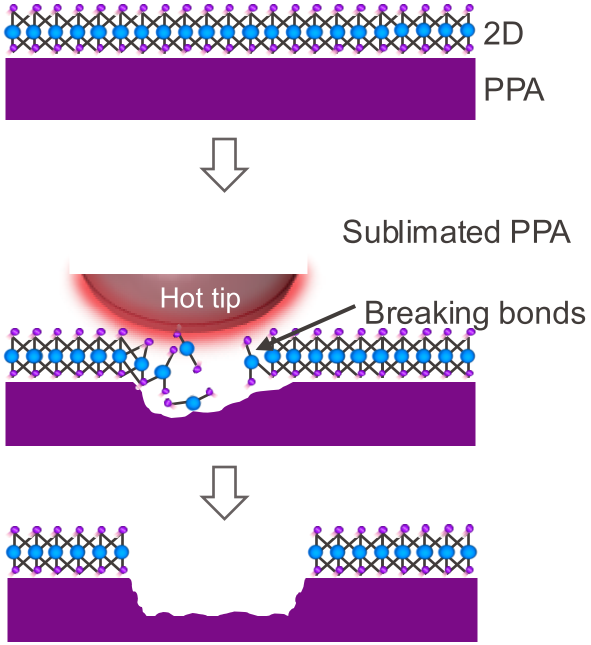
Gedankenexperiment: what happens if we add an atomically thin 2D material between hot tip and PPA resist?



Possible scenarios:

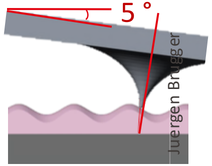
- High force: **Cutting**, PPA can escape
- Low force: **Indentation,** PPA cannot escape

Direct nanocutting of 2D materials



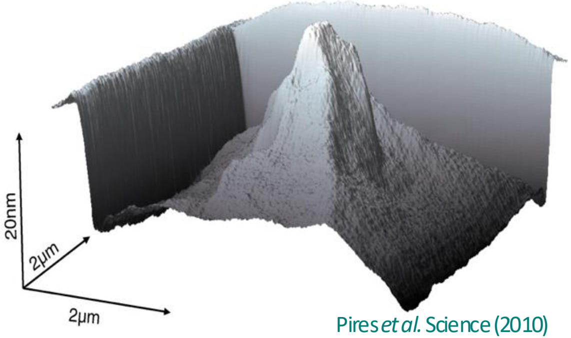
X. Liu et al. Advanced Materials (2020)

Grayscale capabilities by t-SPL



Strengths

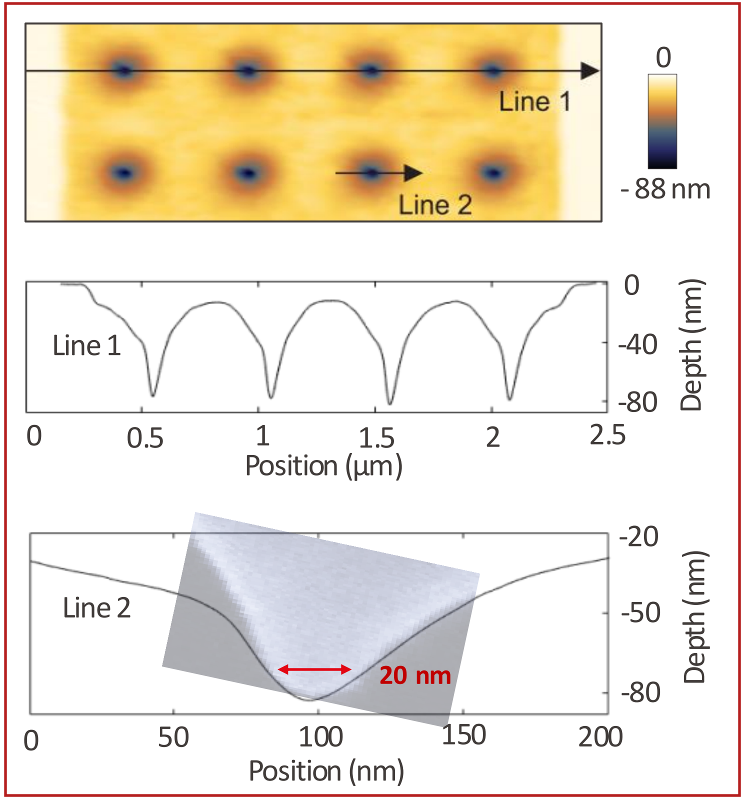
- Sub-1 nm vertical, <10 nm lateral resolution
- Dry resist, no wet development
- Charge-free patterning with heat stimulus
- Instantaneous imaging feedback → depth correction



