POLITECNICO
MILANO 1863

Thermal Scanning Probe Lithography

Nanolito 2021: SUMMER SCHOOL IN BASICS AND APPLICATIONS OF NANOLITHOGRAPHY

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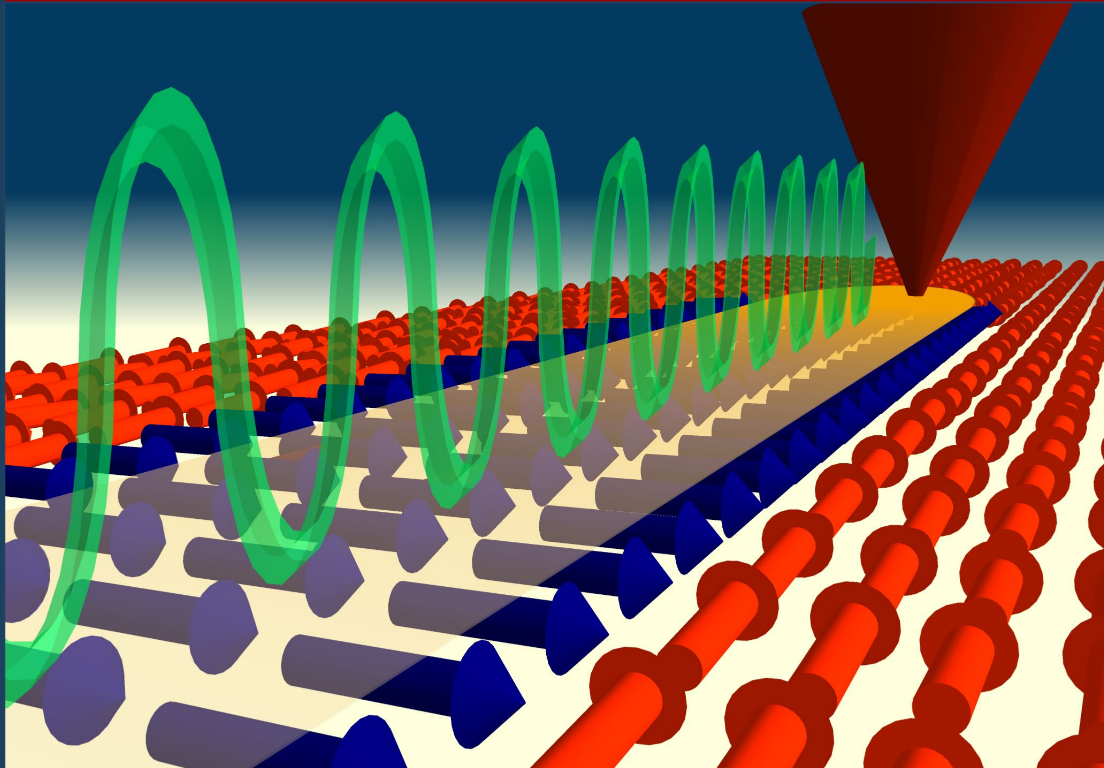
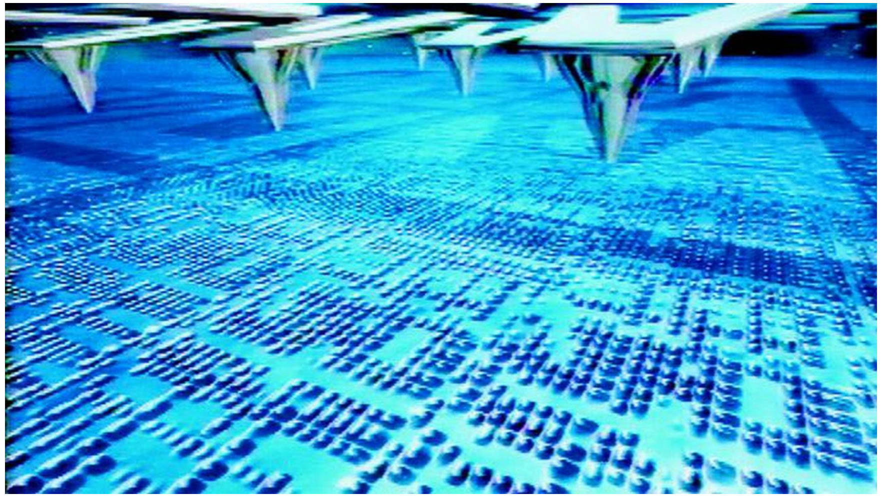
Dipartimento di Fisica - Politecnico di Milano

30/6/21, NanoLito 2021, University of Salamanca



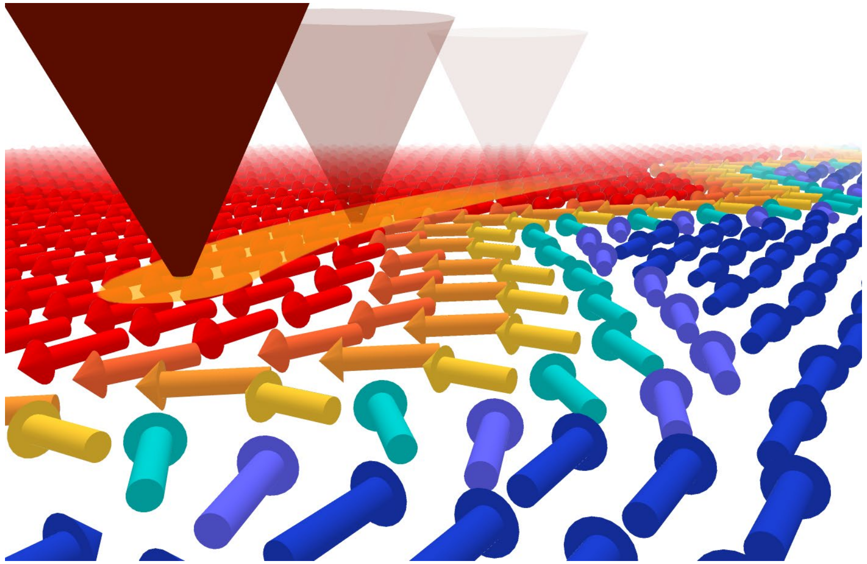
Outlook

- ► *Scanning Probe Microscopy / Lithography*
- ► *Brief history of t-SPL: from milli-pedes to nano-structures*
- ► *Experimental: features and limitations of t-SPL*



- ► *Applications:*

1) *REMOVAL Direct sublimation of organic resists / lithography*
2) *«CHEMICAL conversion» at the nanoscale*
3) *«PHYSICAL conversion»: t-SPL for magnetism*



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- **Brief history of t-SPL: from milli-pedes to nano-structures**
- **Experimental: features and limitations of t-SPL**
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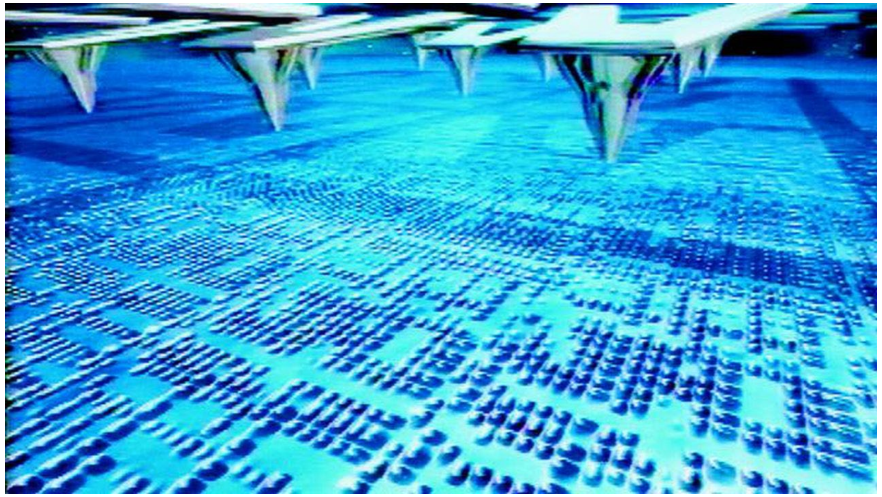
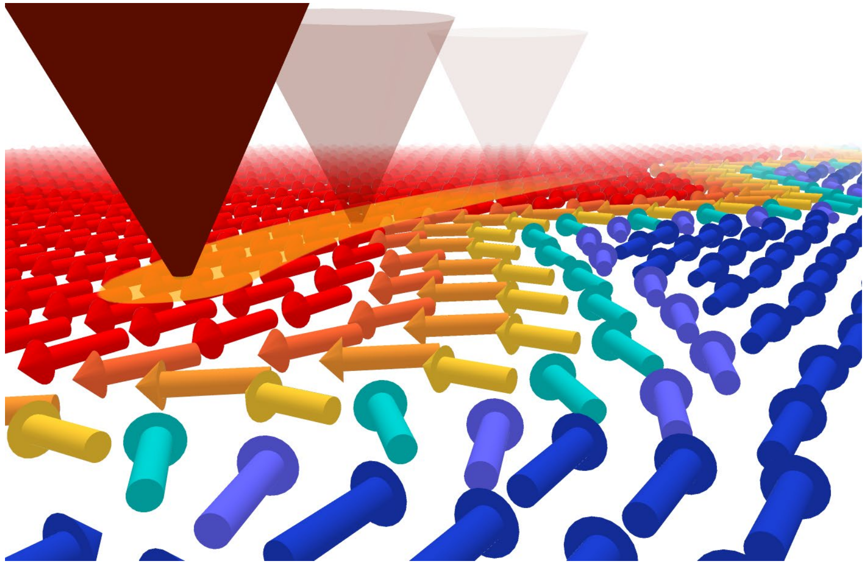
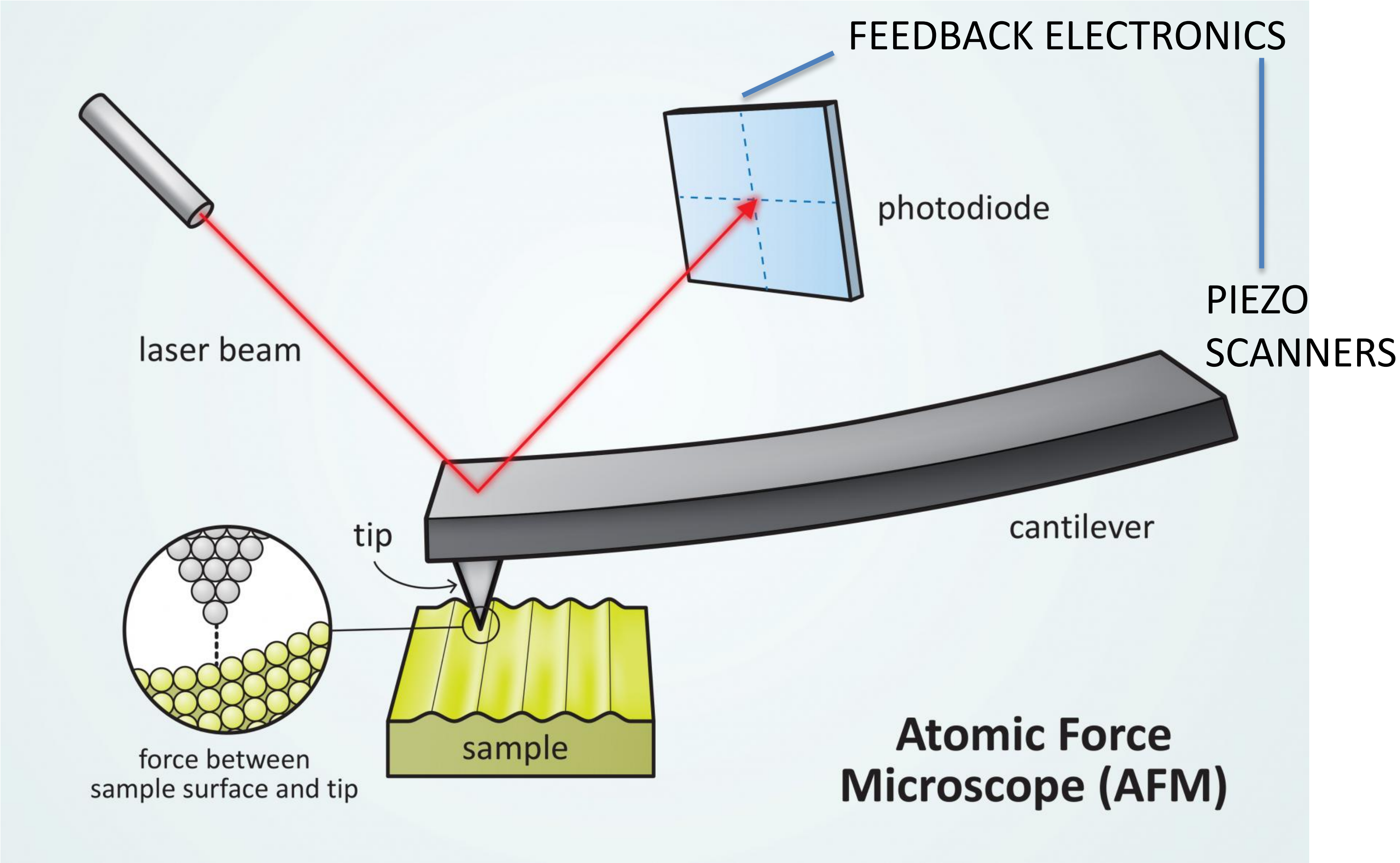




Scanning Probe Microscopy

Atomic Force Microscopy



Scanning Probe Microscopy modes:

Magnetic Force Microscopy (MFM)

Lateral Force Microscopy (LFM)

Intermitant and non-contact AFM

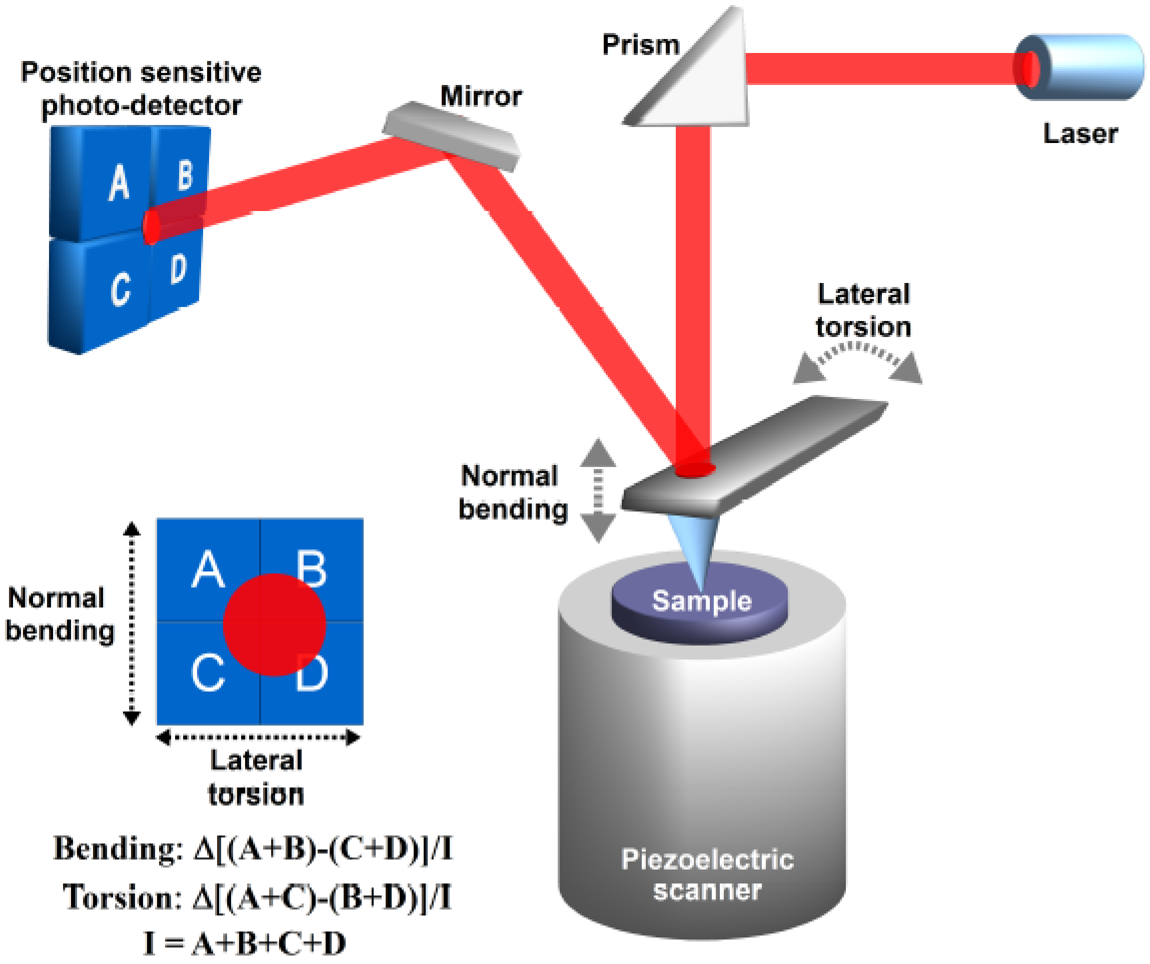
Force Modulation Microscopy (FMM)

Electrostatic Force Microscopy (EFM)

...

