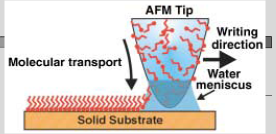
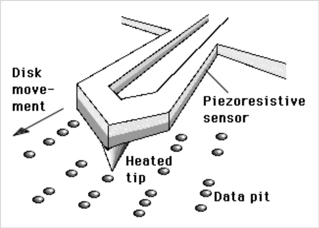
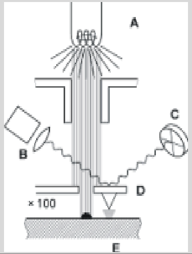
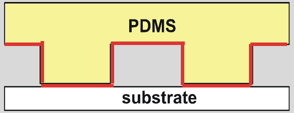
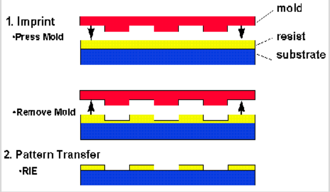
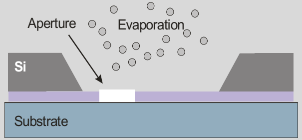
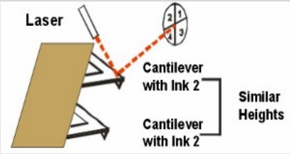
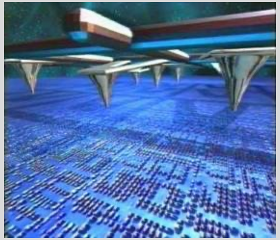
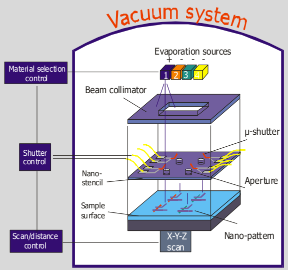
<table>
<tr><th></th><th>Molecule Delivery
Wet, soft-contact,
100 nm scale</th><th>Thermo-mechanical
Nano-imprint, embossing,
hard contact, 10 nm scale</th><th>Local Deposition
Stencil, vacuum, no contact
10-100 nm scale</th></tr>
<tr><td>Single &
Scanning
de novo</td><td>DipPen
NADIS

</td><td>Heated
AFM

</td><td>AFM
Nanostencil

</td></tr>
<tr><td>Parallel &
Static
Replication</td><td>Soft-
litho-
graphy

</td><td>NIL

</td><td>Membrane
Nano-
stencil

</td></tr>
<tr><td>Parallel &
Scanning
Adaptive
mass-
production</td><td>Parallel
NADIS

</td><td>Millipede
</td><td>Smart
Stencil

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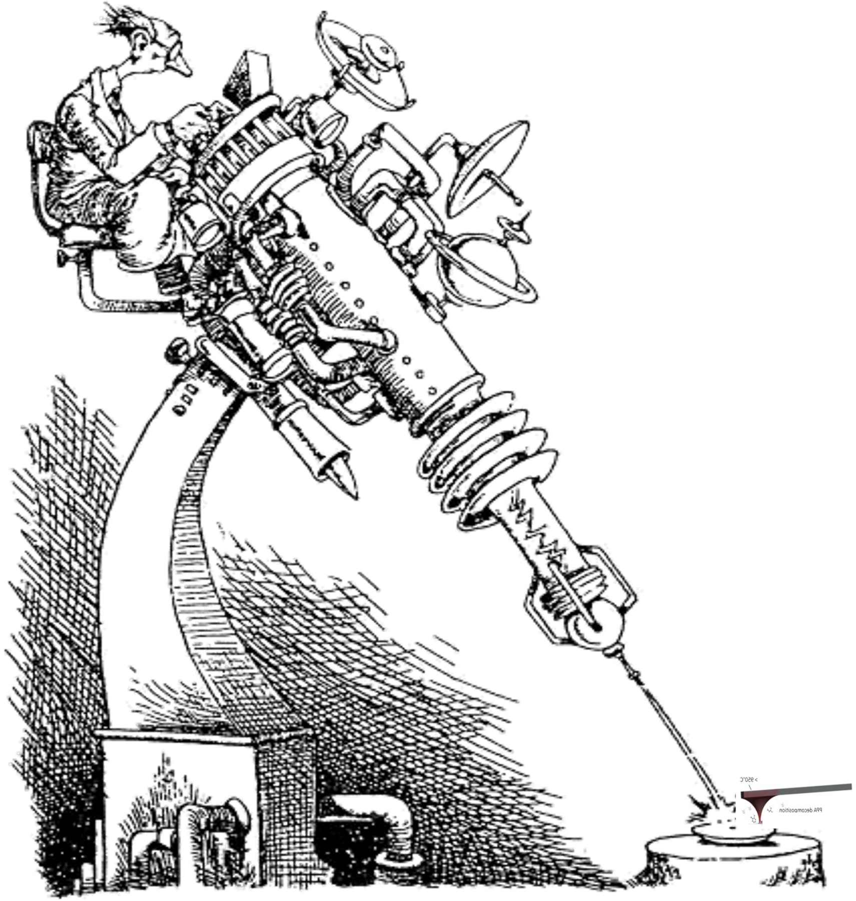