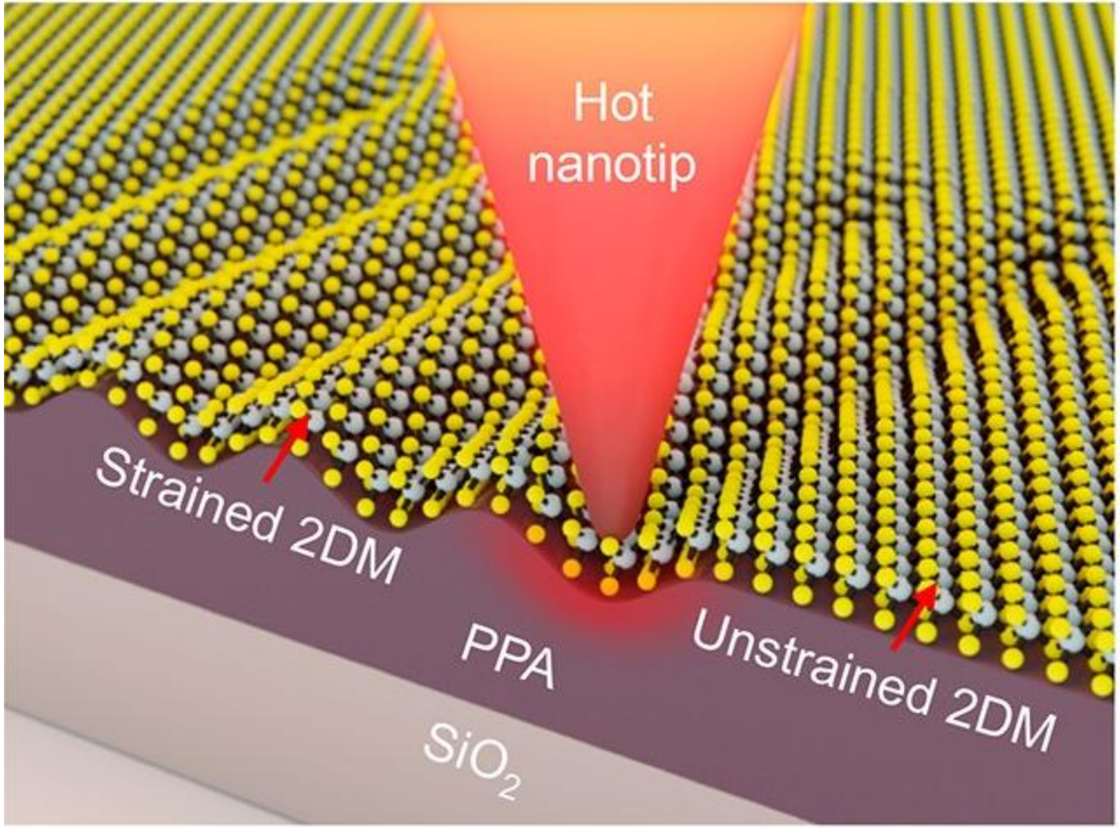
Pires *et al.* Science (2010)

Key challenges

- Limited depth and aspect ratio (tip geometry & cooling) →
- Tip dependent resolution (not always reproducible)
- Low throughput and scalability (mechanical movements)
- Conductive substrate limitation (electrostatic actuation)