Depending on the tip-sample interaction

AFM force detection mechanism



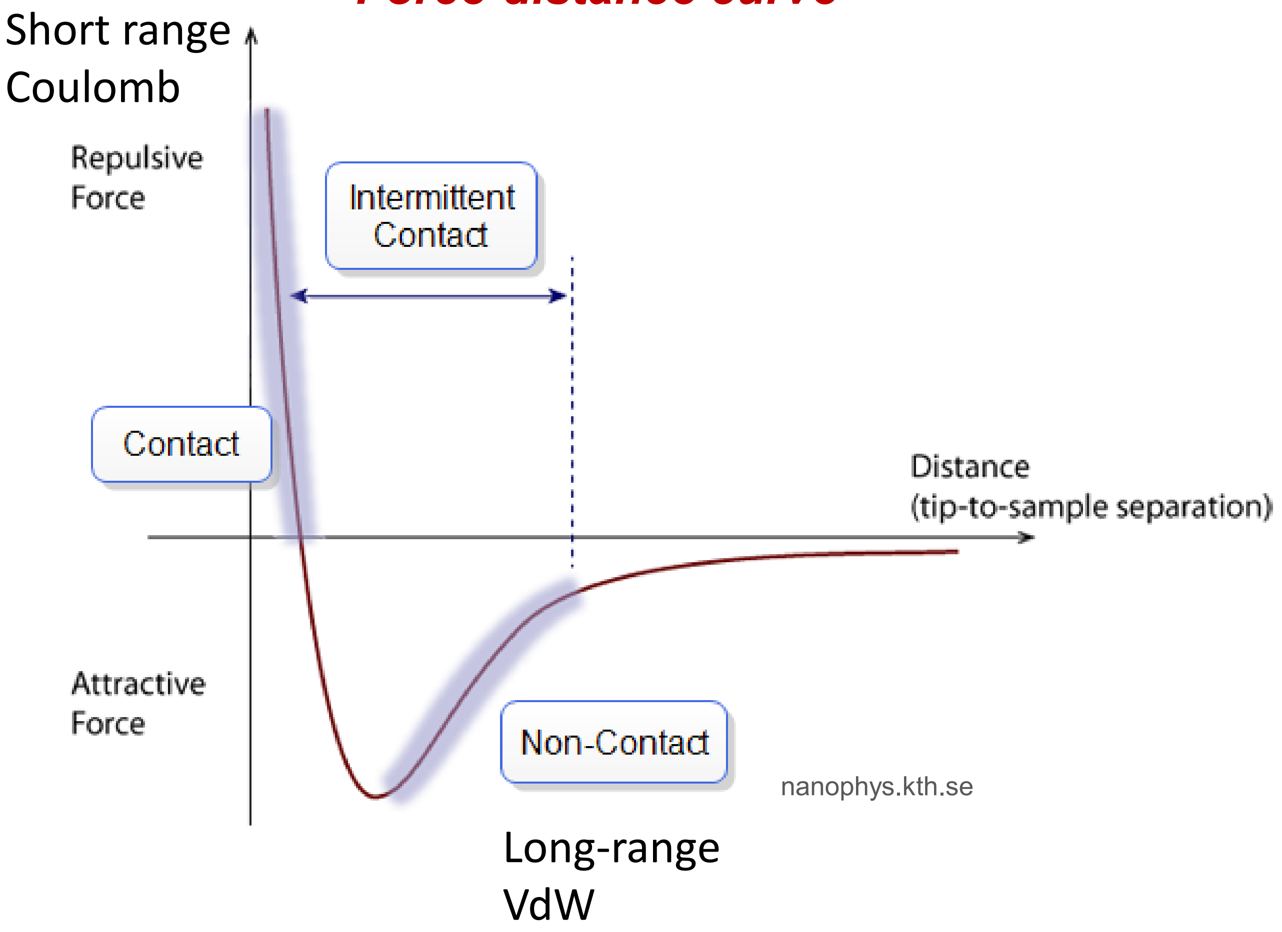
Debin Wang, Ph.D. Thesis GeorgiaTech 2010

Bending + Torsion force detection

A four-quadrant position sensitive photo-detector is used to detect the vertical bending and torsion of the cantilever to measure the normal and lateral forces.

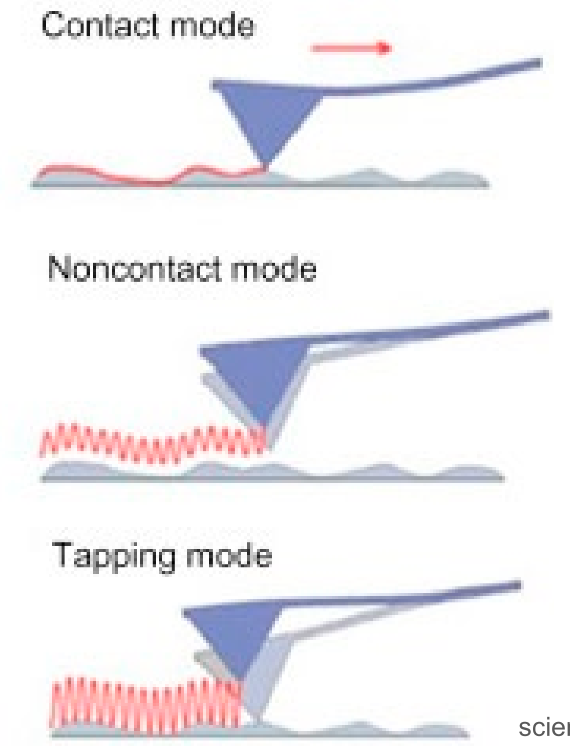
AFM tip-sample interaction

Force-distance curve



nanophys.kth.se

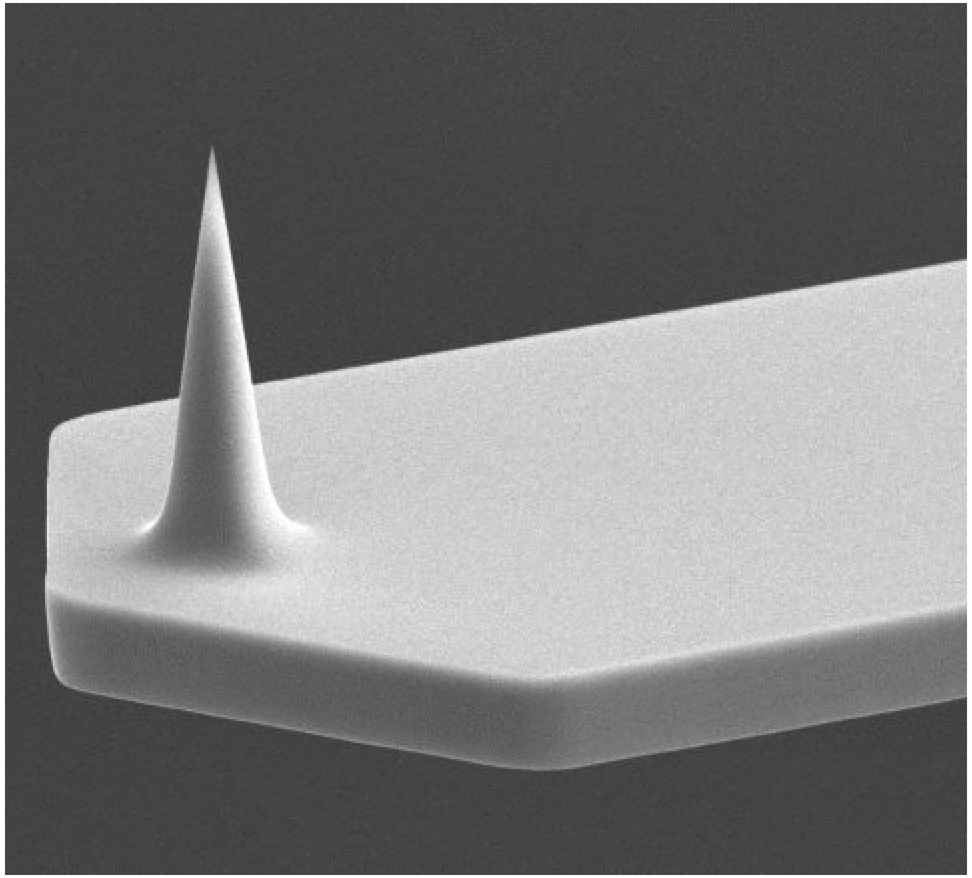
Main AFM modes



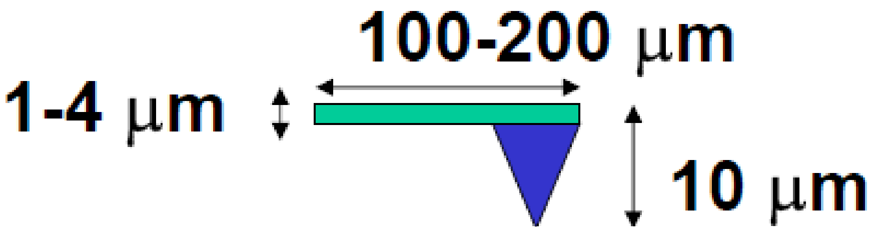
scienceDirect

AFM Standard Scanning Probes

Scanning Probes

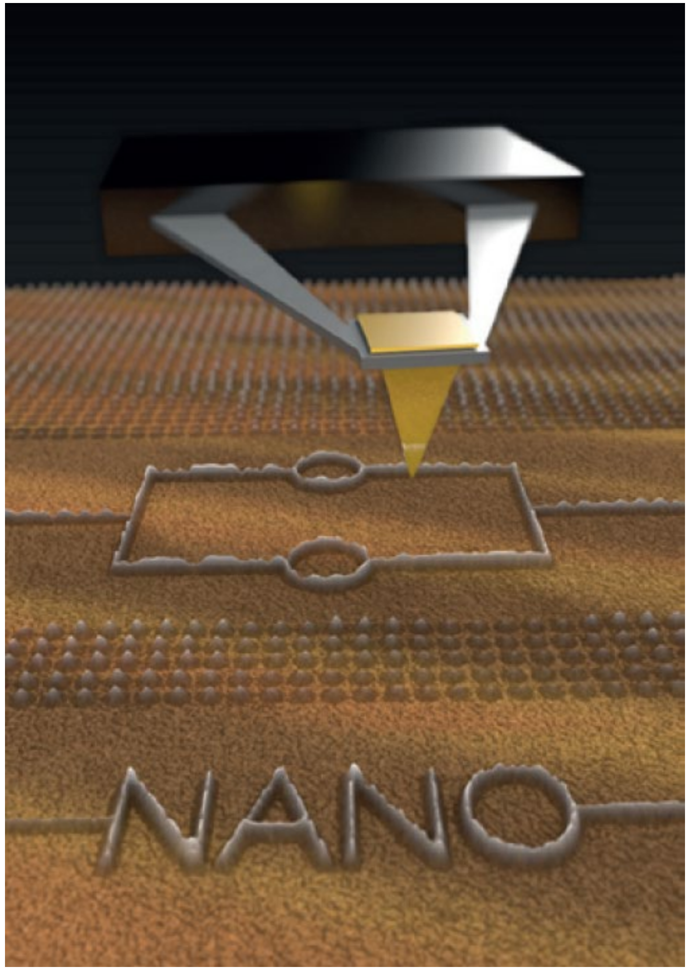


Material: Si, Si3N4
Shape: pyramidal, conical tip
Typical Dimensions:

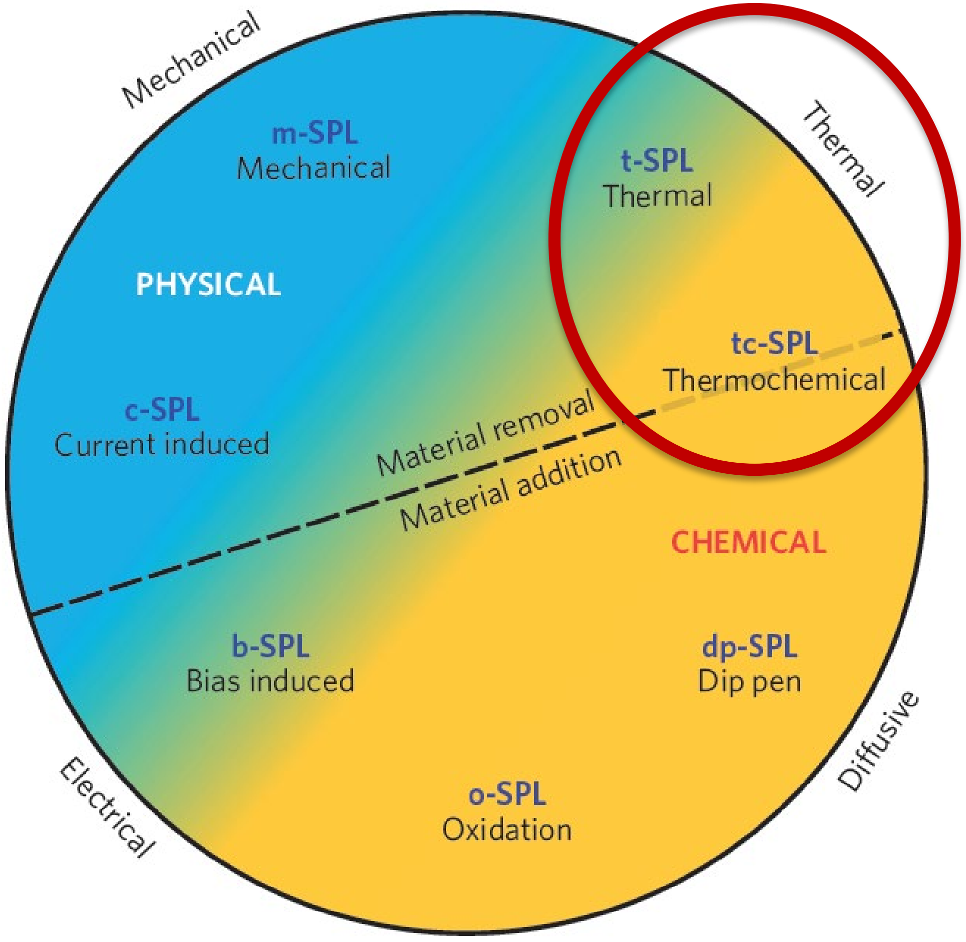


Spring constant (k): 0.1-10N/m
Resonant frequency: 10 kHz-1 MHz
+ different coating depending on the application (magnetic, conductive..)