Thermal Scanning Probe Lithography

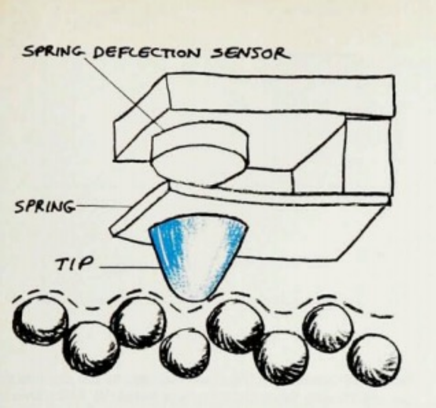
Patterning with heat only

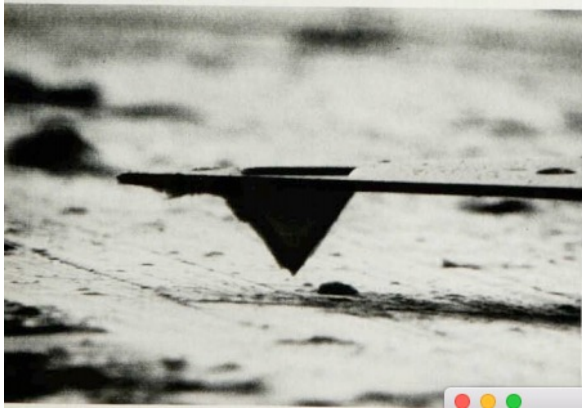
ATOMIC FORCE MICROSCOPY

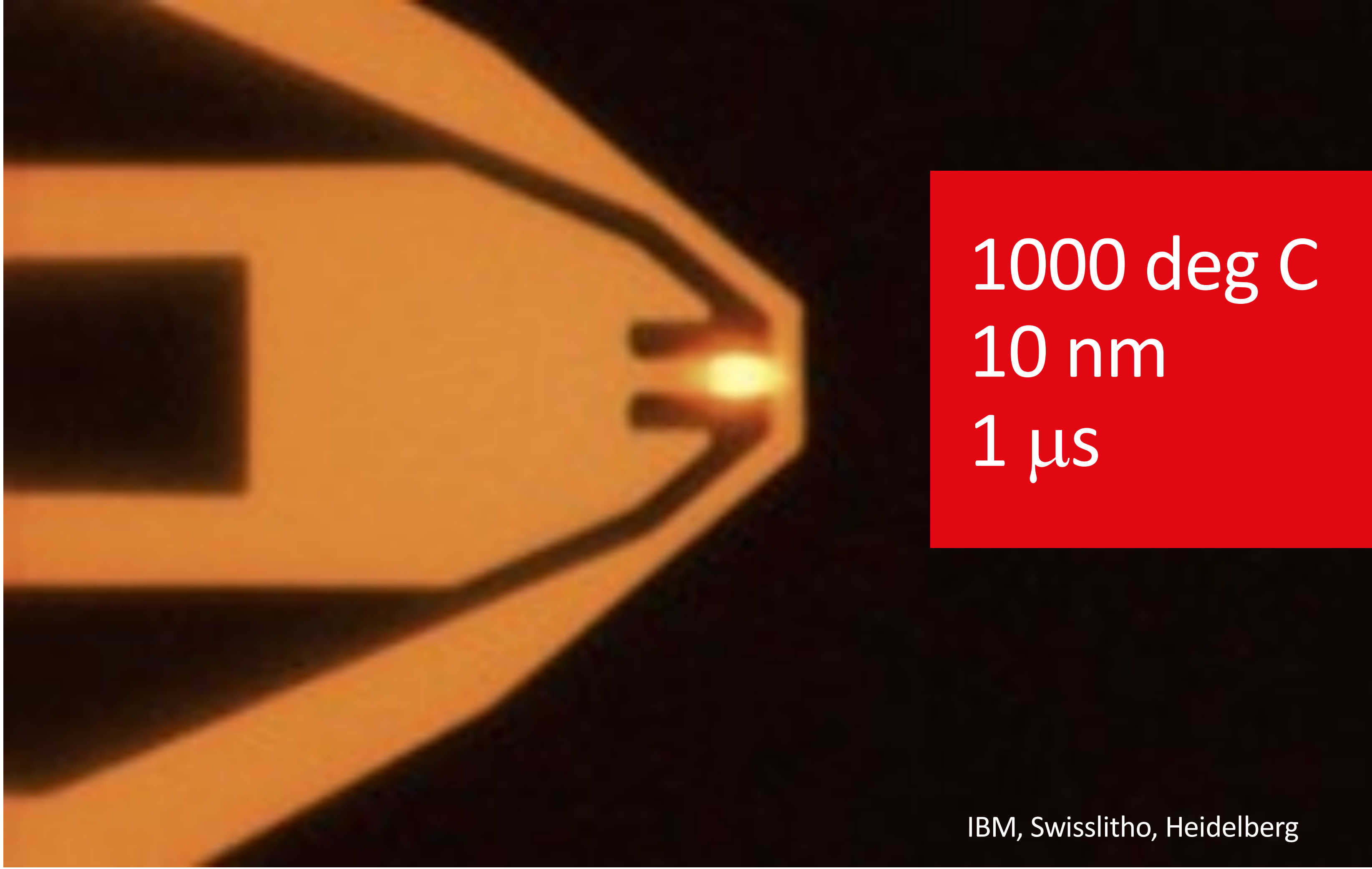
It is surprisingly easy to make a cantilever with a spring constant weaker than the equivalent spring between atoms, allowing a sharp tip to image both conducting and nonconducting samples at atomic resolution.