Straining of 2D materials at nanoscale

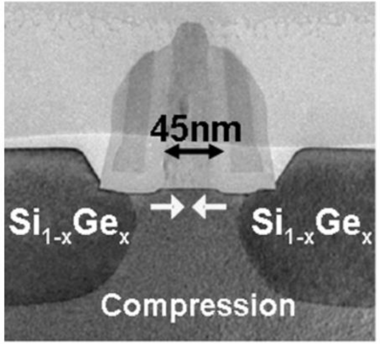


Xia Liu et al., *Nano Lett.* 2020

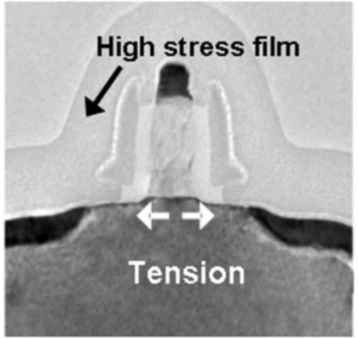
Strain-engineering

Strained silicon transistor

- Proven mobility booster in commercial Si FETs
- Modifies Si band structure → lowers scattering
- Common techniques:
  - Compressive (SiGe source/drain)
  - Tensile (SiGe mismatch or stressed SiN caps)



PMOS

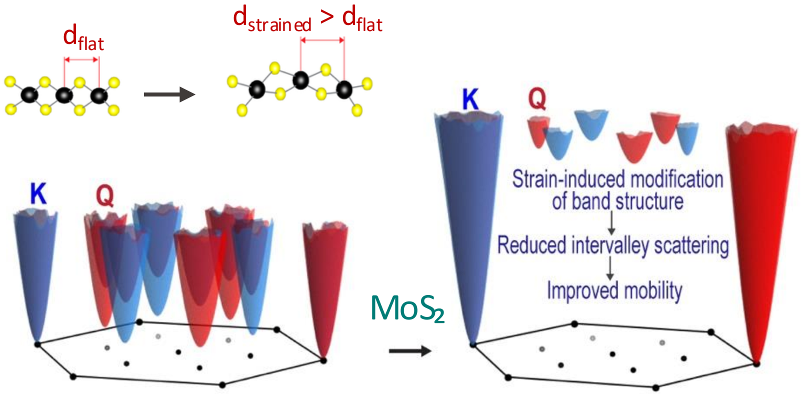


NMOS

Thompson *et al.* IEEE (2004)

Strained 2D semiconductor transistors

- Demonstrated mobility enhancement in 2D FETs
- Strain reduces electron–phonon scattering
- Still under development; no industry-standard process yet