Scanning Probe Lithography



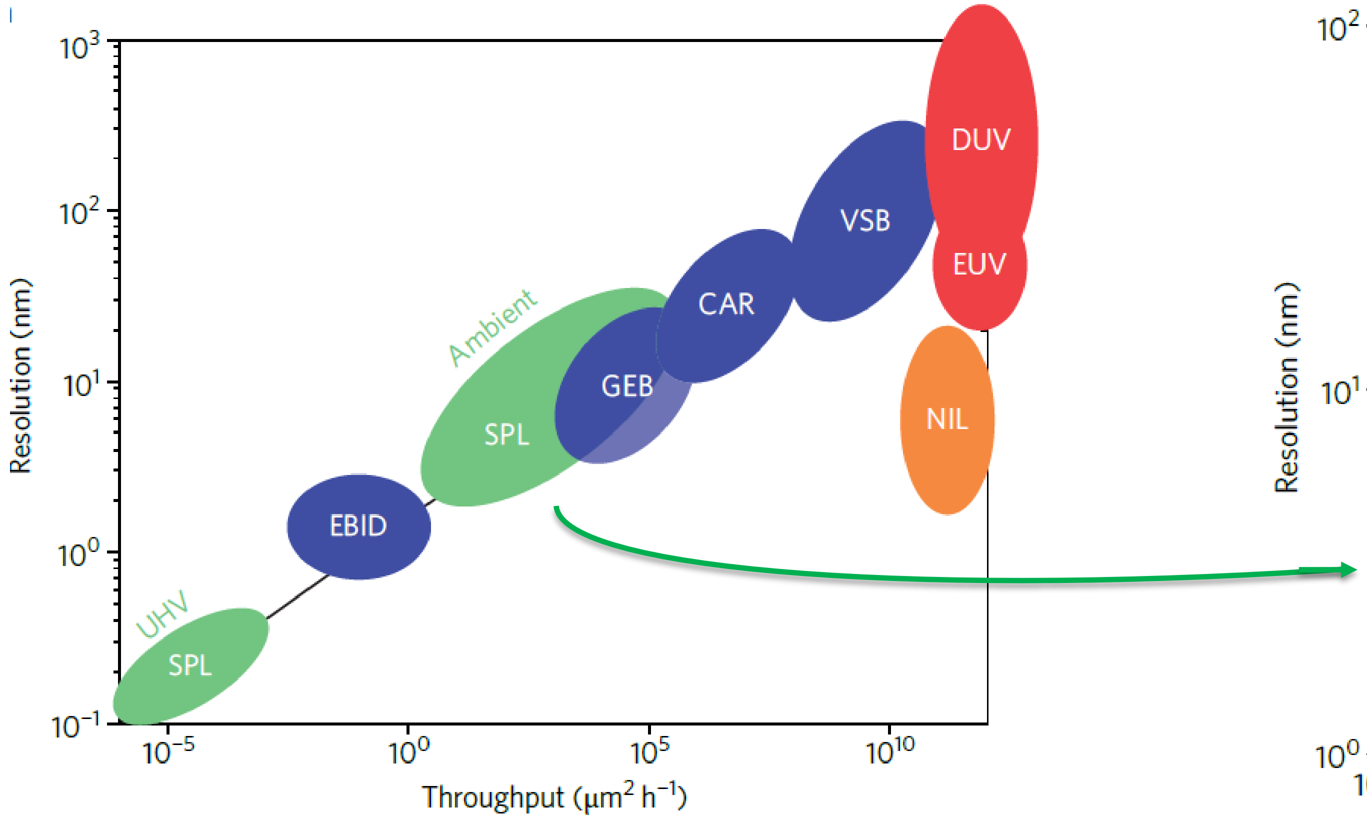
SPL modes



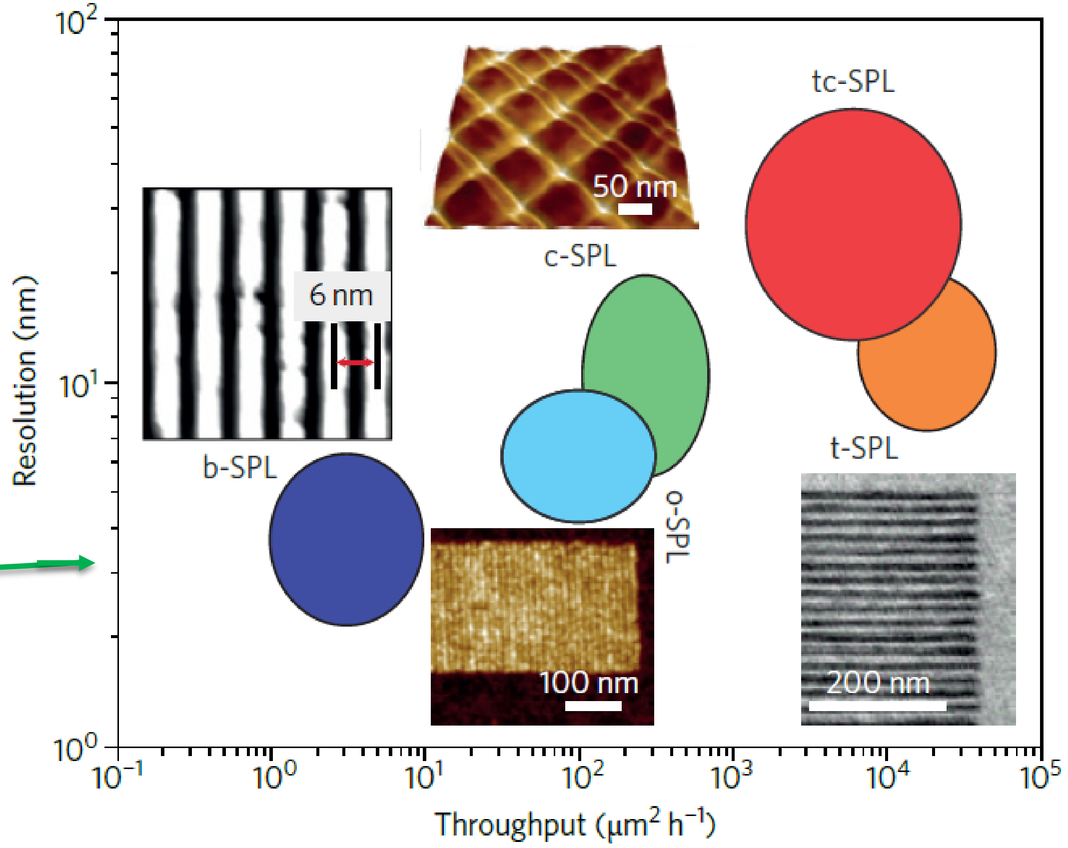
Garcia et al., Nat. Nanotech. 9, 577–587 (2014)

Scanning Probe Lithography: resolution vs throughput

SPL vs others



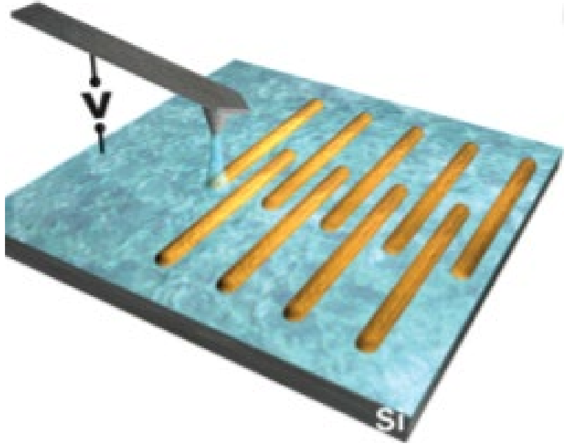
SPL methods

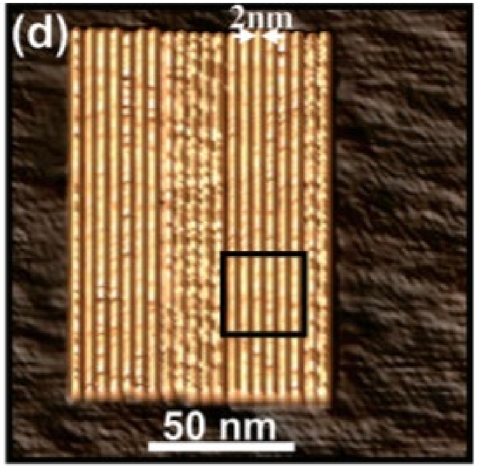


Garcia et al., Nat. Nanotech. 9, 577–587 (2014)

Bias-Scanning Probe Lithography

b-SPL induced deposition

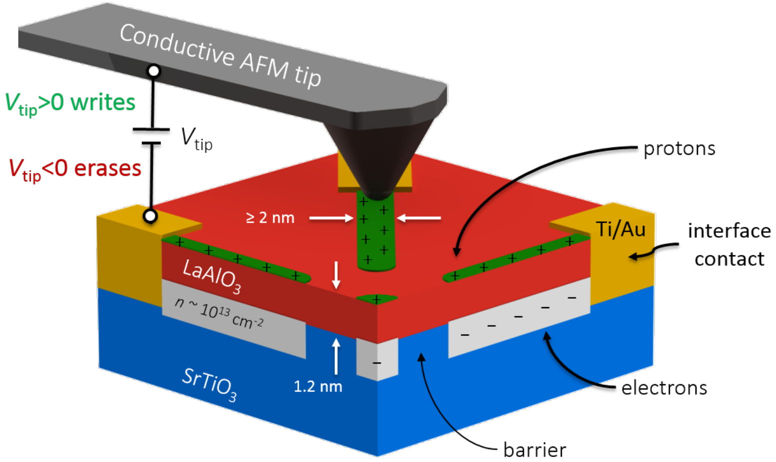




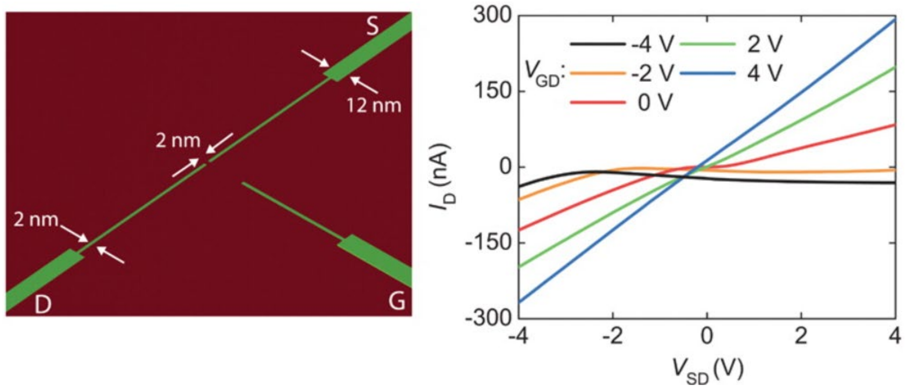
Formation of a nanoscale octane meniscus between a sharp conductive protrusion and a silicon (100) surface. Bias pulse-induced polymerization.

Nano Lett. 2007, 7, 7, 1846–1850

b-SPL conductive nanowires at LAO / STO



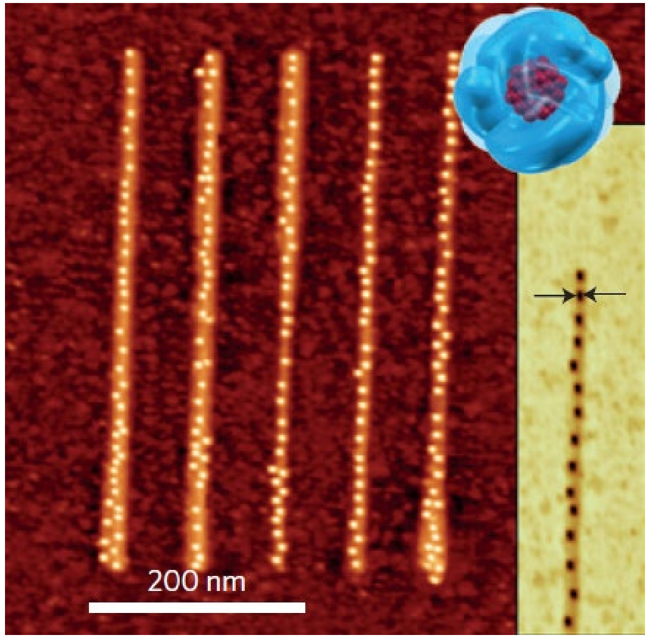
AFM tip moving above LaAlO3-SrTiO3 heterostructure, removing oxygen-containing ions and locally changing the charge state of the surface.



10.1126/science.1168294

Oxidation-Scanning Probe Lithography

o-SPL functionalization & molecular architectures

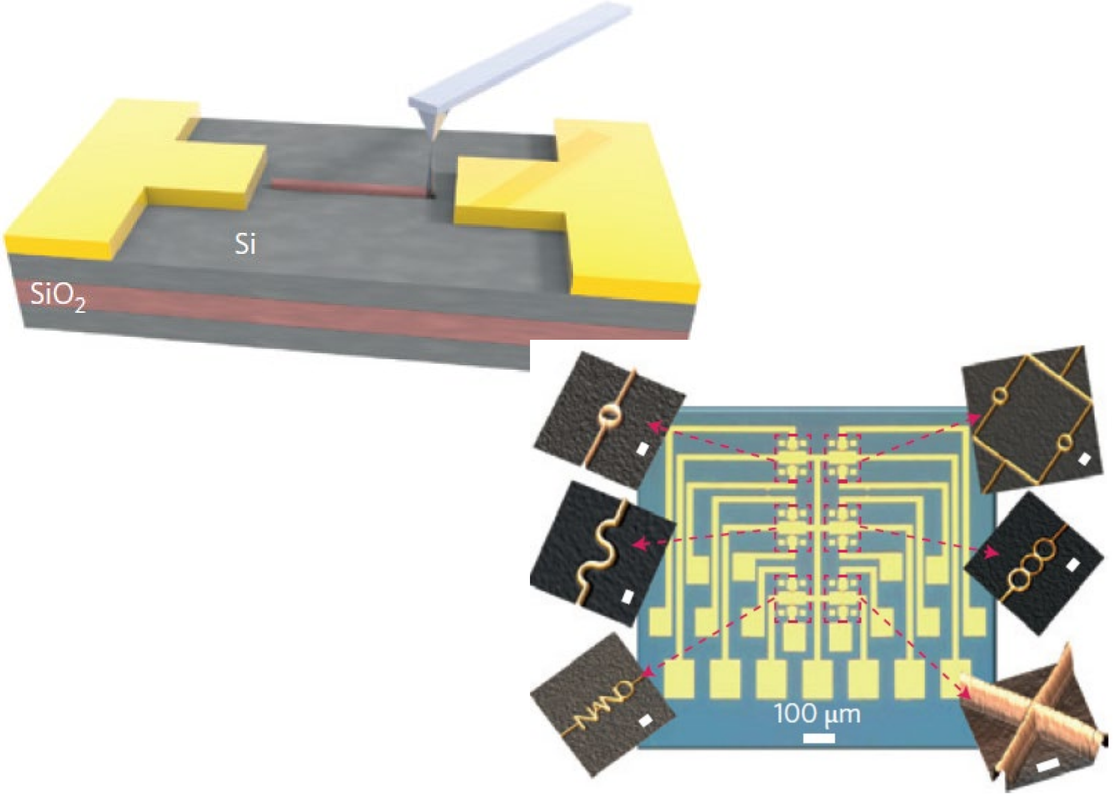


Ferritin
Single-molecule functionalization

Selective oxidation and/or complete removal of self-assembled monolayers and subsequent surface functionalization of the oxidized region.

Martinez, R. V. et al. Adv. Mater. 22, 588–591 (2010).

o-SPL SiO2 nanomasks



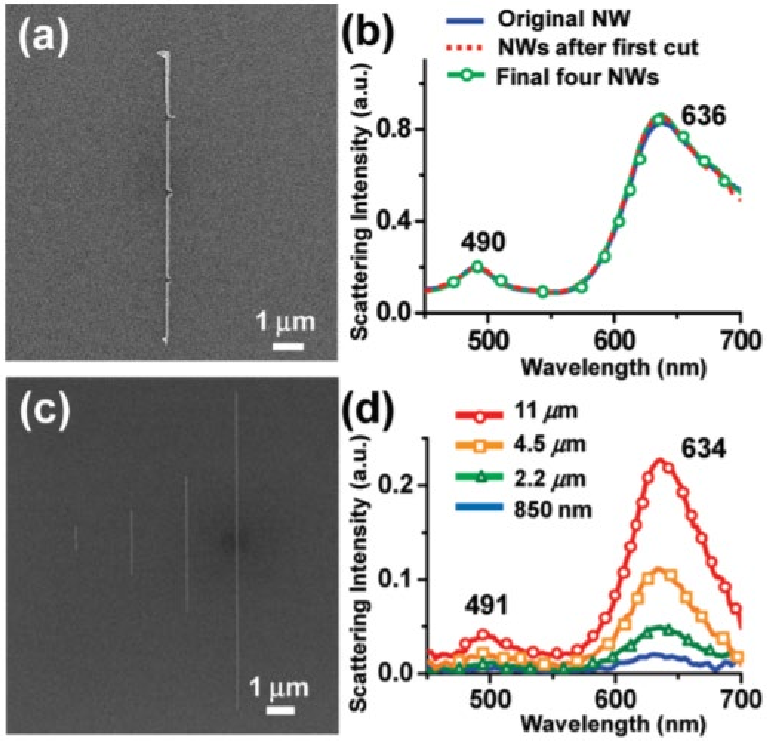
The fabrication of a silicon nanowire transistor involves the patterning of a narrow oxide mask on top of the active layer of a silicon-on-insulator substrate.

Martinez, R. V., Martinez, J. & Garcia, R. Nanotechnology 21, 245301 (2010).

Mechanical-Scanning Probe Lithography

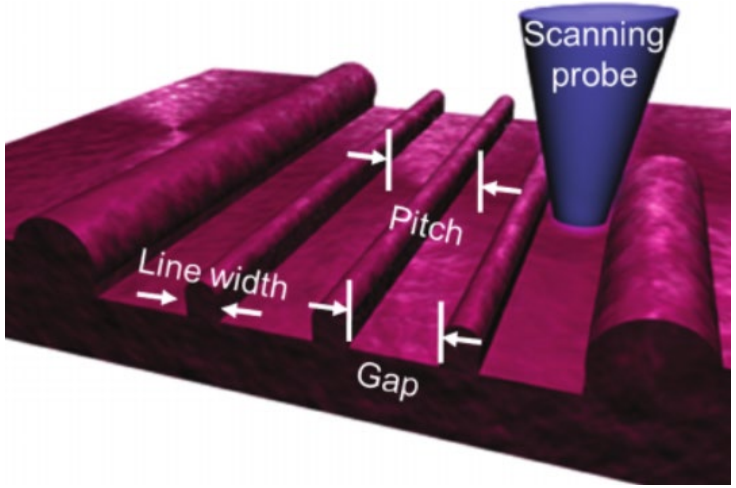
Mechanical SPL (nanomachining) uses the mechanical force exerted by the tip to induce the selective removal of material from a surface.

NW cutting for plasmonics (LSPR)



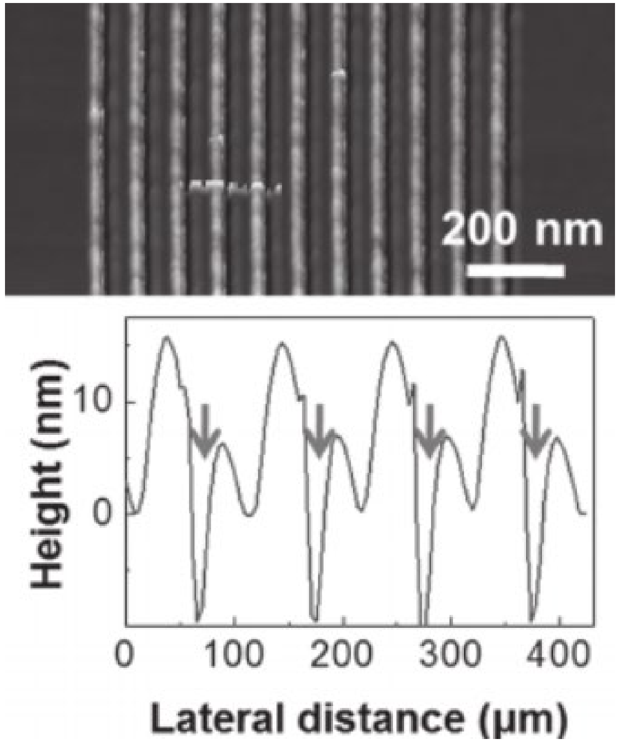
J. Phys. Chem. C, Vol. 114, No. 23, 2010

«Plowing» polymers



utilizes a scanning probe as a plow on a polymer-coated surface to generate ridges that can serve as narrow etch masks.