Daniel Rugar and Paul Hansma

1990 American Institute of Physics
PHYSICS TODAY OCTOBER 1990





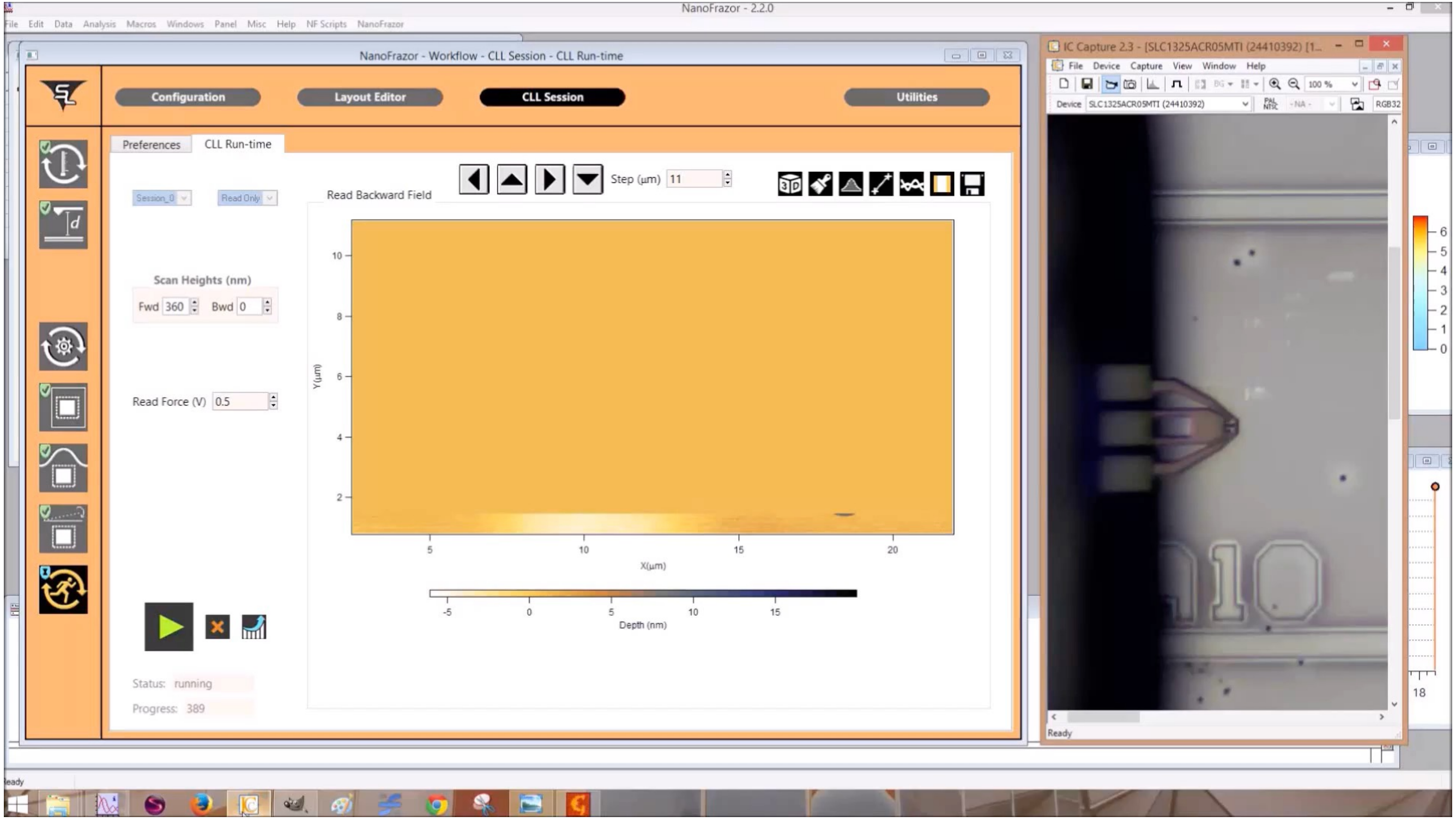


1000 deg C
10 nm
1 µs

IBM, Swisslitho, Heidelberg

École
polytechnique
fédérale
de Lausanne

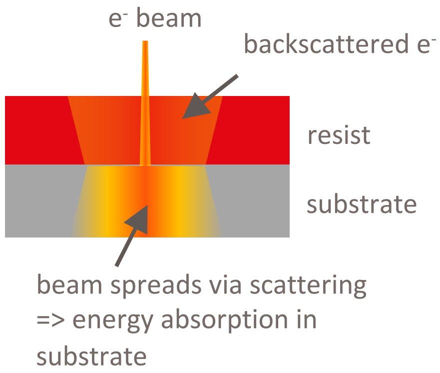
Modern t-SPL system (closed loop)



Courtesy Swisslitho

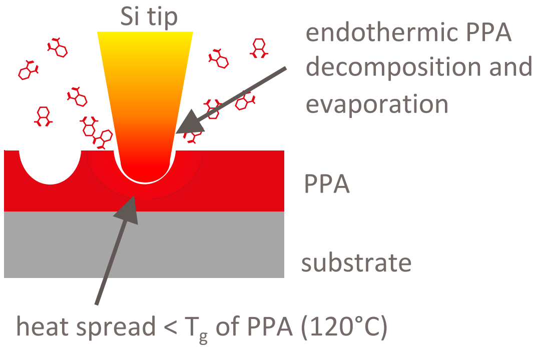
What makes t-SPL unique, specific w/r to EBL ?

Electron Beam Lithography



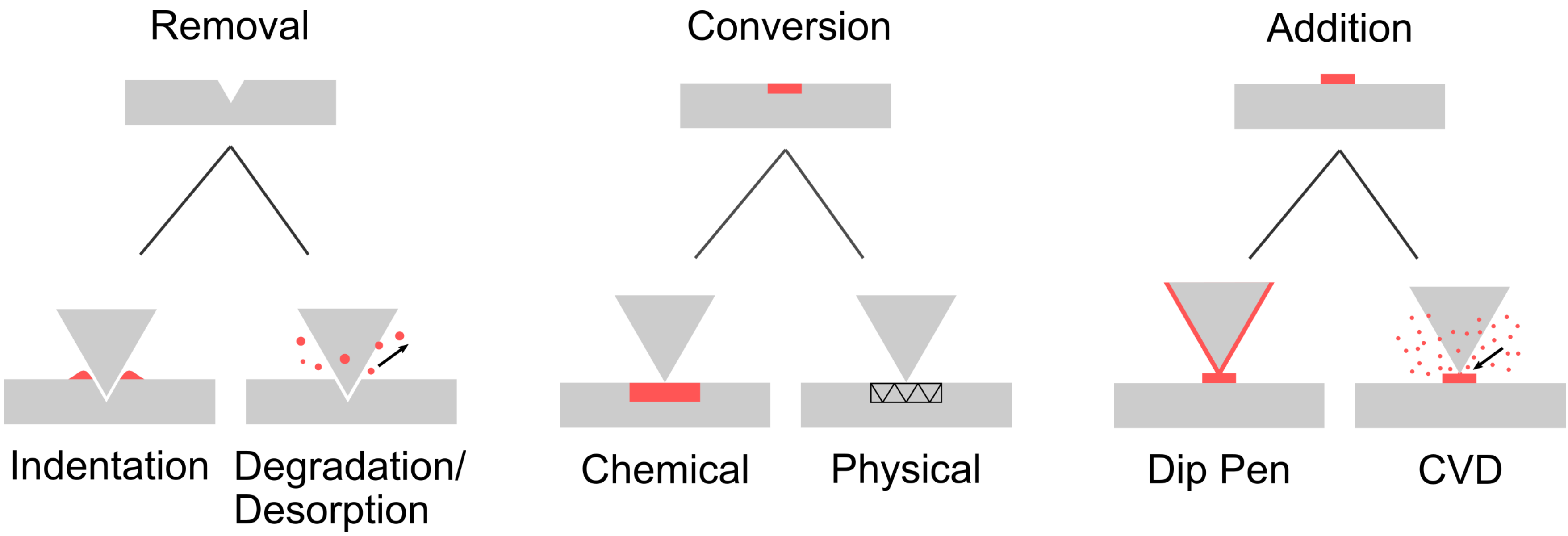
Possible damage of the substrate by lattice defects, vacancies or trapped charges
2D materials, organic molecules, dielectrics

T-SPL



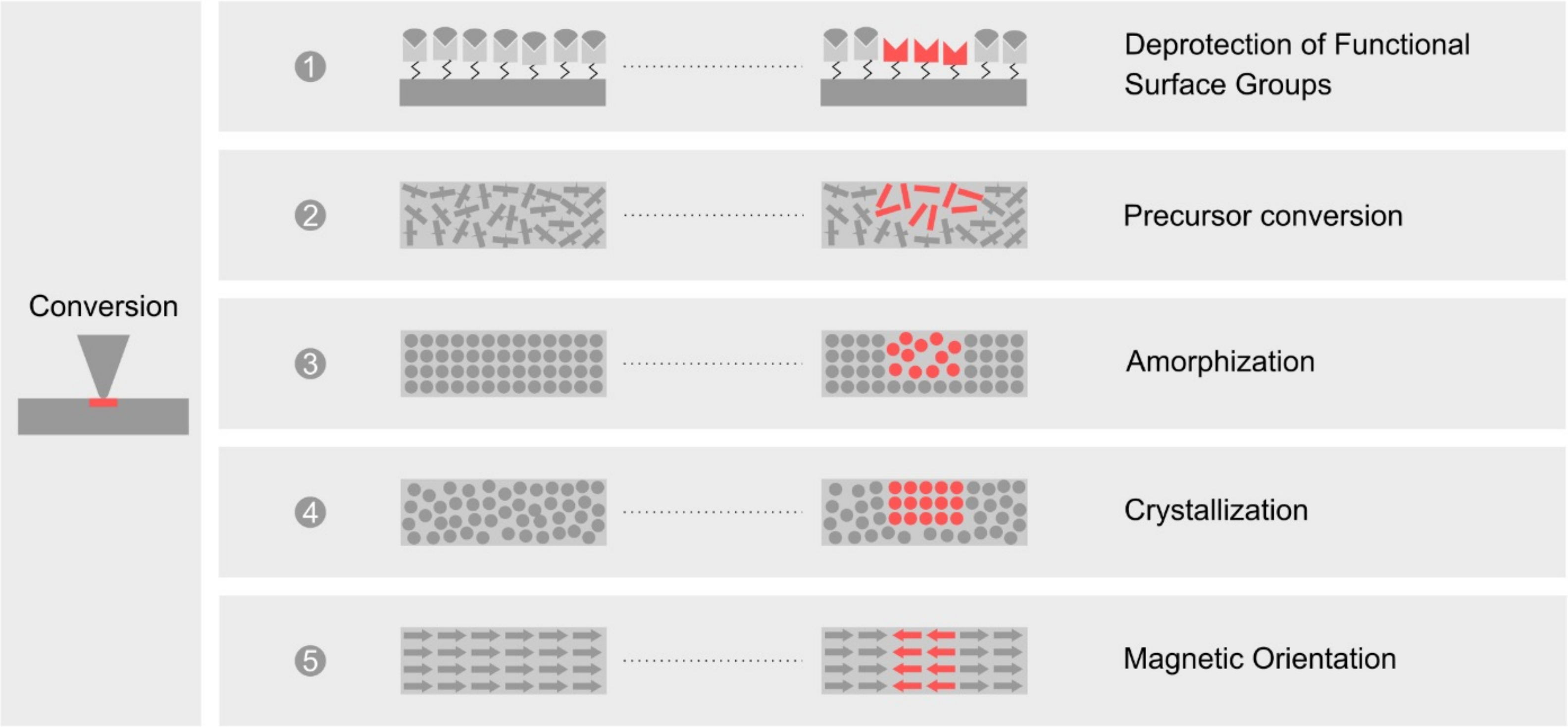
The substrate is hardly heated (in particular for substrates with a high heat conductivity or when a hard mask is applied under the PPA) and hence not damaged