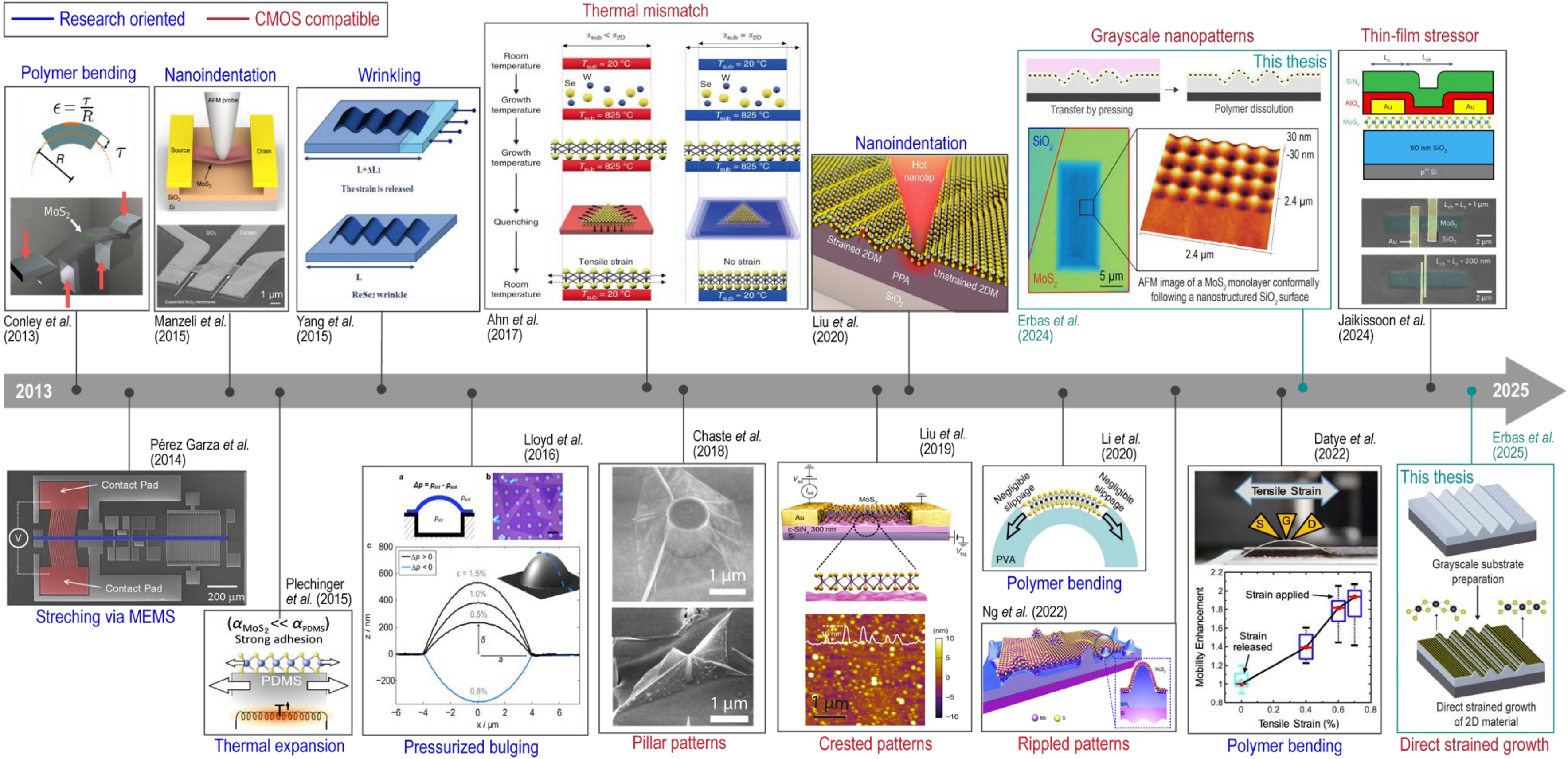


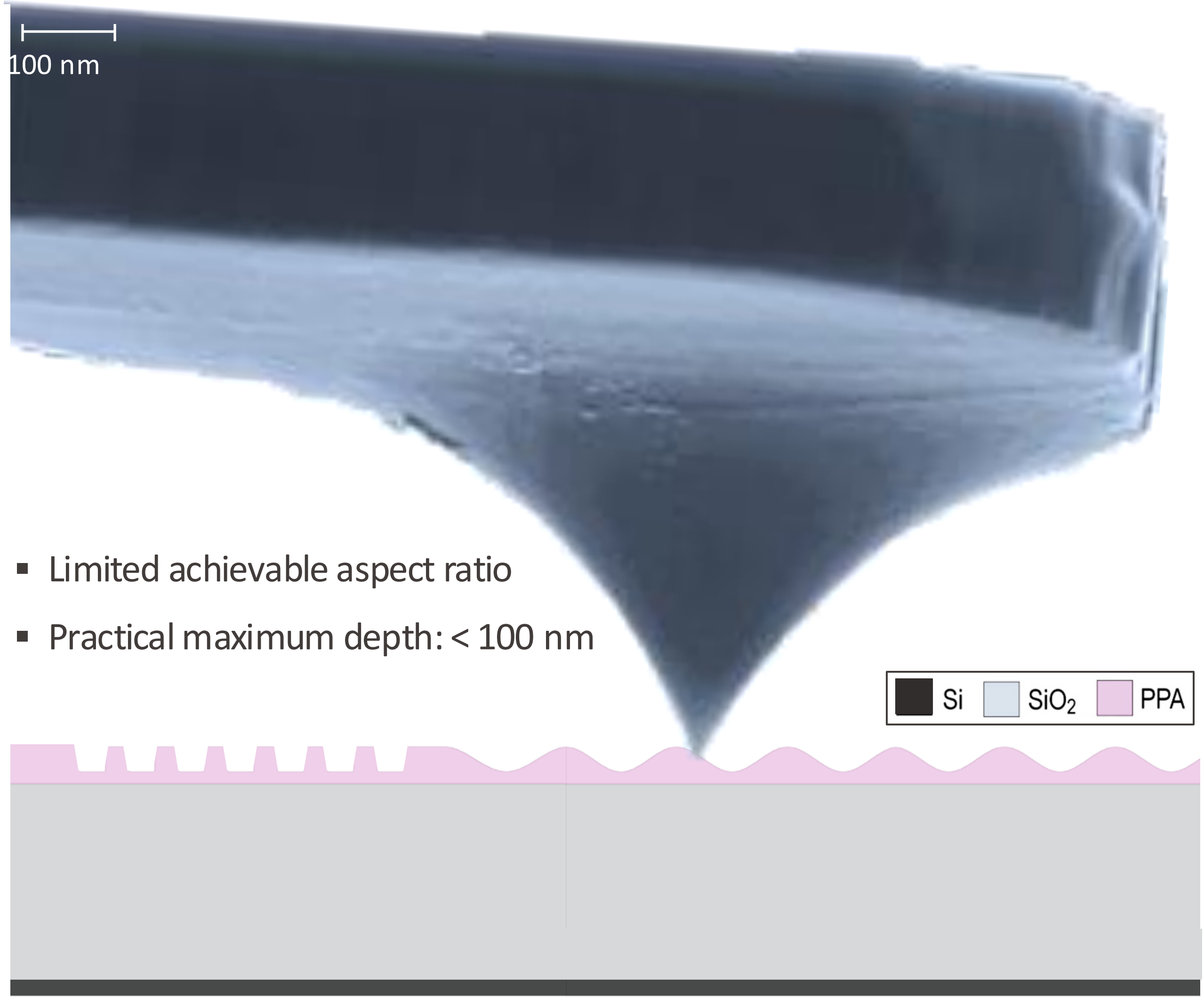
Liu *et al.* Nature Communications (2024)