PMMA polymer

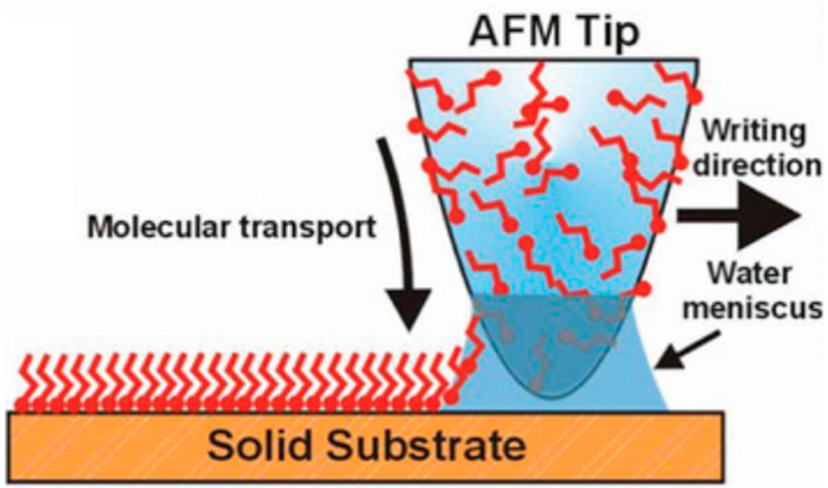


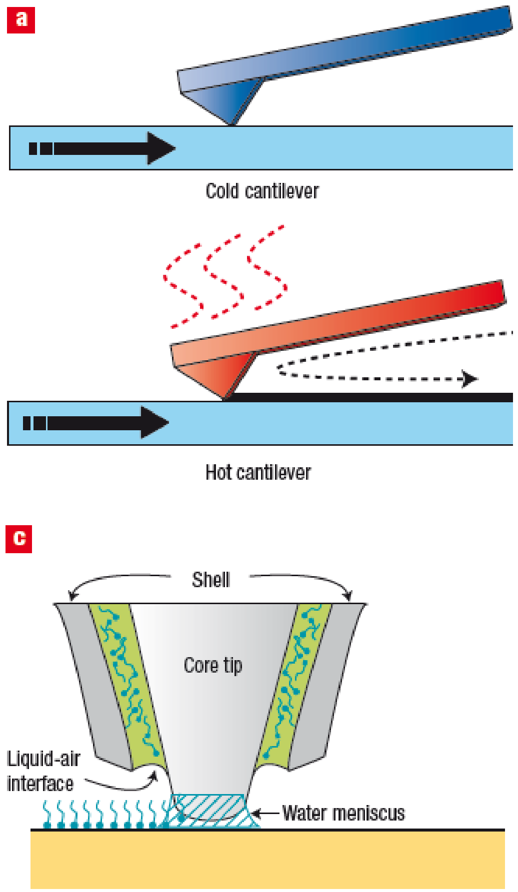
Small 2013, 9, No. 18, 3058–3062

Dip pen-SPL

Direct transport of molecules to surfaces, much like the transfer of ink from a macroscopic dip-pen to paper (sub-100 nm scale)

Dip-pen nanolithography & thermal dip-pen nanolithography





10.1038/nnano.2007.39

Examples of Inks
Protein, peptide, DNA, Hydrogels, Sol gels, Conductive inks, Lipids, Silanes (liquid phase) written to glass or silicon

Thermal DPN: AFM cantilever whose tip is coated with a solid 'ink'. When the tip is hot enough, the ink melts and flows onto the substrate.

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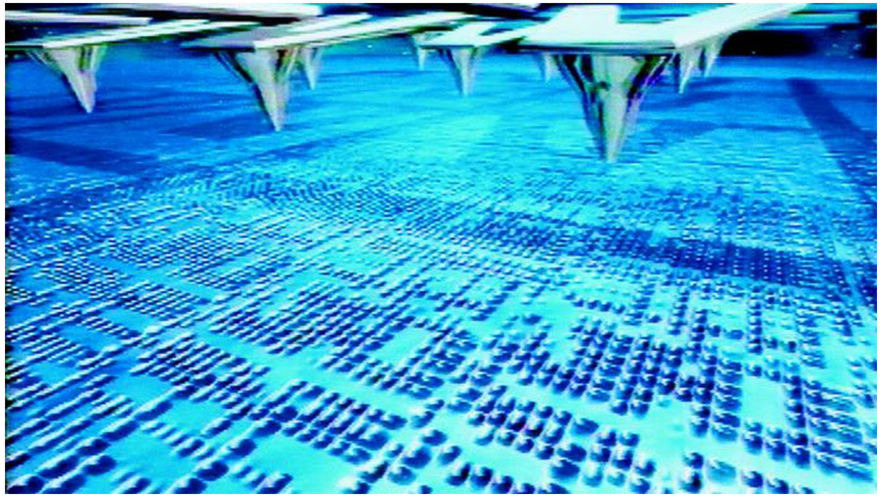

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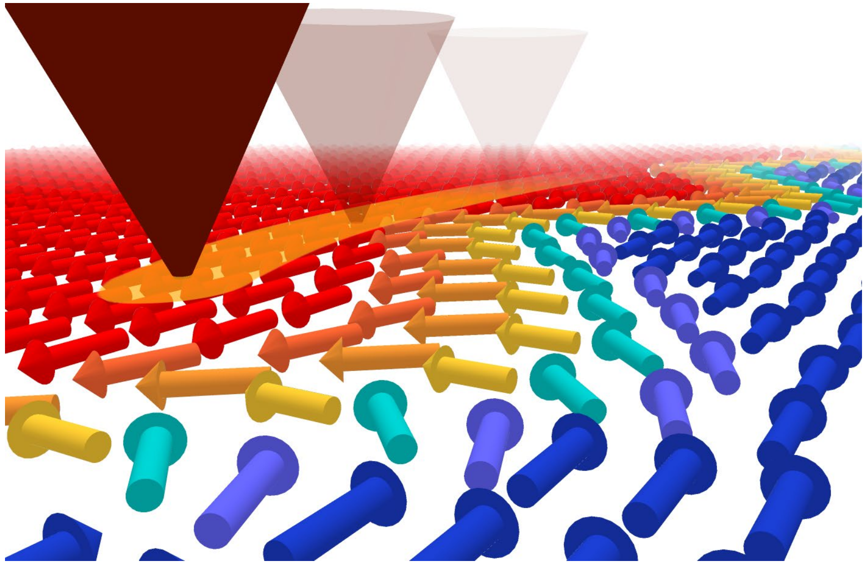
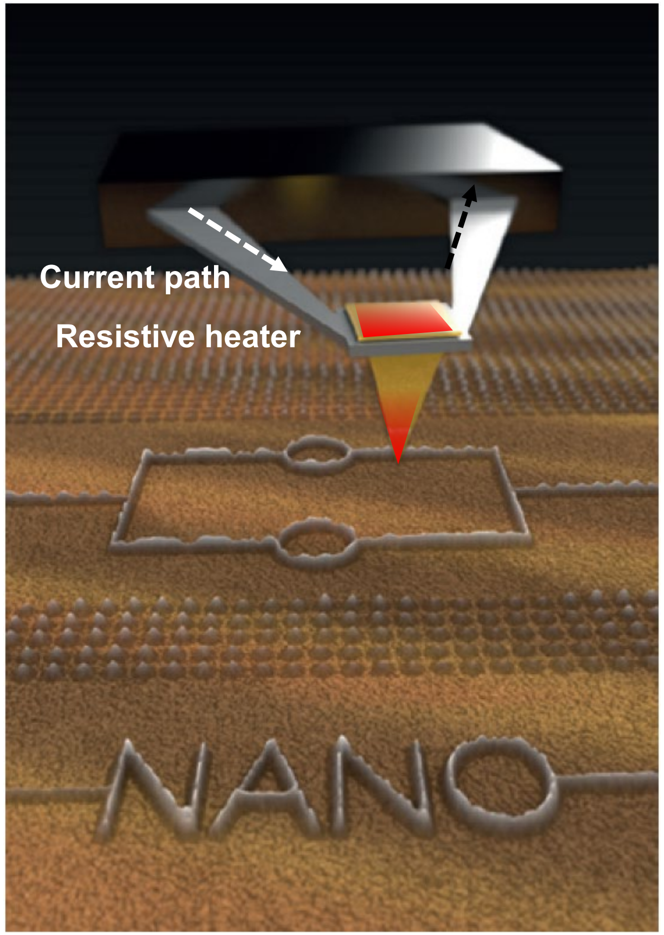


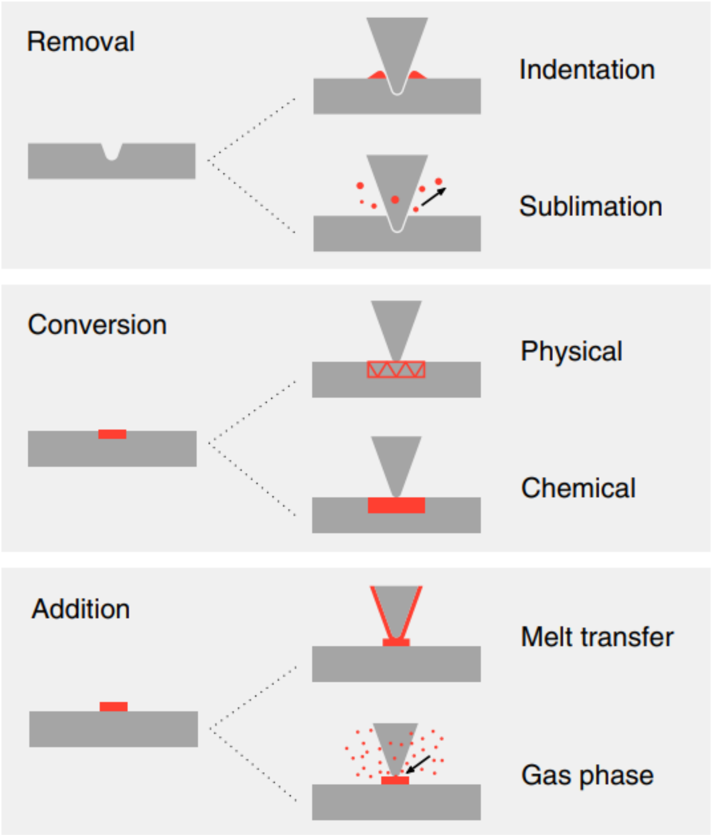
Thermally Assisted Scanning Probe Lithography (t-SPL)

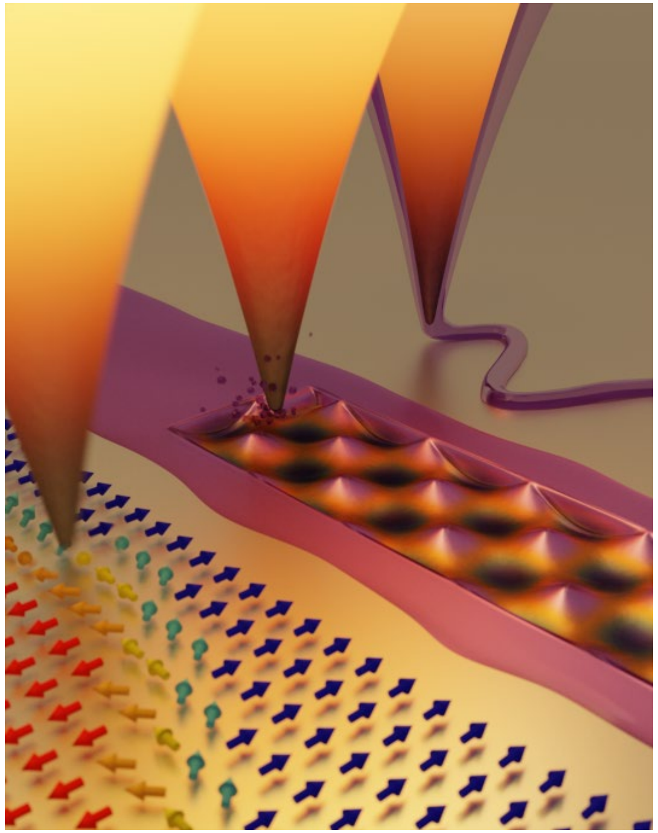
Working principle



Garcia *et al.*, Nat. Nanotech. **9**, 577–587 (2014)

Heat as a localized universal stimulus



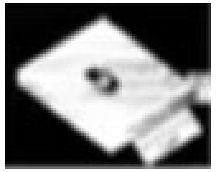


Howell et al. Microsystems & Nanoengineering (2020) 6:21

- Sub-10 nm spatial resolution
- Microsecond timescale
- Precise control of temperature (up to 1200°C) / duration (from few us/px)

A brief history of t-SPL

1° patterning with thermal-AFM @IBM



Thermomechanical

Appl. Phys. Lett. 61, 1003–1005 (1992)

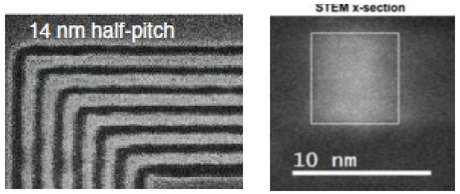
Lithography with t-SPL

Thermochemical
Thermal Dip-pen

Appl. Phys. Lett. 85, 1589 (2004)
Nano Lett. 7, 1064–1069 (2007)

1st Commercial t-SPL Tool

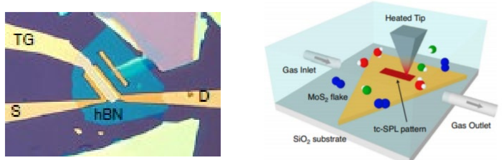
Sub-10 nm Resolution in Silicon



Subl. + Pattern transfer

ACS Nano 11, 11890–11897 (2017)

FETs, doping of 2D materials

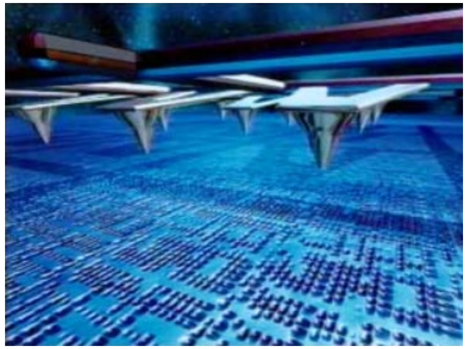


Subl. + Pattern transfer
Defect engineering

Nat. Electron. 2, 17–25 (2019).
Nature Communications 11, 3463 (2020)

1992 1995 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019

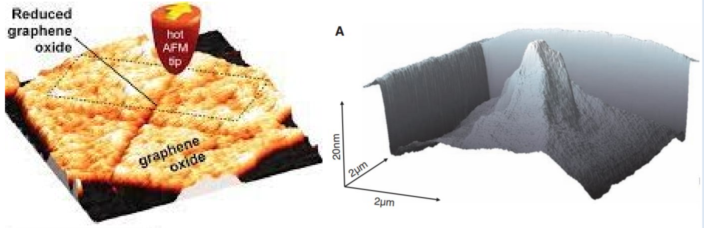
Millipede project by IBM



Thermomechanical for data storage

Microelectron. Eng. 46, 11–17 (1999).

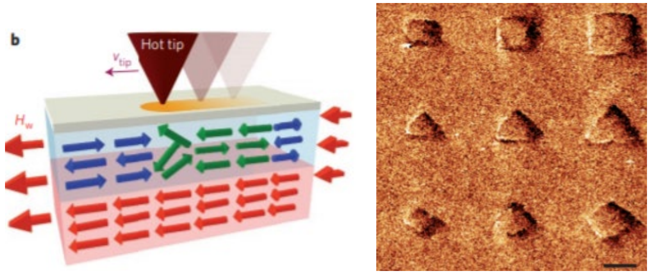
Graphene Oxide, 3D topography



Thermochemical, Sublimation

Science 328, 1373–1376 (2010).
Science 328, 732–735 (2010).