T-SPL surface patterning



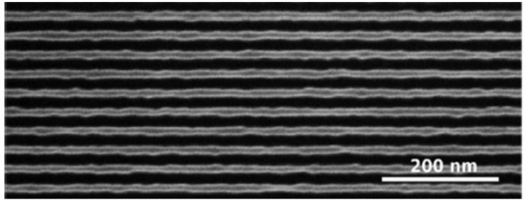
Thermal scanning probe lithography—a review
Samuel Tobias Howell, Anya Grushina, Felix Holzner & Juergen Brugger
Microsystems & Nanoengineering volume 6, Article number: 21 (2020)

Conversion

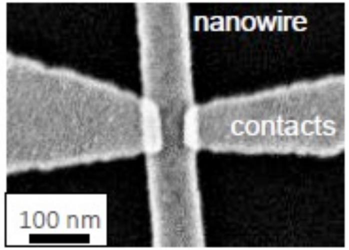


ST Howell et al. Microsystems & Nanoengineering, 2020

Typical t-SPL device fabrication

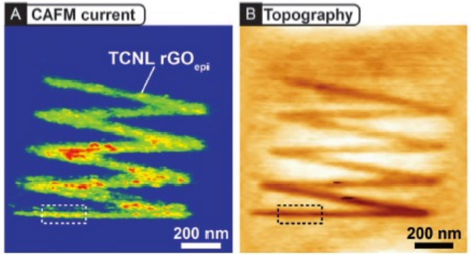


10-20 nm half-pitch into Si
Cho et al. ACS Nano 2017

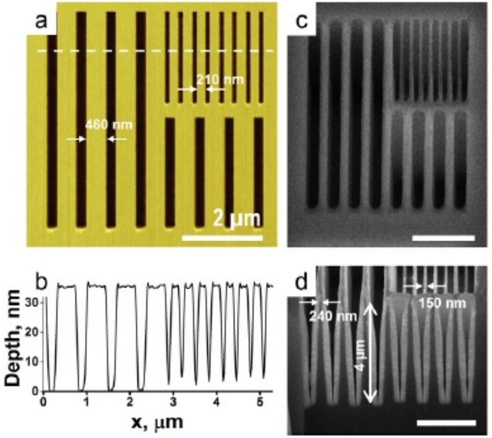


Side gates, contacts on nanowire

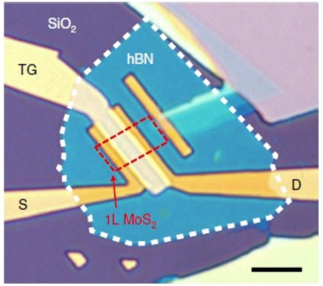
Lift-off
Wolf et al. J. Vac. Sci. Tech. B 2015,



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



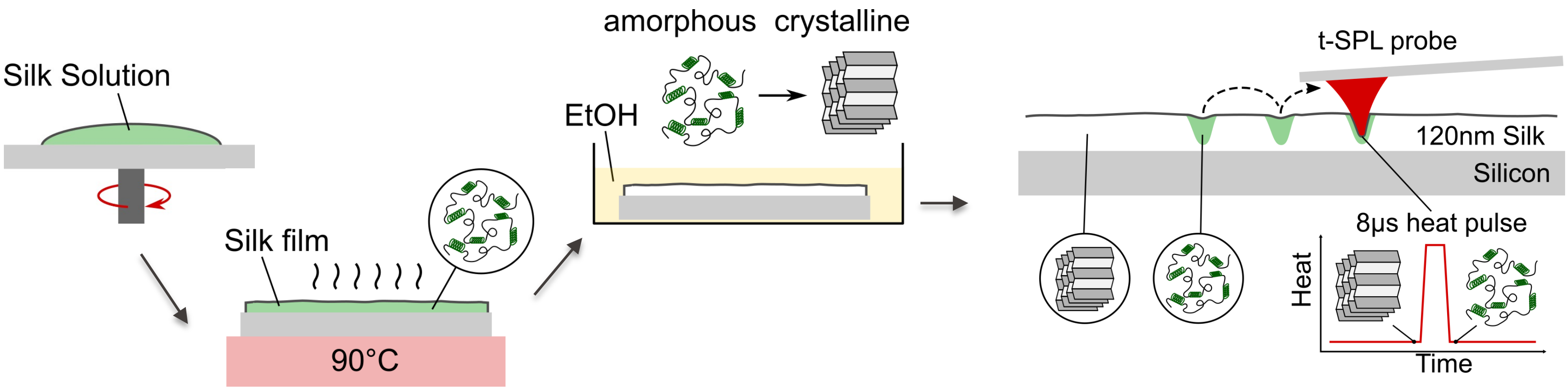
Dry Etching amplification, high aspect ratio
Lisunova et al. MEE 2017



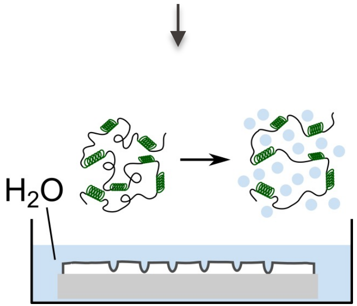
2D material electronics
Zheng et al. Nature Electronics 2019