2D material strain: state-of-the-art

Polymer bending/stretching; Mechanical displacement; Substrate/thin-film stress;

Pre-patterned substrates;

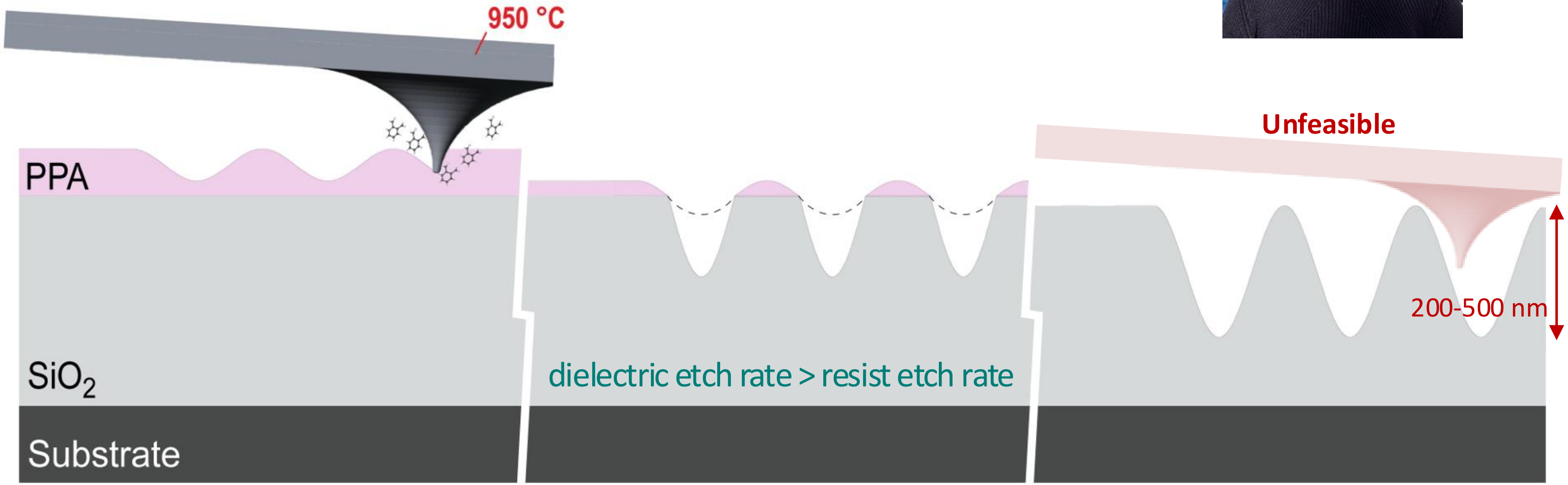




- Limited achievable aspect ratio
- Practical maximum depth: < 100 nm

Image drawn to scale

Solution: etch transfer

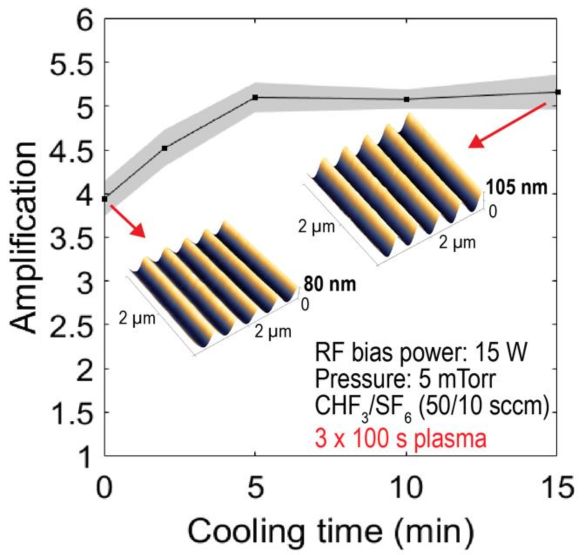


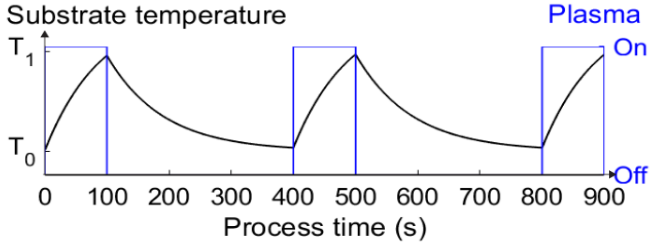
High resolution but shallow patterning on polymer via t-SPL → **Nanopattern depth amplification during etching** → **Deeper grayscale nanopatterns in hard materials**

Erbas *et al.* Microsystems & Nanoengineering (2024)

What is the trick? Cycled etching-cooling

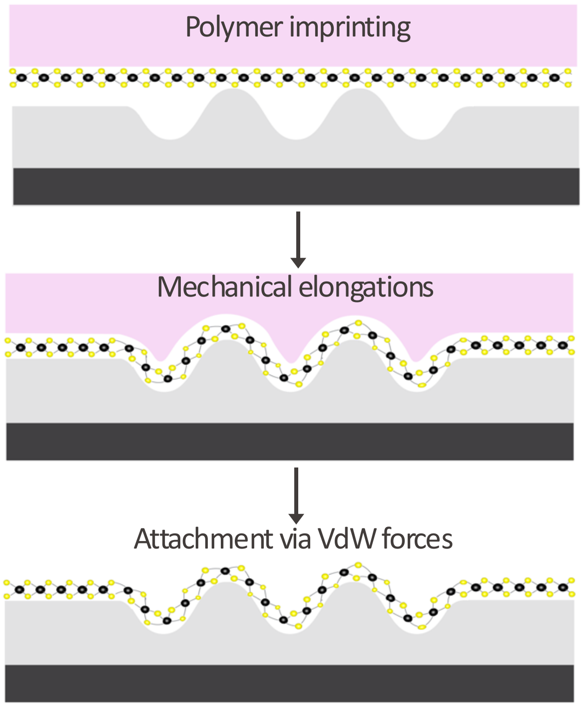
- Gas Composition: CHF_3 / SF_6
  - Smooth pattern transfer and high SiO_2 etch selectivity
- Flow Rate: 50/10 sccm
  - Optimal balance between polymerization and etching
- Chamber Pressure: 5 mTorr
  - Optimal physical-chemical etching dynamics
- RF Bias Power: 12–80 W
  - Controlled vertical ion bombardment
  - Depth amplification from 1 to 10×
- Cycled etching-cooling transfer
  - Prevent substrate overheating
  - Enhanced sidewall protection
  - Higher and repeatable depth amplification





Erbas *et al.* Microsystems & Nanoengineering (2024)

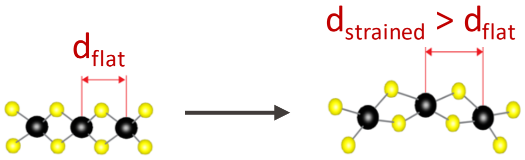
Strain engineering in 2D material by mechanical deformation