Magnetic domains, spin textures



«Physical» magnetic phase transition

Nature Nanotechnology 11, 545–551 (2016)

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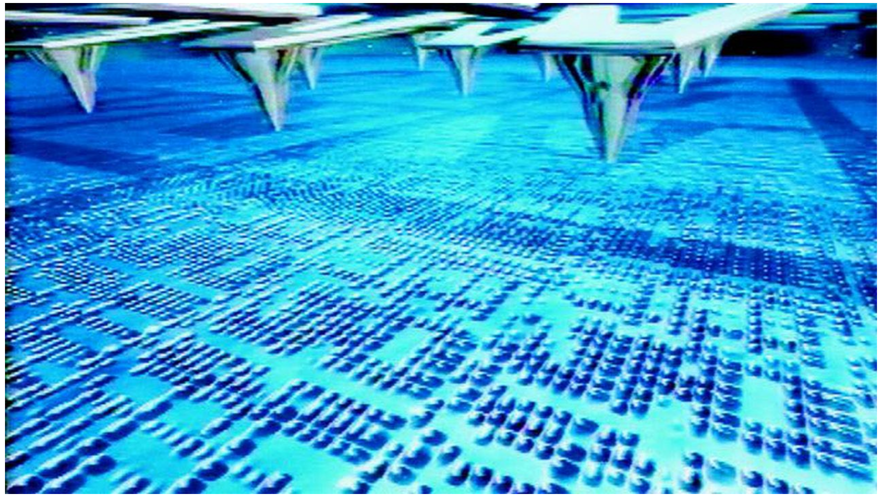
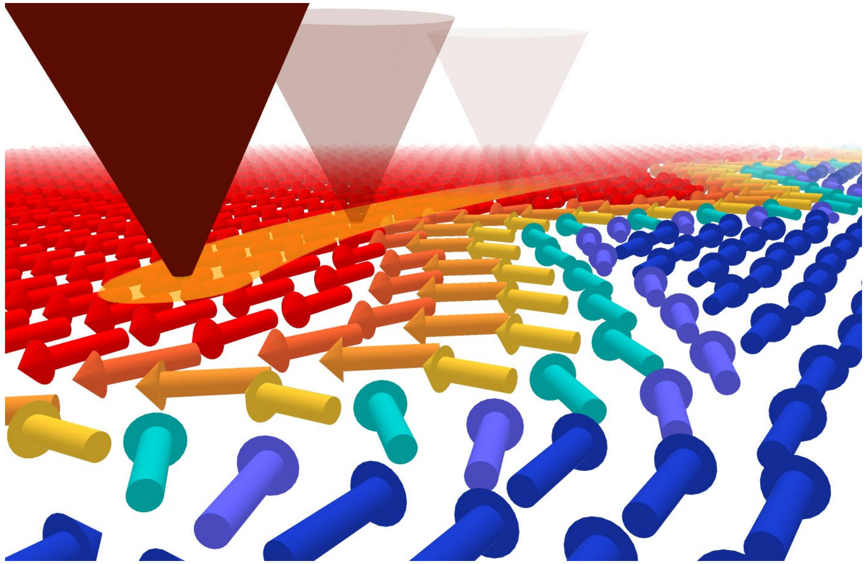
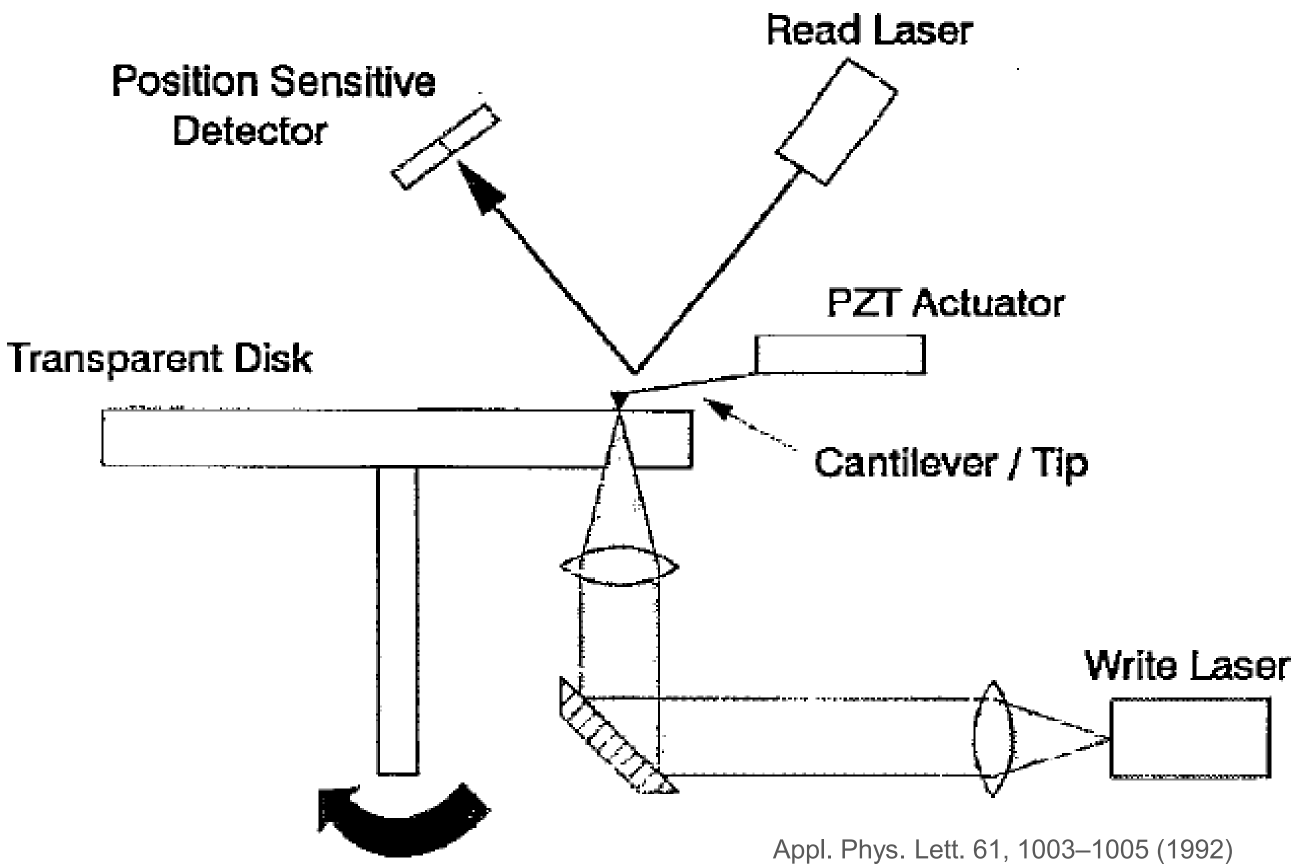




Thermal cantilevers #1: laser heating on standard AFM tip

Conventional AFM tip, heated by a laser focused on the cantilever

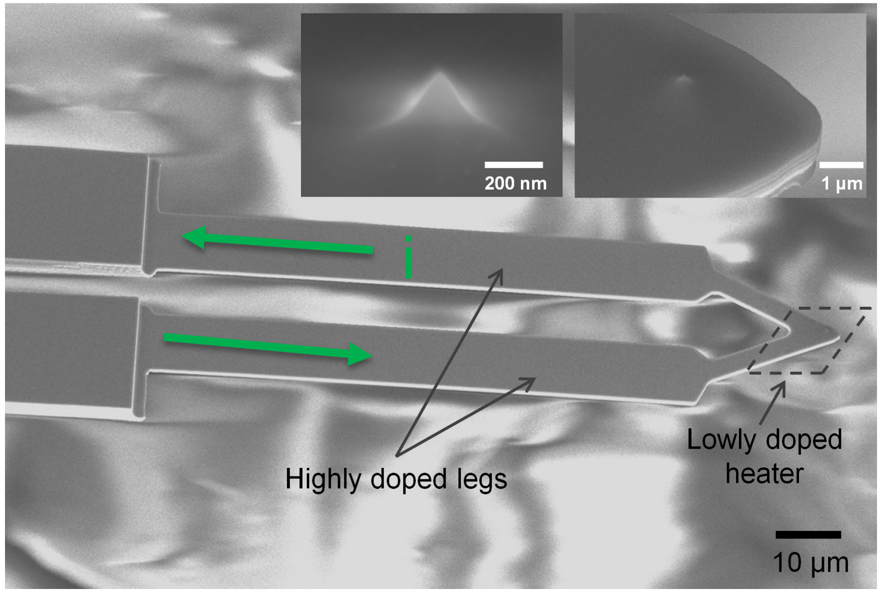


Appl. Phys. Lett. 61, 1003–1005 (1992)

Pros / cons

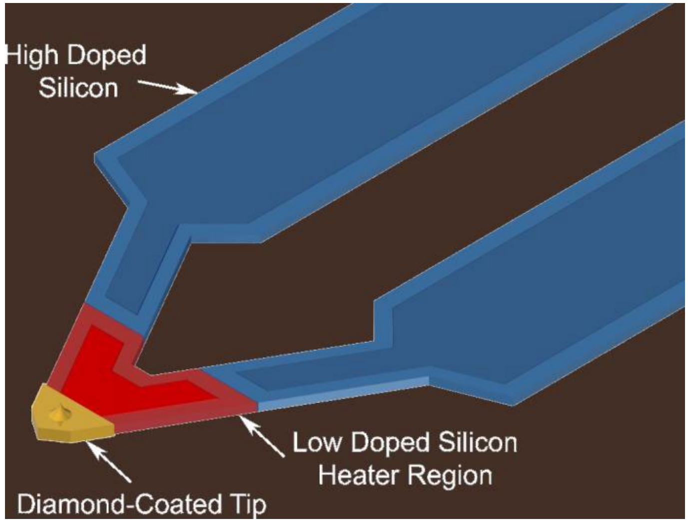
+ Uses standard AFM tips
- Hard to scale and integrate
- Complex setup (laser, lenses, focusing..)

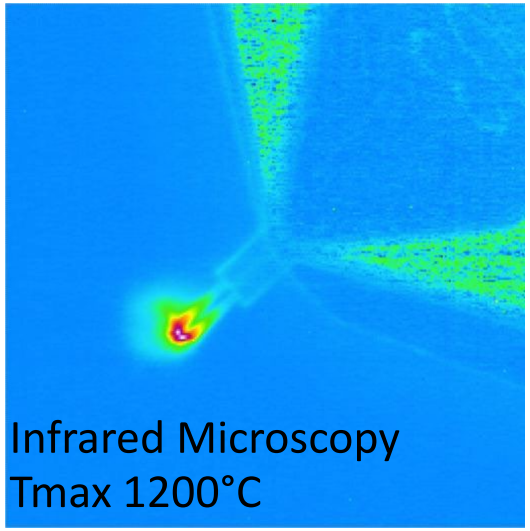
Thermal cantilevers #2: resistive heating for writing



D. Wang Ph.D. Thesis, GeorgiaTech 2010

Microfabricated AFM tip, with a resistive heater located on top of the tip, which can be heated controllably via Joule effect. The sensing is performed via conventional optical lever + photodetector





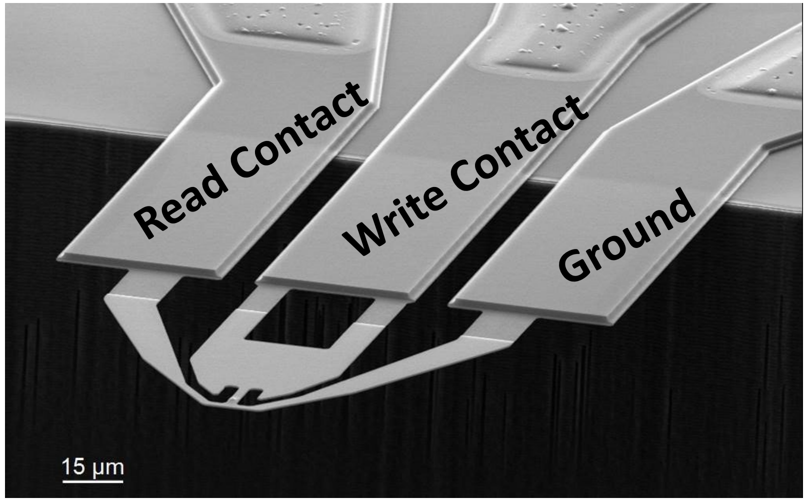
Fletcher et al., ACS Nano (2010) 4:3338

Pros / cons

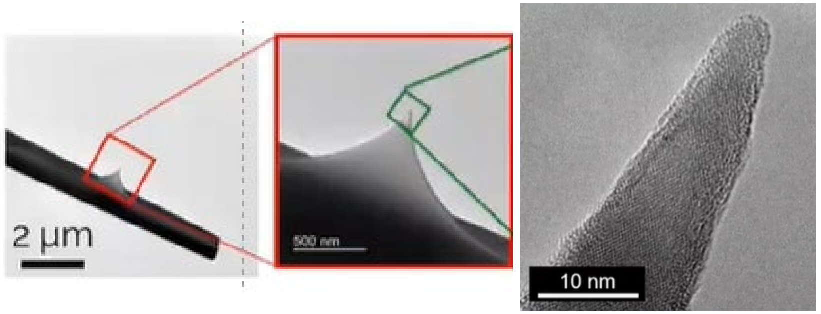
- \+ Integrated
- \+ Highly controlled temperature
- \- Complex fabrication with respect to standard TIP
- \- Hardly scalable (reading is still via laser)

Thermal cantilevers #3: resistive heating for writing AND reading

"Millipede concept". Microfabricated AFM tip, with a resistive heater located on top of the tip, which can be heated controllably via Joule effect. The sensing is performed via a second resistive heater which is used as a distance sensor (resistance changes when approaching the surface).

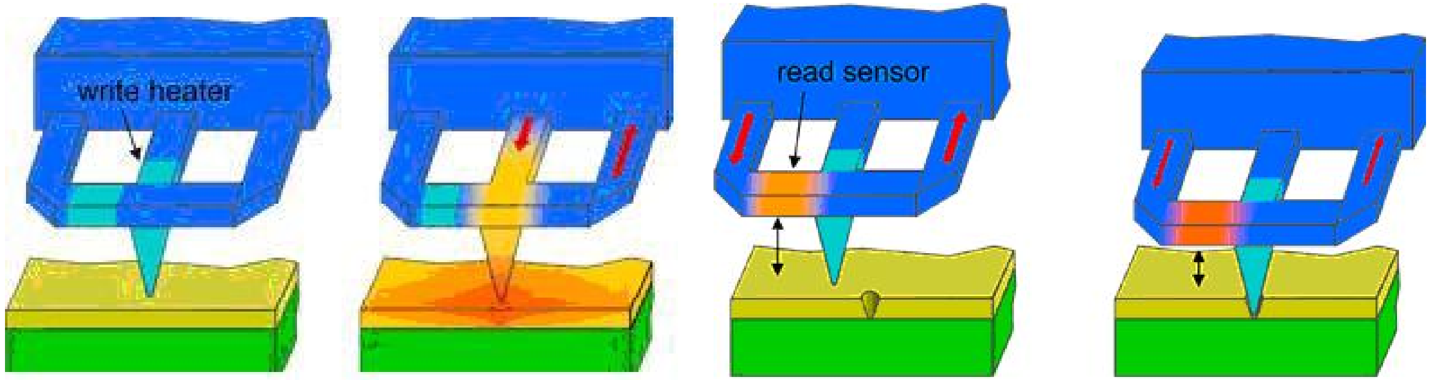


Quantum Design

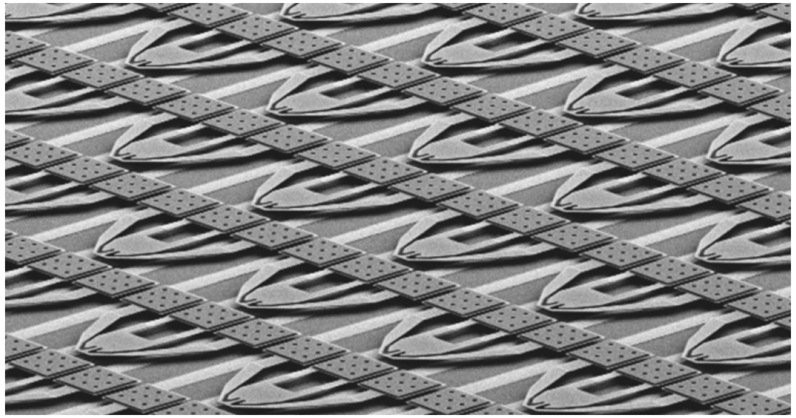


Heidelberg Instruments

Writing operation ***Reading operation***



Parallelization



Pros / cons

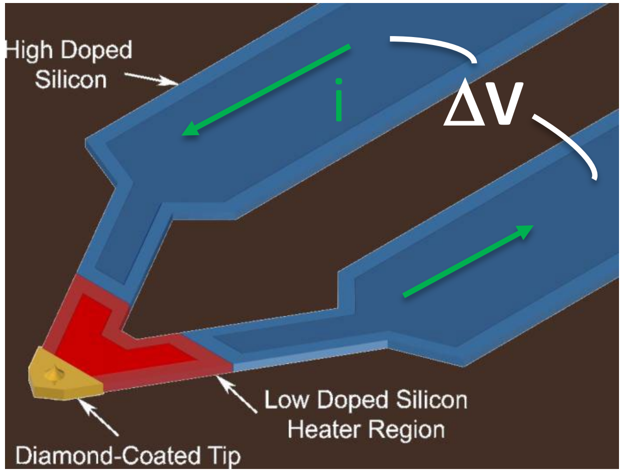
- \+ Integrated
- \+ Controlled temperature
- \+ Multiplexing capability
- \- Complex fabrication with respect to standard TIP

Thermal cantilevers: thermal characteristics

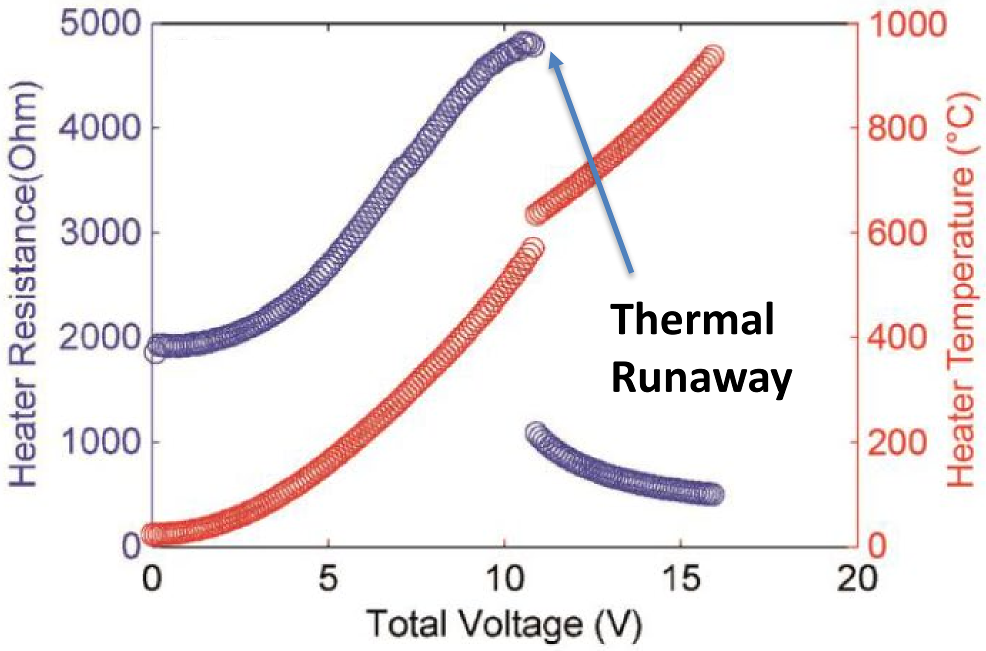
In semiconducting Si, the intrinsic carrier density varies widely with temperature. When the temperature of the heater region reaches a certain level (Ti), the intrinsic carrier density in the silicon exceeds the dopant carrier density. Above Ti, the extra carriers that become available cause the heater region to decrease in resistance, which in turn allows more current to flow,
thereby generating more resistive heating (P = Vi).