Nanopatterning in silk using T-SPL

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



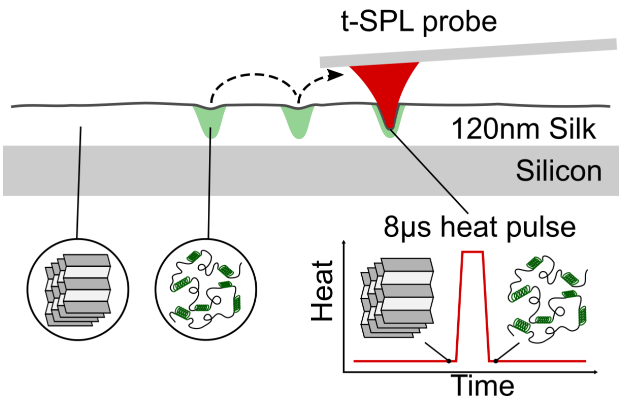
- Silk fibroin extracted from bombyx mori cocoons
- Spin-coating 4% solution (4000 RPM) → ~150 nm thin film
- Soft-baking at 90 °C to remove residual water
- Annealing by immersion in EtOH, MeOH or water steam
- Local heating with a t-SPL probe (400-500 °C for 8 µs)
- Development in water (10 sec)

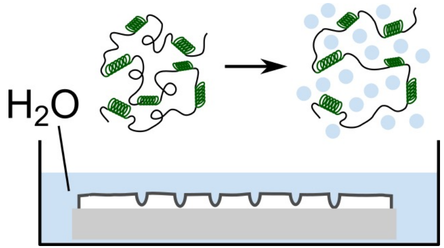


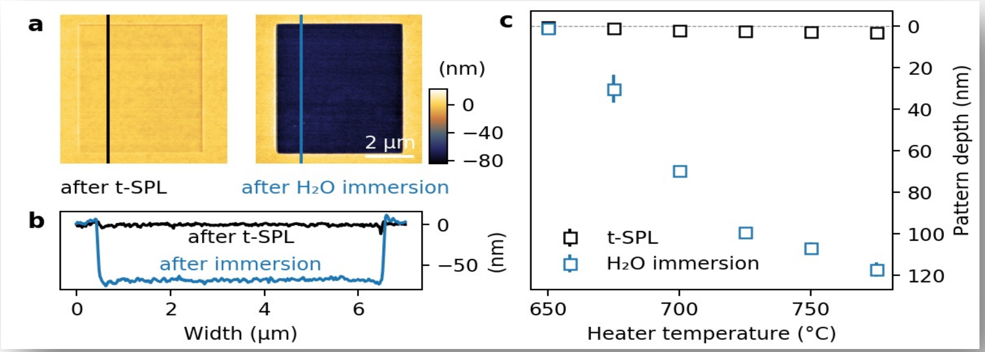
S. Howell et al., (in prep)

EPFL

Nanopatterning in silk using T-SPL



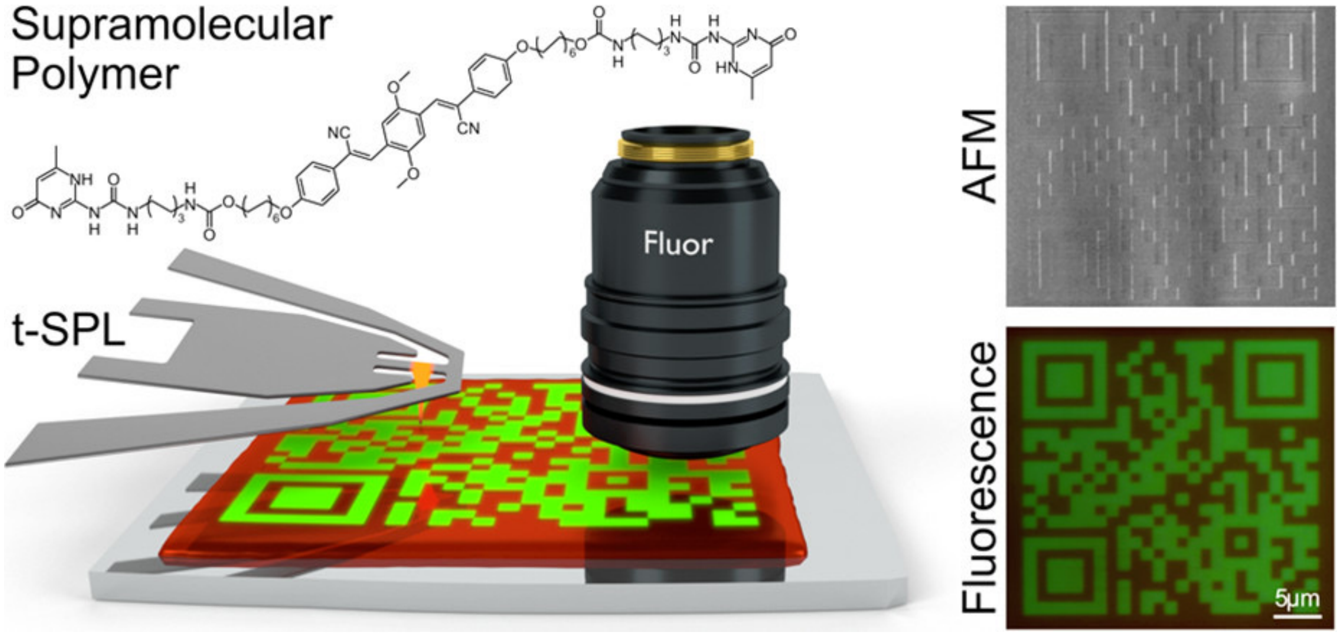




Silk as biomaterial has excellent properties for functional devices, sensors, actuators, medical implants.