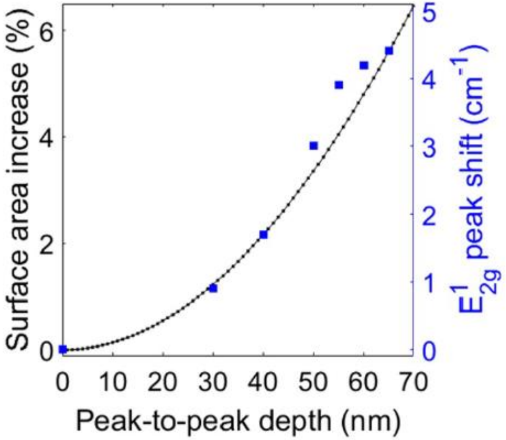


Polymer imprinting

Mechanical elongations

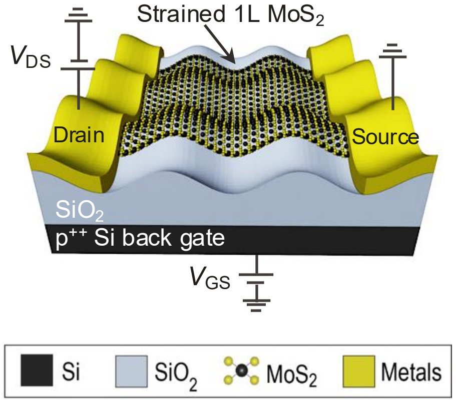
Attachment via VdW forces

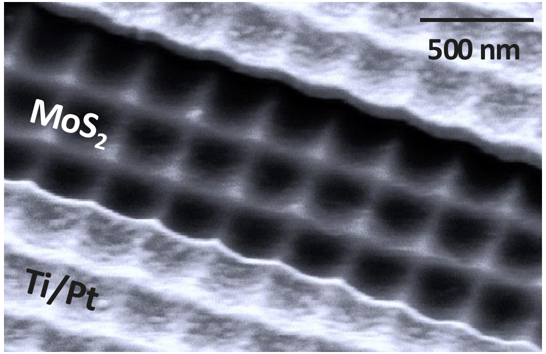


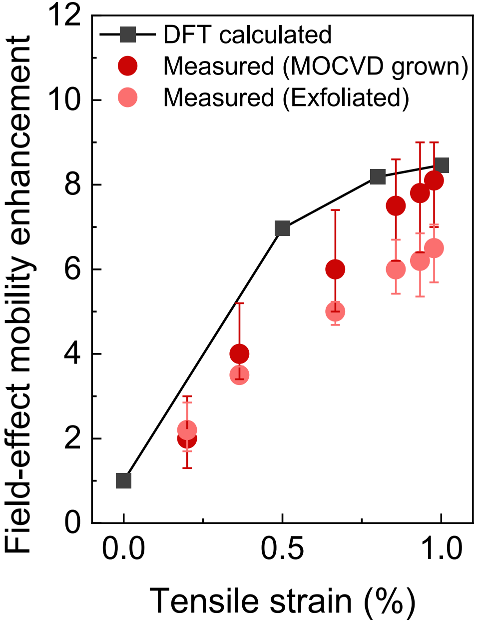


Liu, Erbas et al. Nature Communications (2024)