$$T_H = RT + \frac{T_i - RT}{P_i} P_H$$

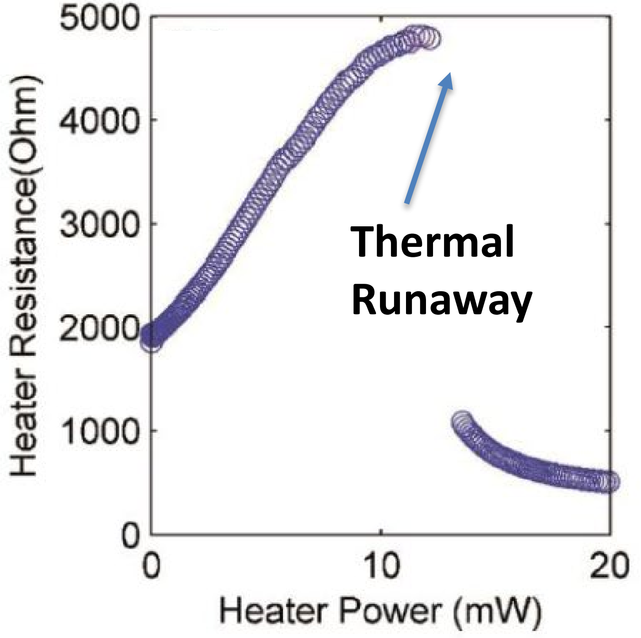
Ti around 550°C



Applied Voltage vs Resistance / Temp



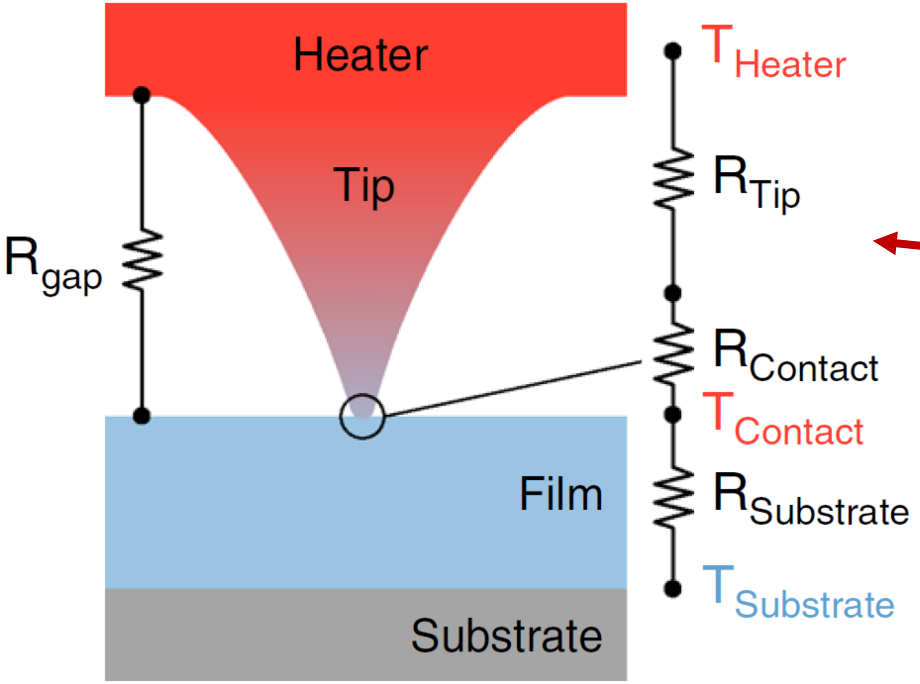
Power vs Resistance



Fletcher et al., ACS Nano (2010) 4:3338

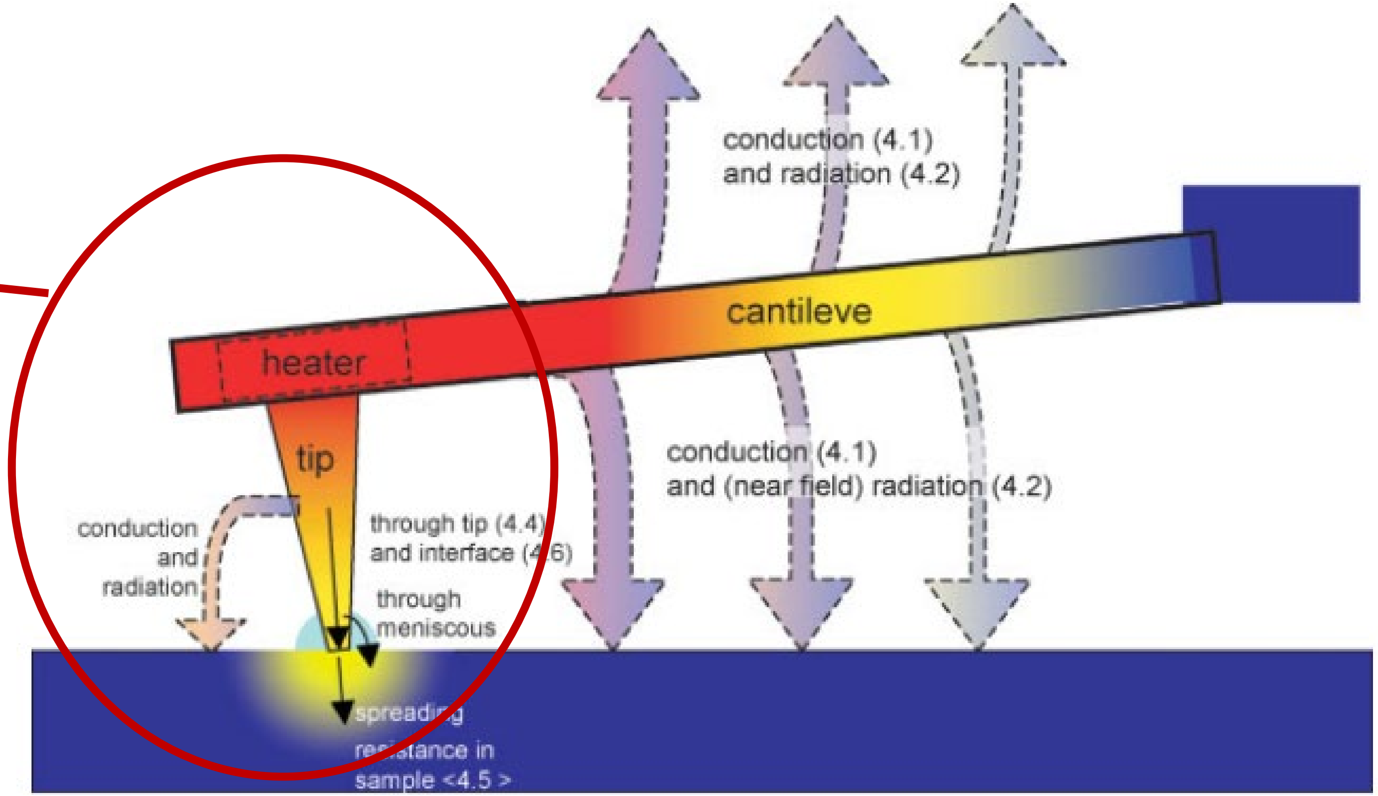
Thermal transport from tip to sample

Tip/Sample Thermal resistance model



Howell et al. Microsystems & Nanoengineering (2020) 6:21

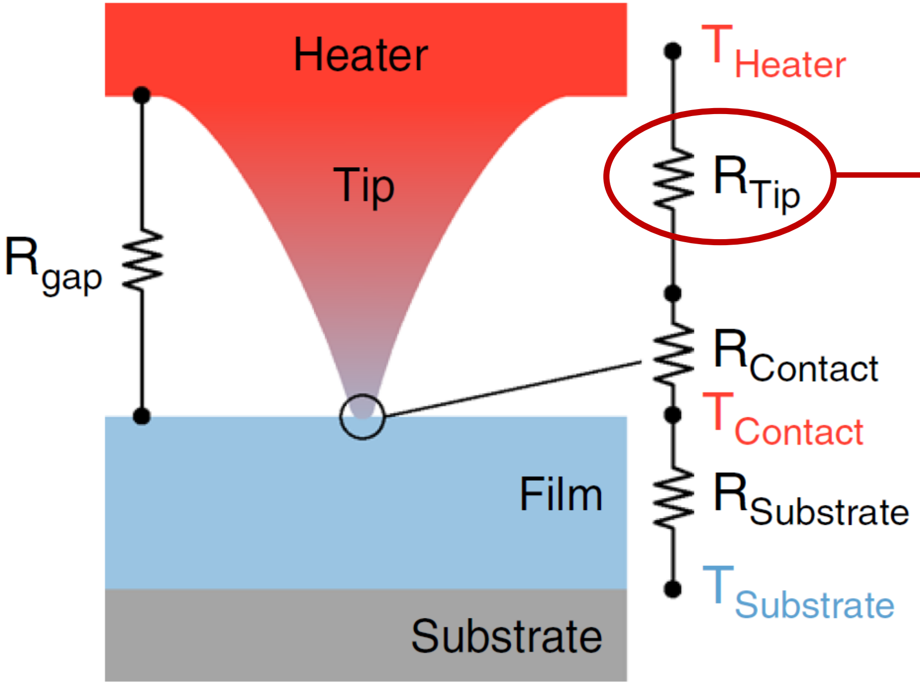
Heat transfer pathes



Nanotechnology 121–169, https://doi.org/10.1002/9783527628155.nanotech066

Thermal transport from tip to sample

Tip/Sample Thermal resistance model



Howell et al. Microsystems & Nanoengineering (2020) 6:21

Conductance of the phonons within the silicon tip and from the layer of native oxide covering it. R > Rbulk

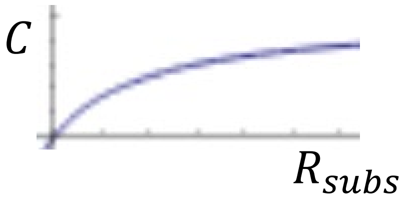
- Enhanced phonon scattering with boundary surfaces.
- Reduction of the cross section area towards the tip apex (T over 90% of R_{tip} occurs at the first 10% of the tip length).

Sharp tips, lower opening angle -> Lower T

$$k = \frac{1}{3} C v \left(\Lambda_0^{-1} + d^{-1}\right)^{-1}$$

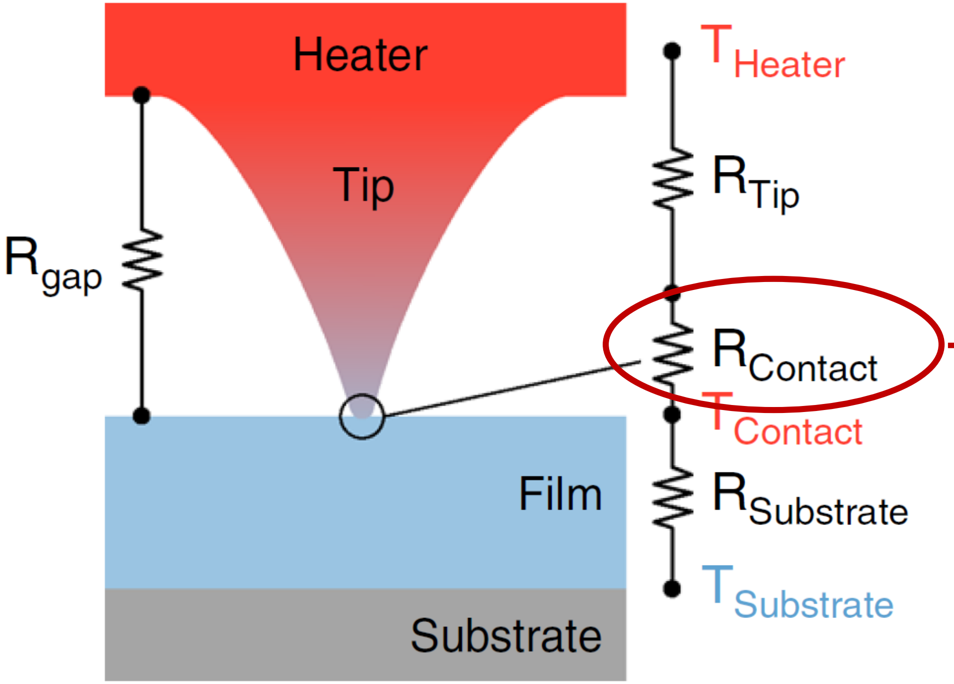
C heat capacity
v phonon speed
Gamma0 phonon mean free path
d diameter

$$C = \frac{T_{cont}}{T_{heat}} = \frac{R_{subs}}{R_{tip} + R_{cont} + R_{subs}}$$



Thermal transport from tip to sample

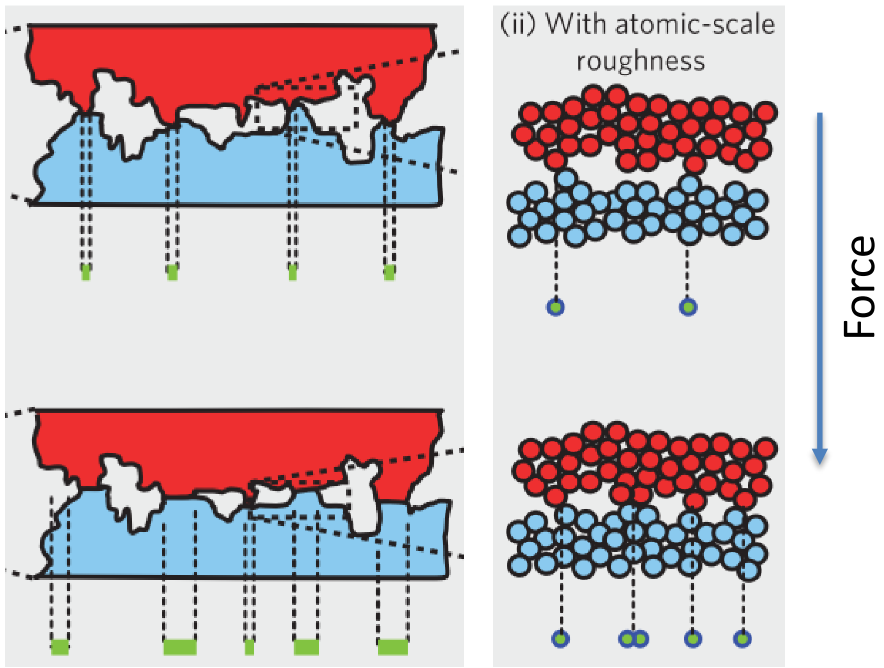
Tip/Sample Thermal resistance model



Howell et al. Microsystems & Nanoengineering (2020) 6:21

$$C = \frac{T_{cont}}{T_{heat}} = \frac{R_{subs}}{R_{tip} + R_{cont} + R_{subs}}$$

Quantum thermal transport across individual contact points.
The number of contact points increases with the applied force
+ Thermal conduction through meniscus.
Extremely complex to predict!
Approx: a single-asperity contact characterized by a contact diameter d0.



Thermal transport from tip to sample

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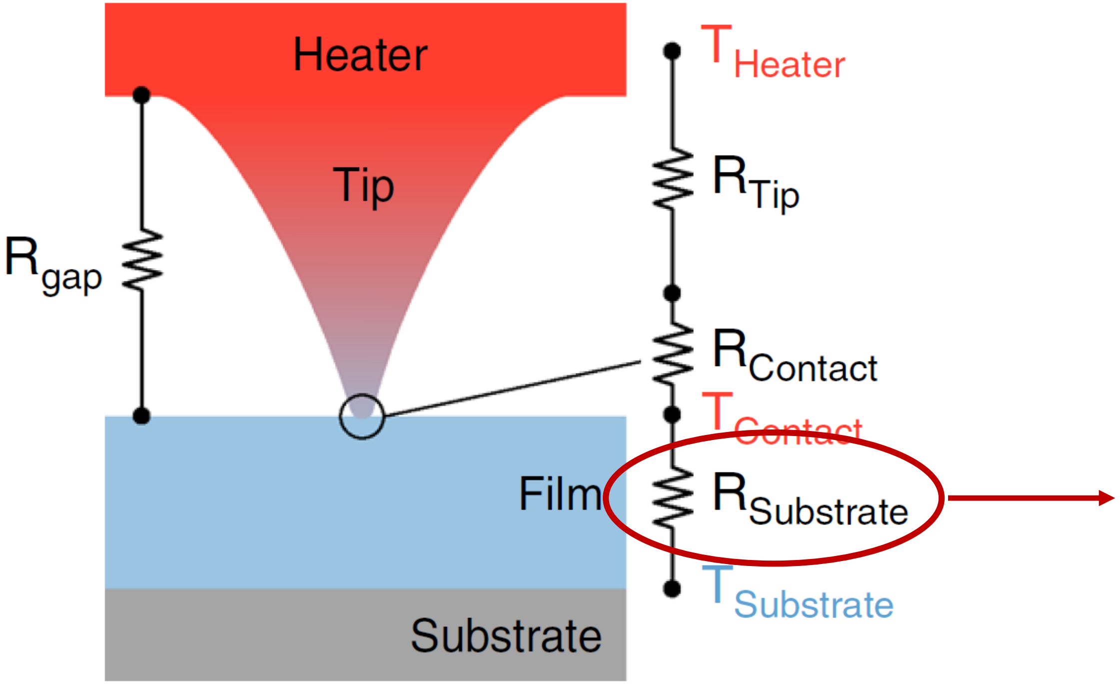


Howell et al. Microsystems & Nanoengineering (2020) 6:21

Well understood and depends on the thermal conductance of the film, film thickness, contact point diameter, substrate thermal conductance.