S. Howell et al., (in prep)

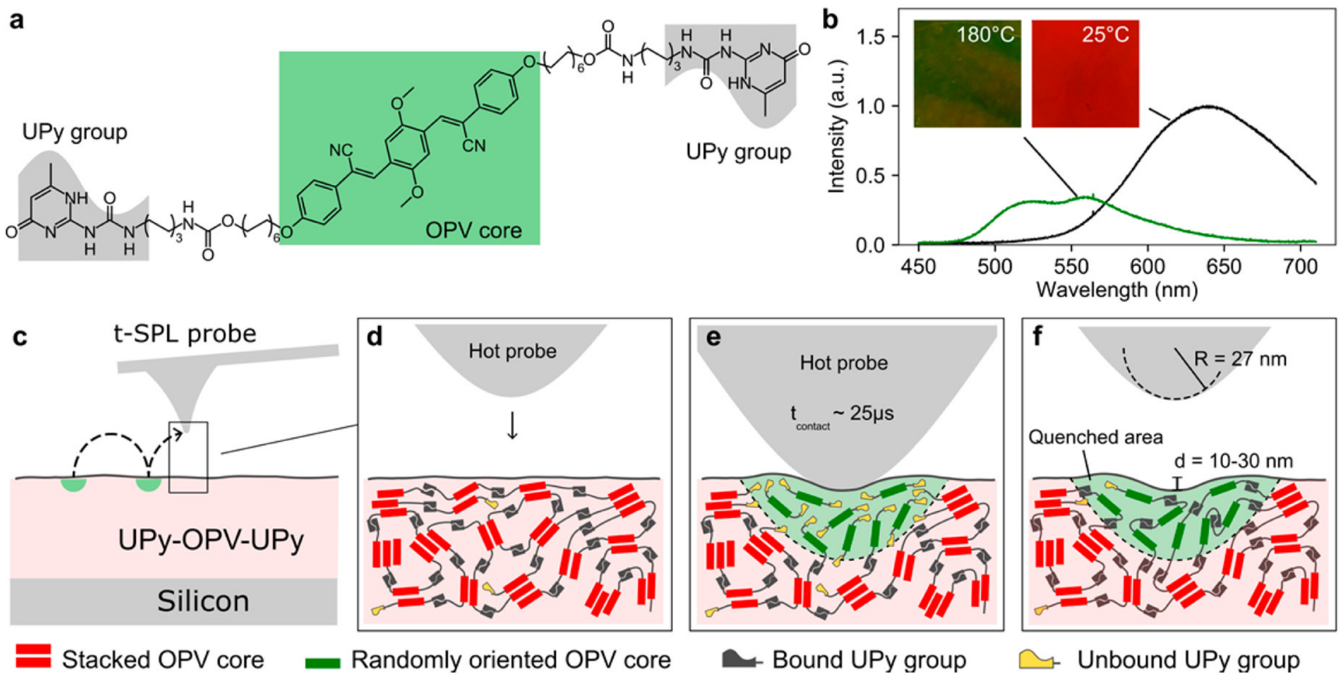
T-SPL on stimuli-responsive, thermochromic film



With Adolphe Merkle Institute Fribourg, Switzerland

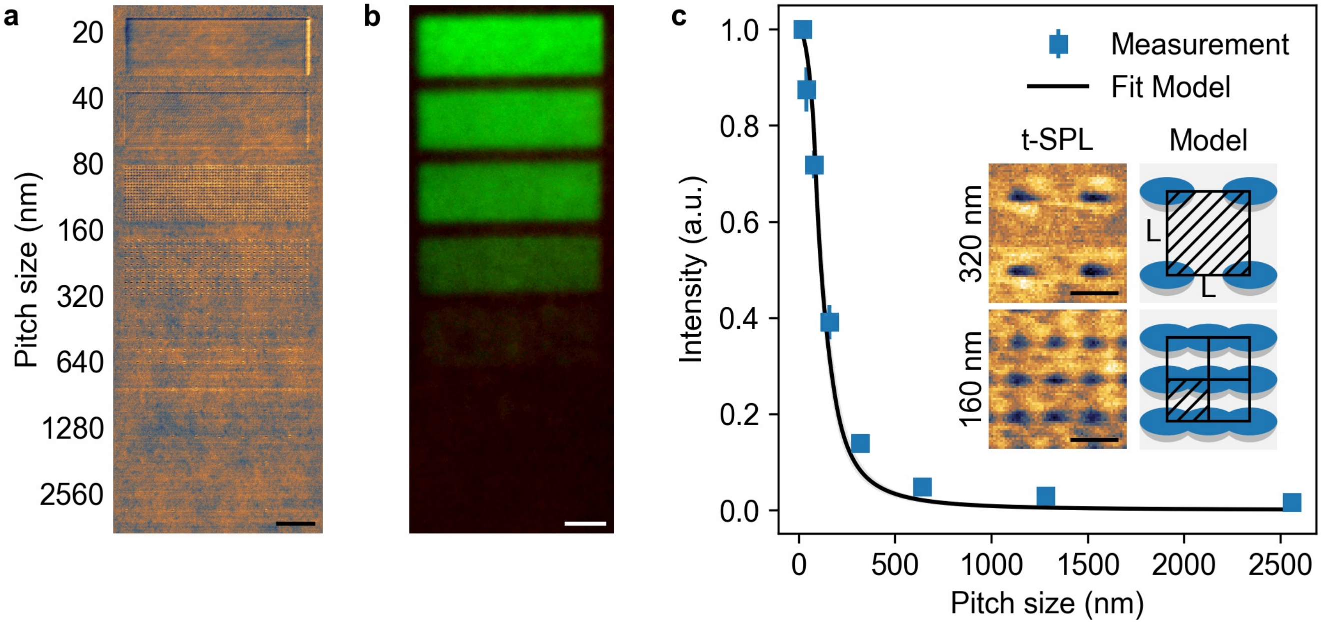
S. Zimmermann et al. ACS AMI (2017)

T-SPL on stimuli-responsive, thermochromic film



S. Zimmermann et al. ACS AMI (2017)

T-SPL on stimuli-responsive, thermochromic film



S. Zimmermann et al. ACS AMI (2017)

Shift from red to green fluorescence when heated

.

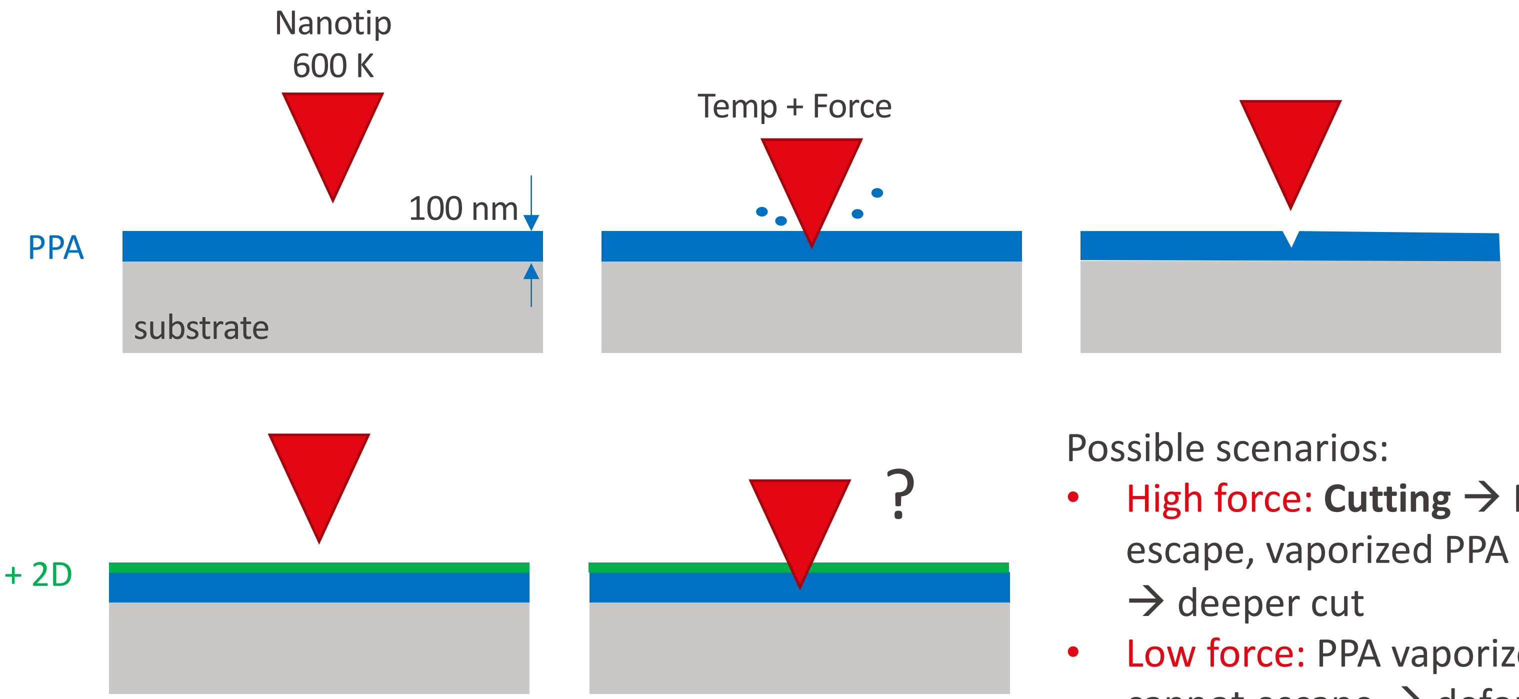
.