Engineered mobility in strained MoS_2 FET



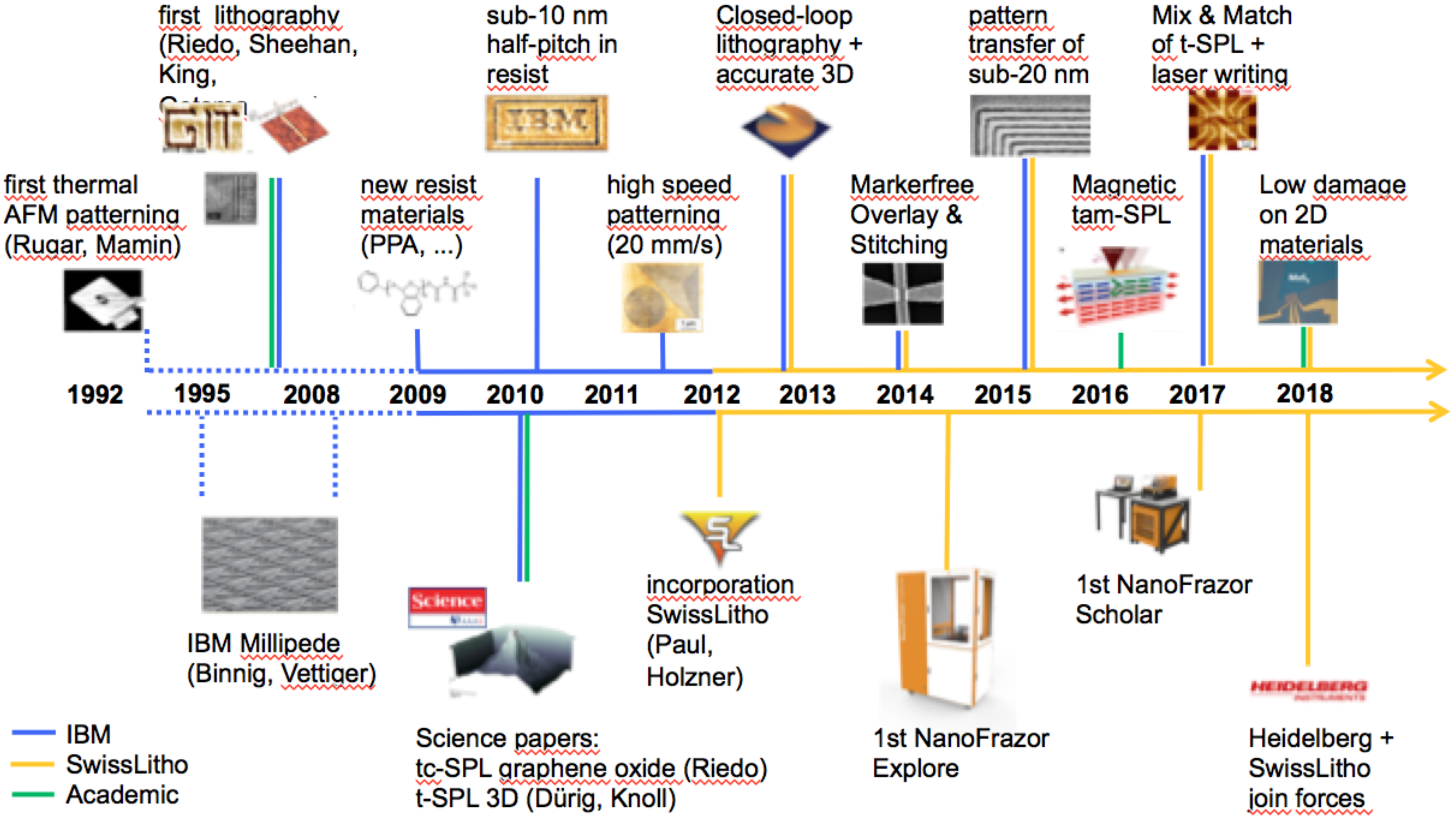




- **Strained 2D FETs** with grayscale-patterned oxide
- FET mobilities reaching **~185 cm^2/Vs** under ~1% tensile strain
- **Up to 8x** improvement compared to flat devices
- **Strain level** controlled via grayscale nanopattern depth
- Consistent experimental results with DFT predictions

Liu, Erbas et al. Nature Communications (2024)

30 years of t-SPL .. and counting



first thermal AFM patterning (Rugar, Mamin)

first lithography (Riedo, Sheehan, King,

new resist materials (PPA, ...)

sub-10 nm half-pitch in resist

high speed patterning (20 mm/s)

Closed-loop lithography + accurate 3D

Markerfree Overlay & Stitching

pattern transfer of sub-20 nm

Magnetic tam-SPL

Mix & Match of t-SPL + laser writing

Low damage on 2D materials

1992 1995 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018

IBM Millipede (Binnig, Vettiger)

Science papers:
tc-SPL graphene oxide (Riedo)
t-SPL 3D (Dürig, Knoll)

incorporation SwissLitho (Paul, Holzner)

1st NanoFrazor Explore

1st NanoFrazor Scholar

Heidelberg + SwissLitho join forces

🟦 IBM
🟨 SwissLitho
🟩 Academic