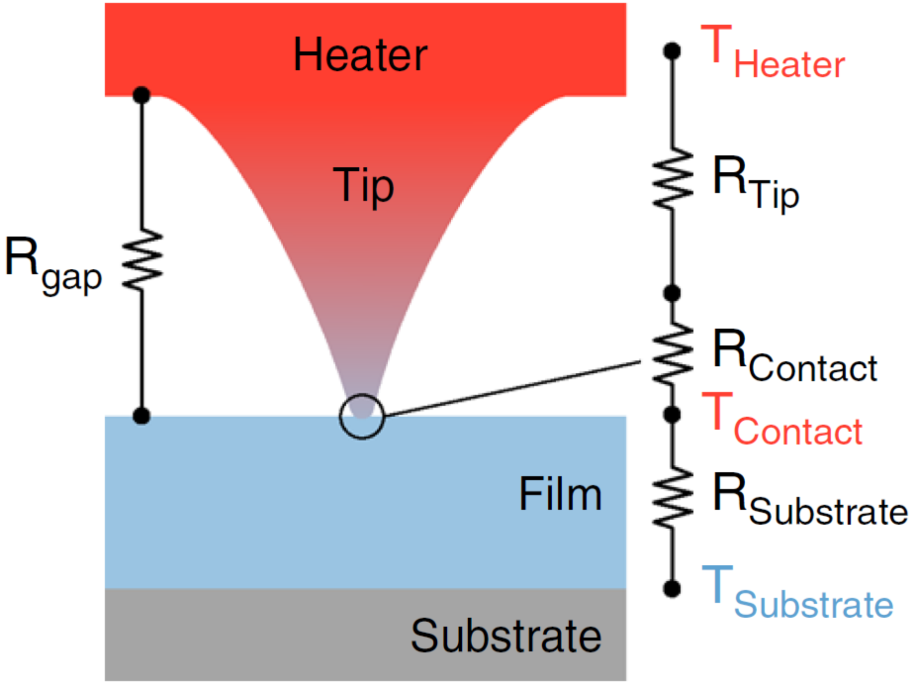
$$R_{sp} = \frac{1}{2\kappa_s d_0} - \frac{1}{2\pi\kappa_s t}\log\left(\frac{2}{1+\kappa_s/\kappa_{sub}}\right)$$

ks thermal cond film
d0 contact diameter
t film thickness
ksub thermal cond substrate

$$C = \frac{T_{cont}}{T_{heat}} = \frac{R_{subs}}{R_{tip} + R_{cont} + R_{subs}}$$

Thermal transport from tip to sample

Tip/Sample Thermal resistance model

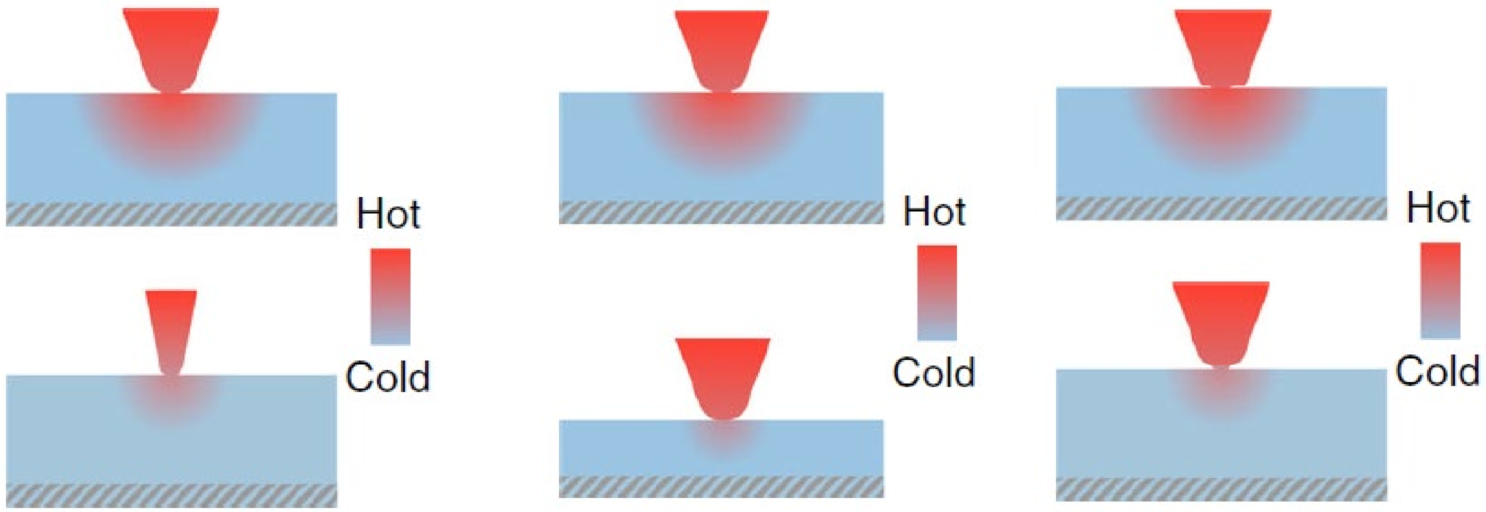


Howell et al. Microsystems & Nanoengineering (2020) 6:21

$$C = \frac{T_{cont}}{T_{heat}} = \frac{R_{subs}}{R_{tip} + R_{cont} + R_{subs}}$$

Parameters influencing T contact

▶ Tip apex size ▶ Film thickness ▶ Load



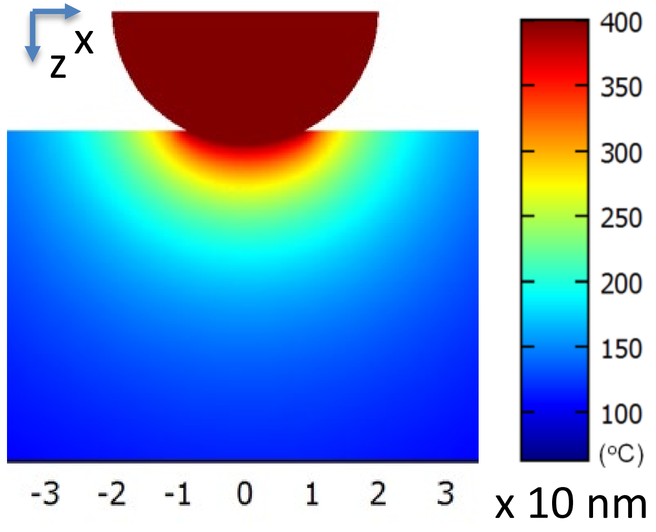
Howell et al. Microsystems & Nanoengineering (2020) 6:21

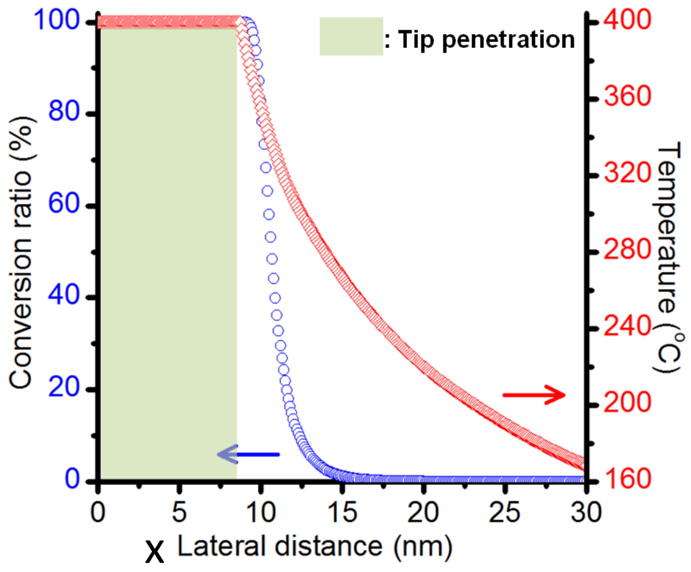
▶ Film thermal conductivity (Higher K: lower T, higher resolution)

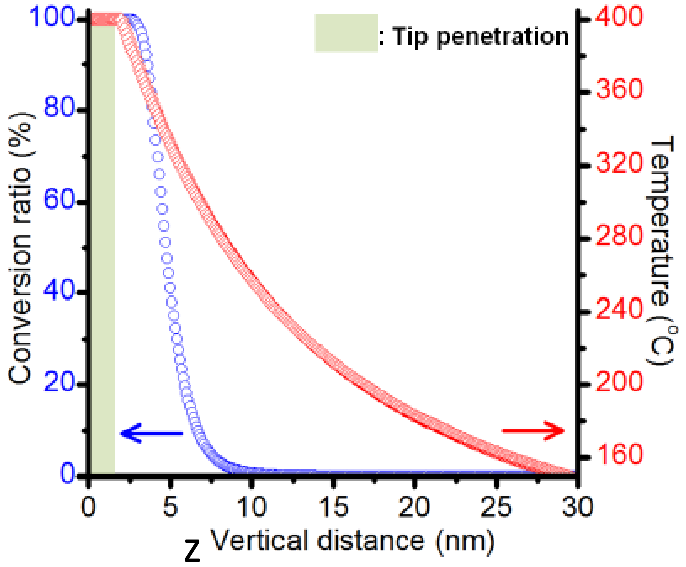
Influence of the temperature on the conversion efficiency

Finite element modelling (FEM) of the temperature and amine conversion profile inside a carbamate copolymer.

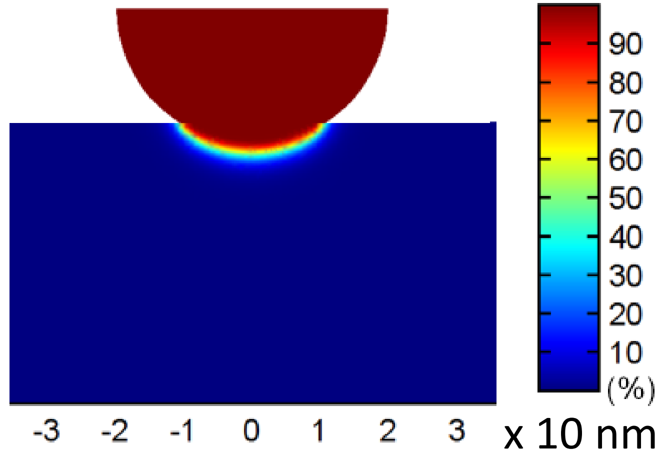
Temperature vs distance

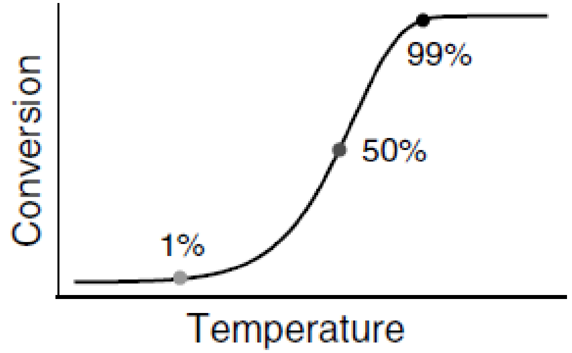






Conversion ratio vs distance





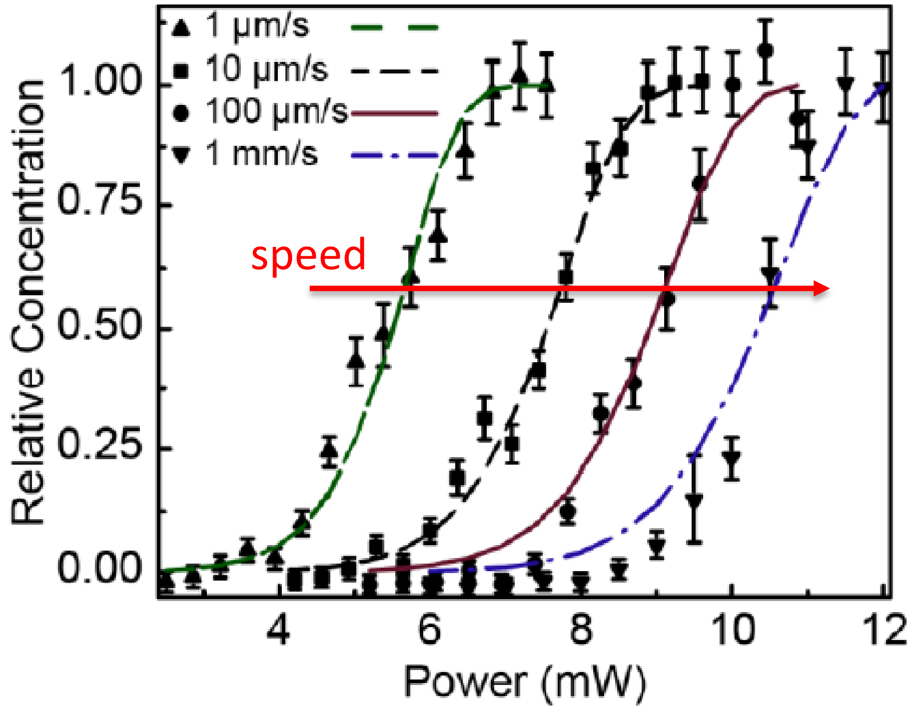
The effective conversion profile depends on the COMBINATION of the <u>thermal profile</u> and the <u>temperature dependence of the reaction</u>

Debin Wang, Ph.D. Thesis GeorgiaTech 2010

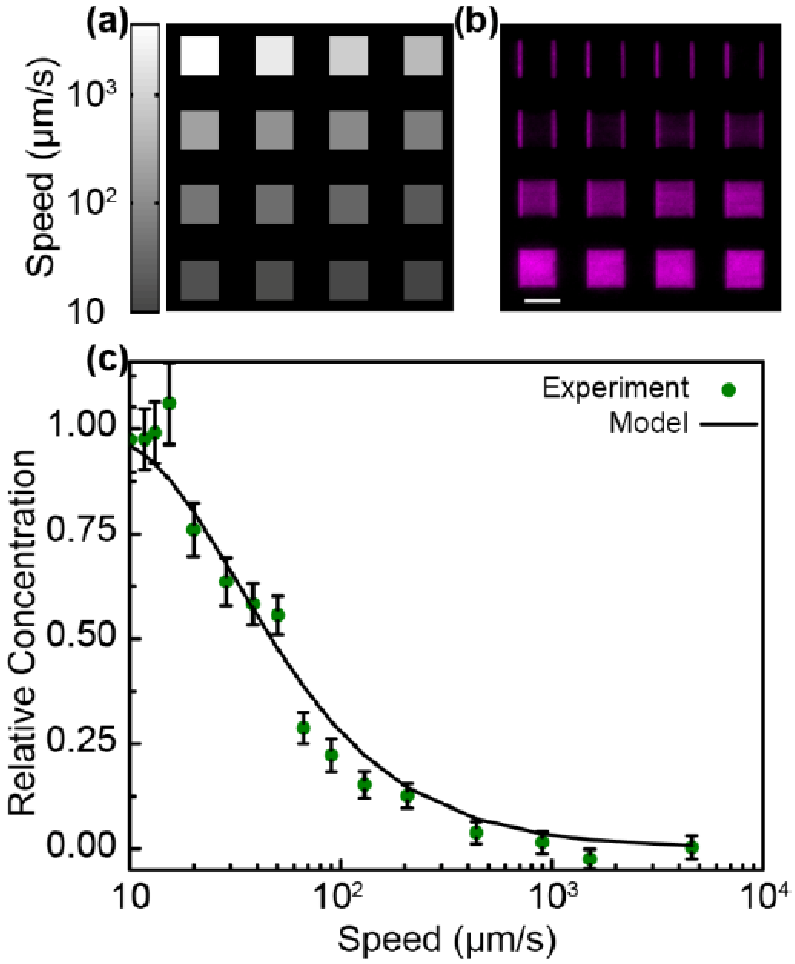
Influence of the patterning speed on the conversion efficiency

Controlled thermally-induced deprotection of amine groups from a polymeric film

Conversion efficiency at different speed



Fixed temperature, varying speed



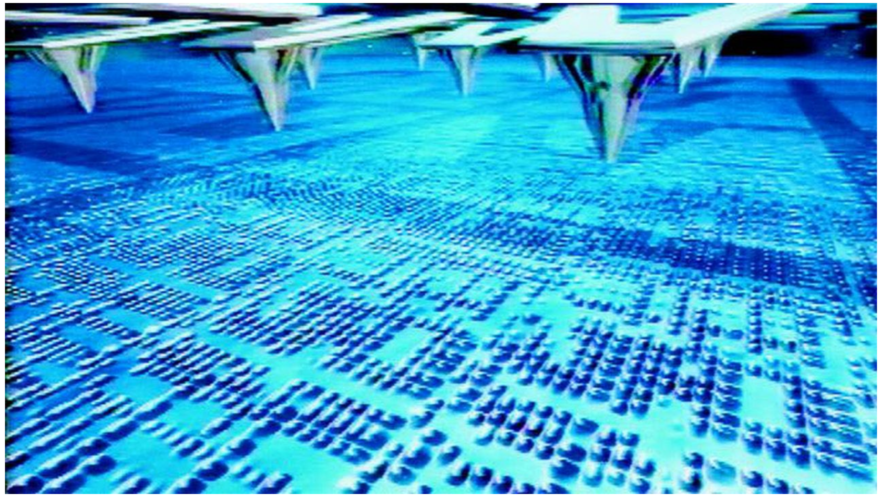
Higher speed exposes the system to the temperature profile for less time, resulting in a decreased rate of reaction.