.

Kinetic trapping when cooled down fast (heater switched off)

With Adolphe Merkle Institute, Fribourg, Switzerland

Gedankenexperiment

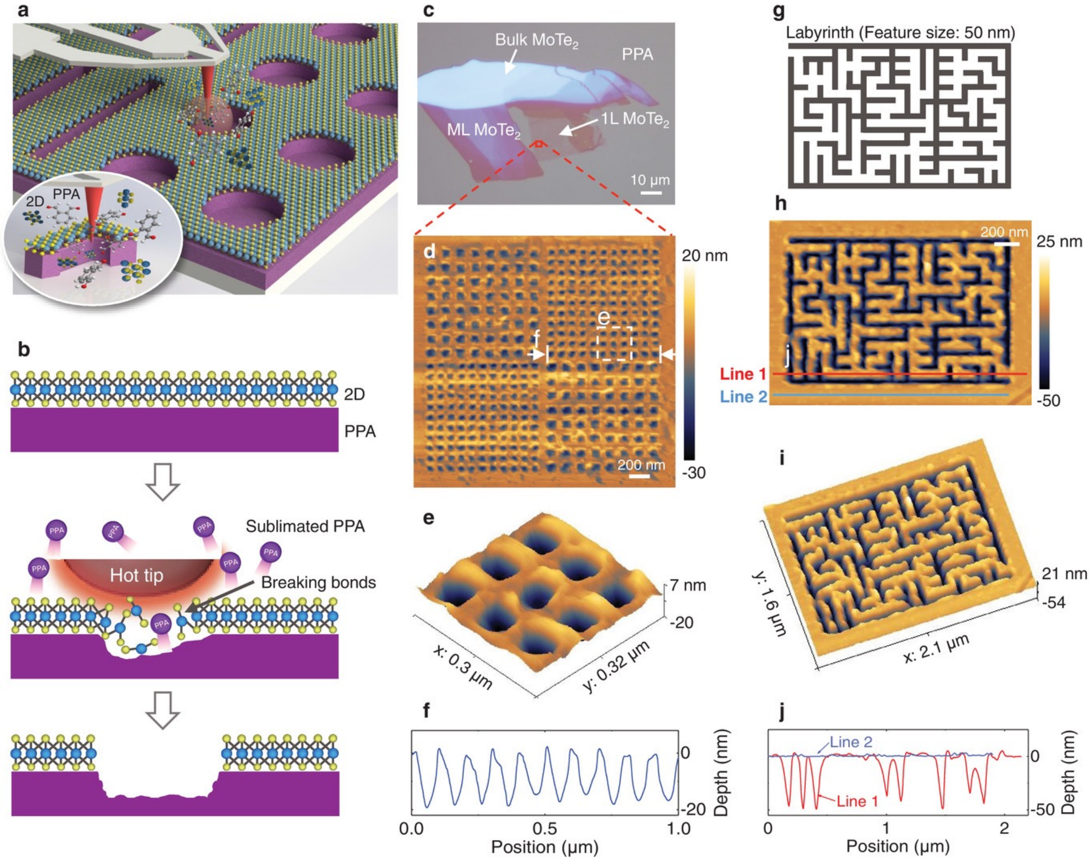


Possible scenarios:

- High force: **Cutting** → PPA can escape, vaporized PPA can escape → deeper cut
- Low force: PPA vaporizes but cannot escape → deformation → fast cooling → **Permanent Indentation**

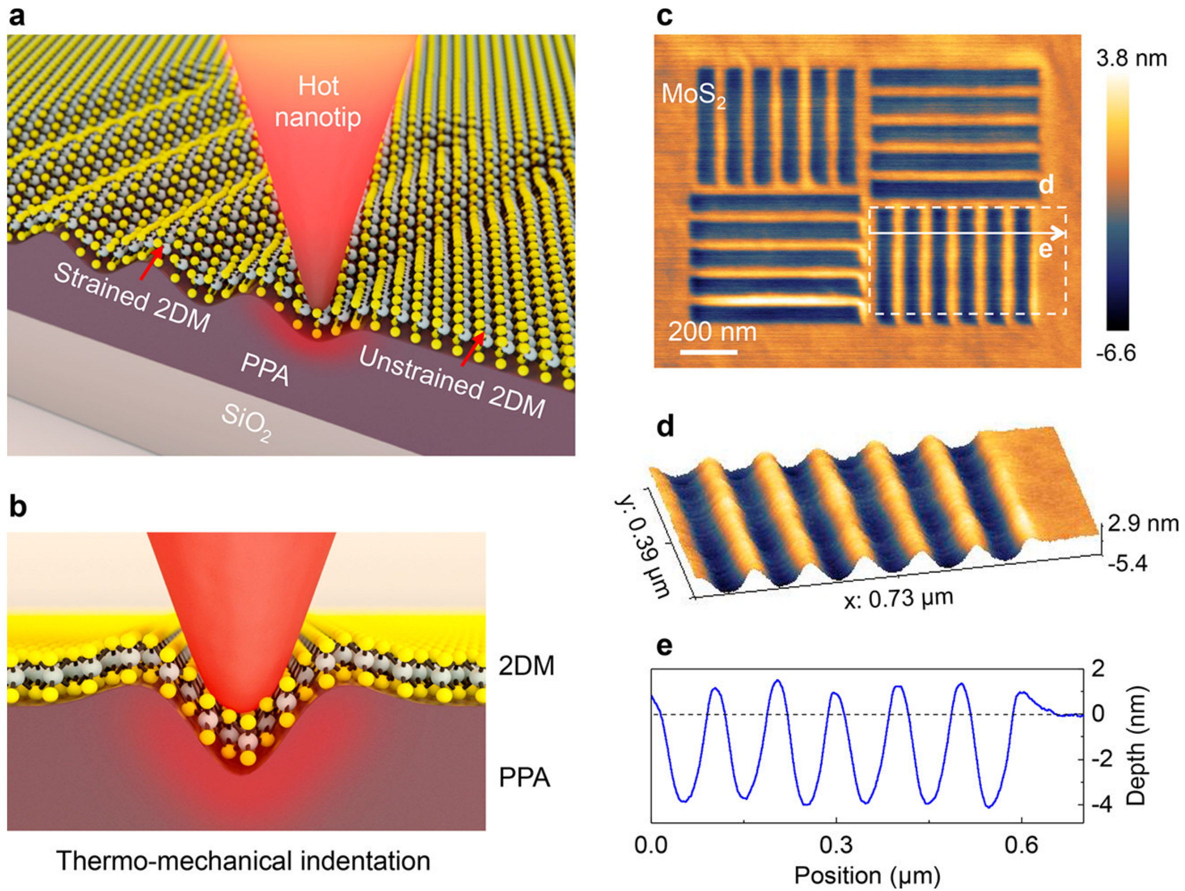
PPA: Polyphthalamide (thermal resist)
2D: ML of Graphene, MoS_2

Direct nanocutting of 2D materials



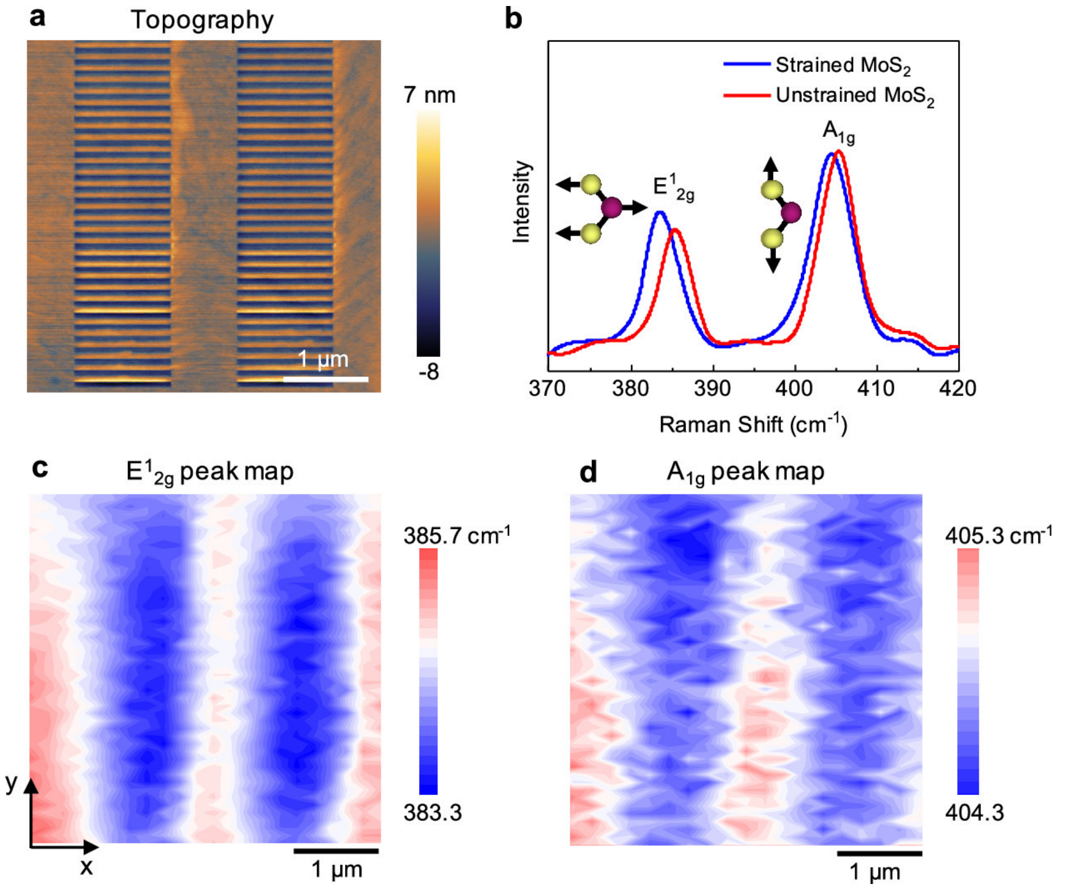
X. Liu et al. *Advanced Materials (2020)*

Straining of 2D materials at nanoscale



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

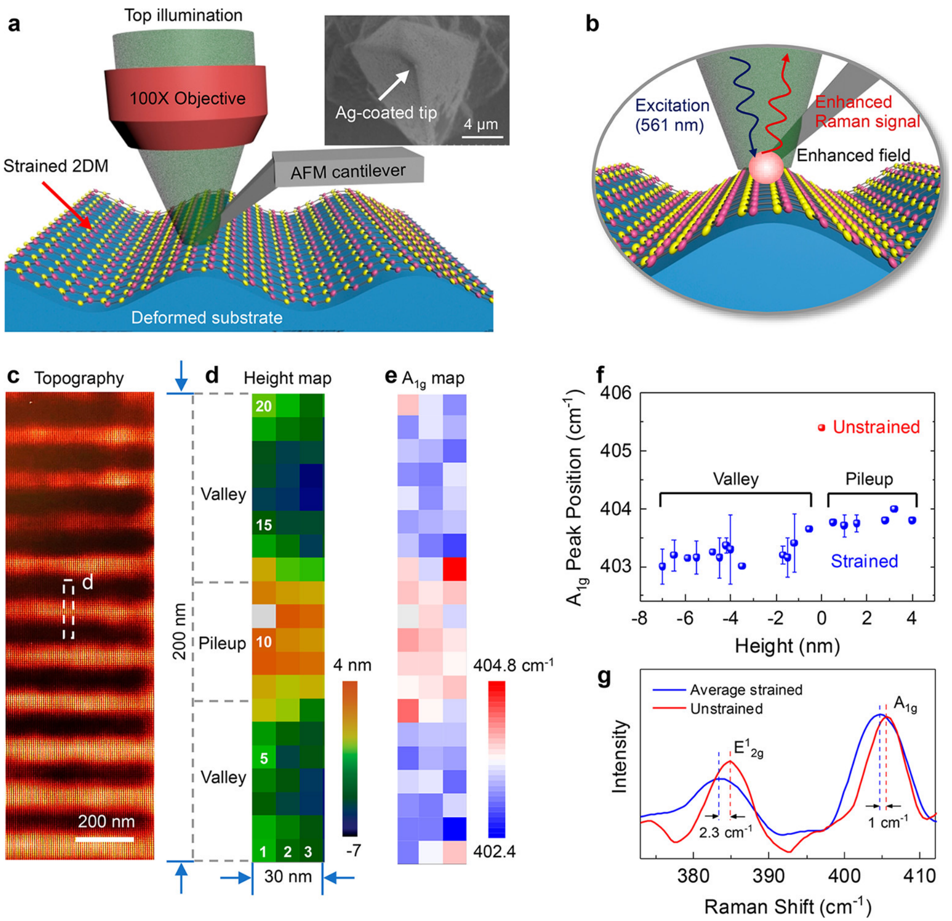
Straining of 2D materials at nanoscale



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

EPFL

Straining of 2D materials at nanoscale



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

30 years of t-SPL .. and counting