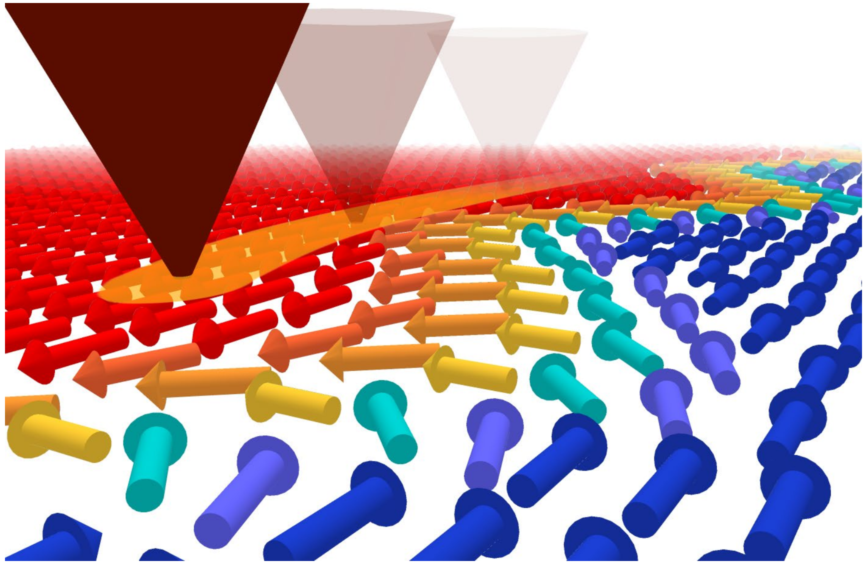
Keith Carroll, Ph.D. Thesis GeorgiaTech 2013

Outlook

- Scanning Probe Microscopy / Lithography
- Brief history of t-SPL: from milli-pedes to nano-structures
- Experimental: features and limitations of t-SPL
- Applications:

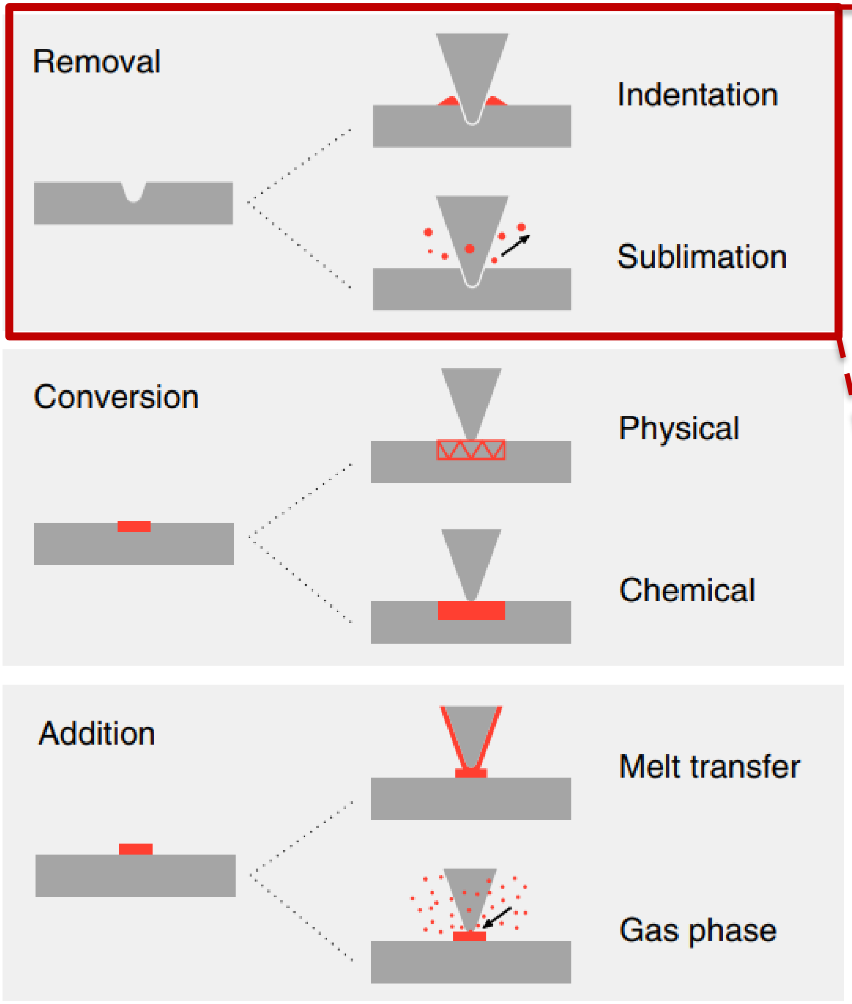
1) REMOVAL Direct sublimation of organic resists / lithography
2) «CHEMICAL conversion» at the nanoscale
3) «PHYSICAL conversion»: t-SPL for magnetism





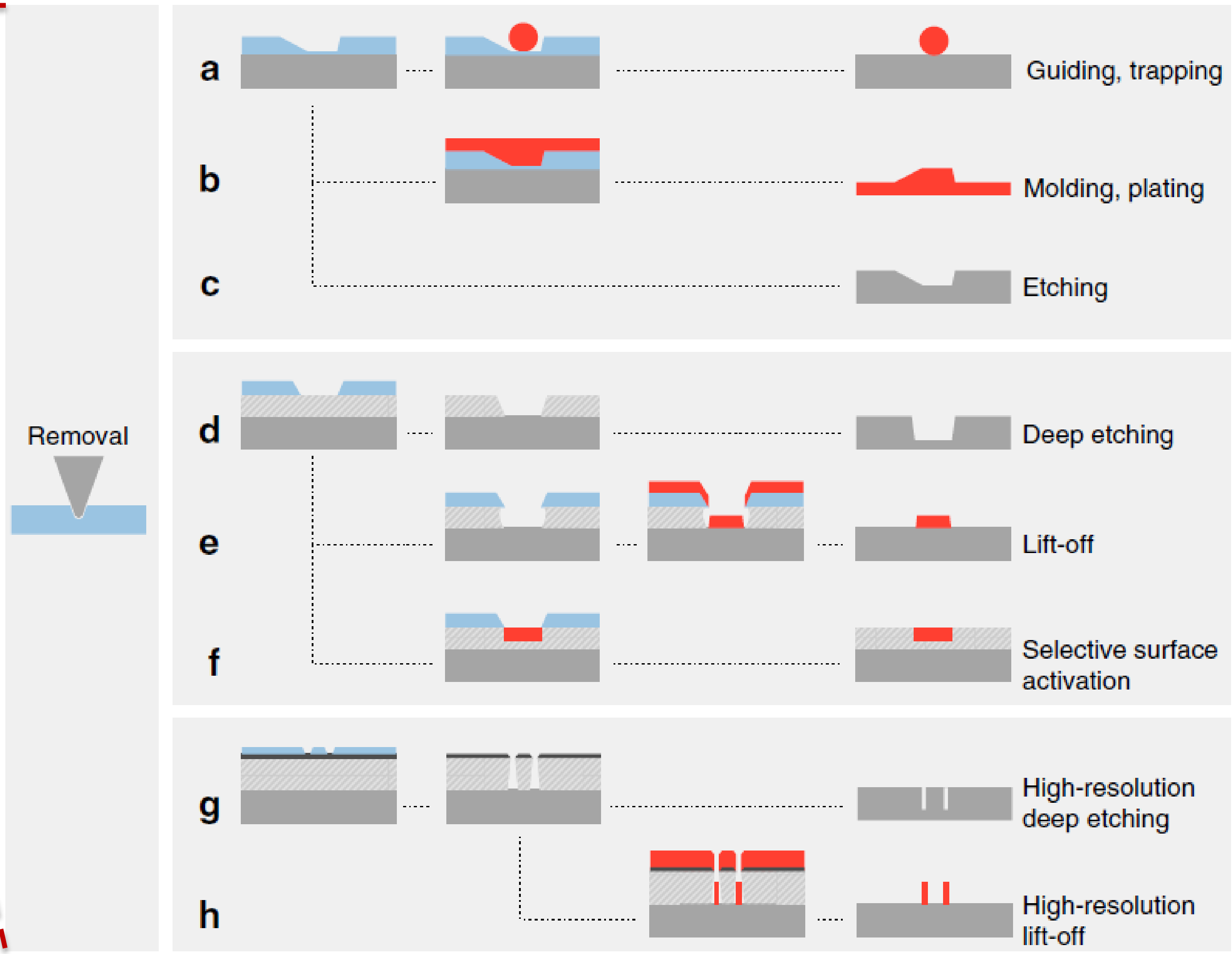
Applications of t-SPL: material removal

Heat as a universal stimulus



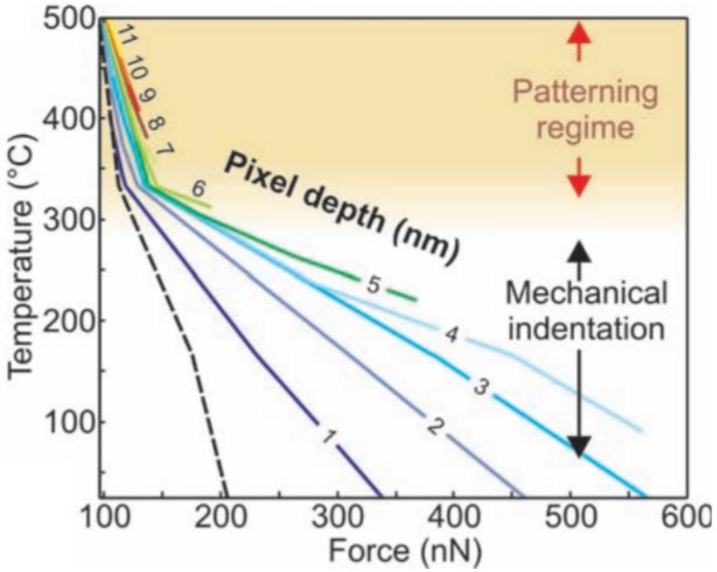
Howell et al. Microsystems & Nanoengineering (2020) 6:21

Processes involving material removal



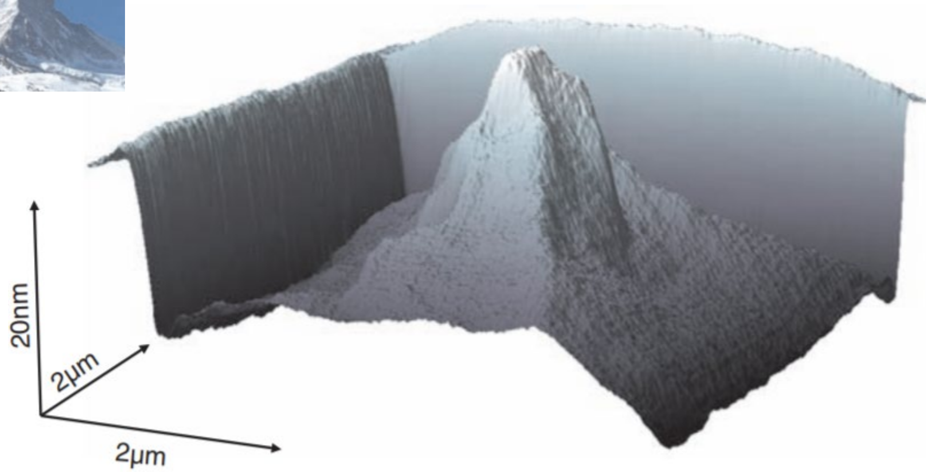
3D nanostructures in resist and transfer in Si

Equi-depth lines in resist

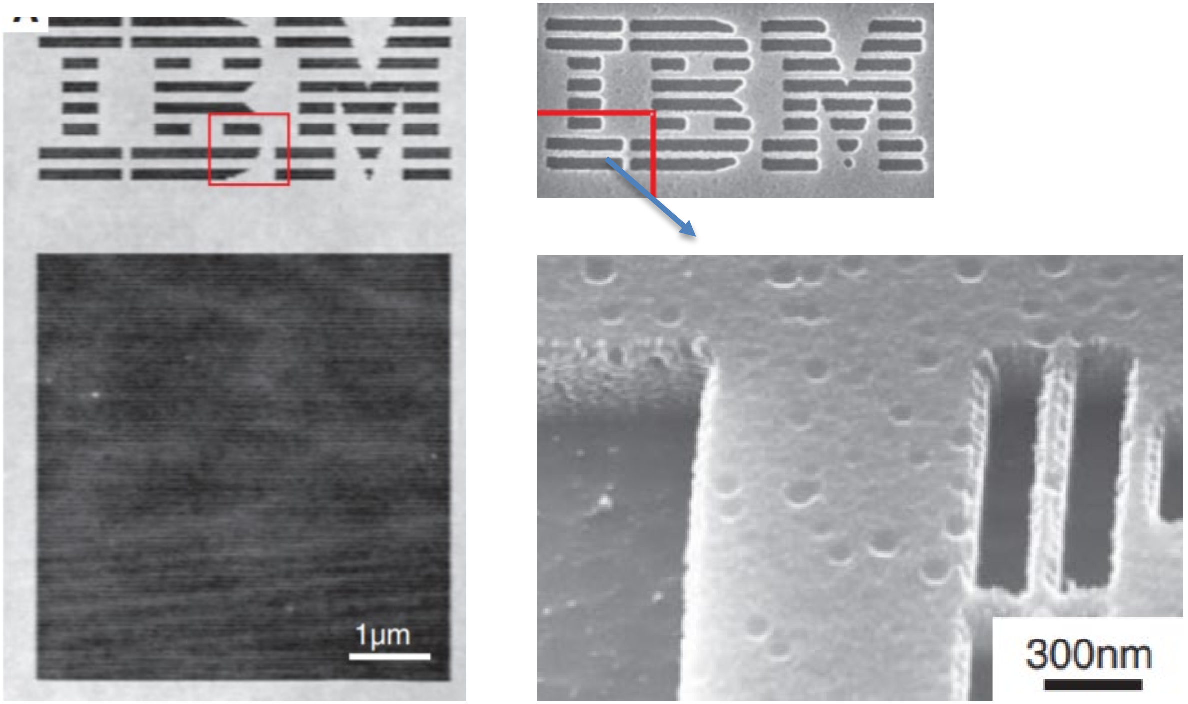


Local desorption of a glassy organic resist. Smallest width in Si 30 nm, by first transferring the pattern into a SiO2 etch mask, and then performing a second etching step.

3D replica in resist



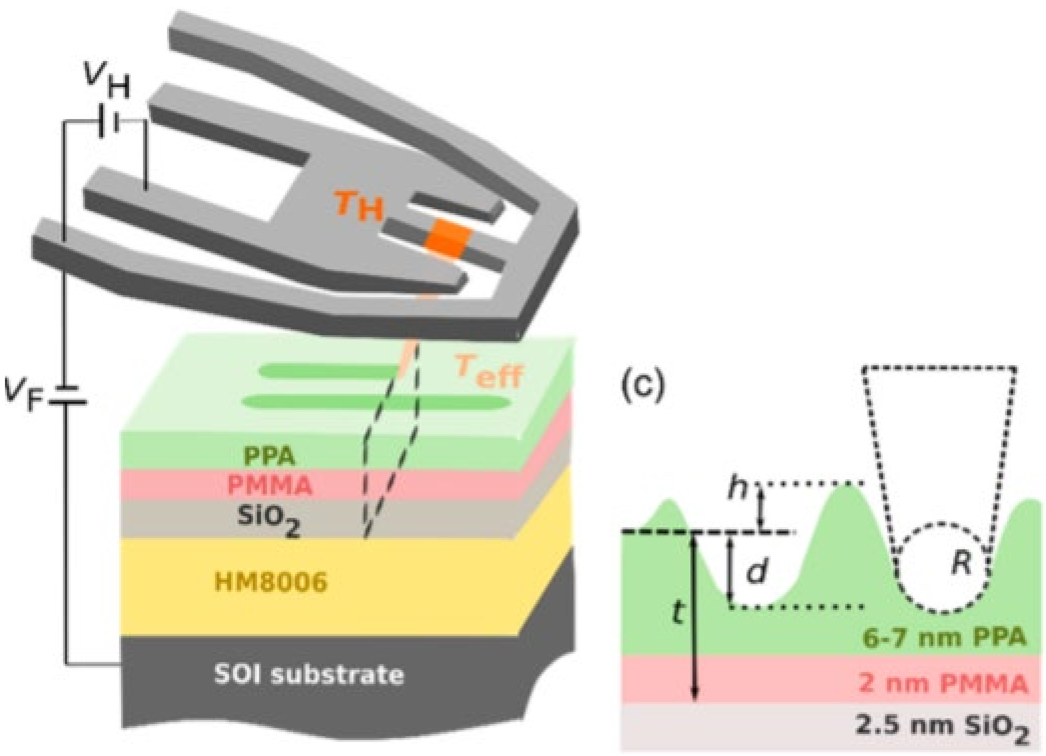
Pattern transfer in Si

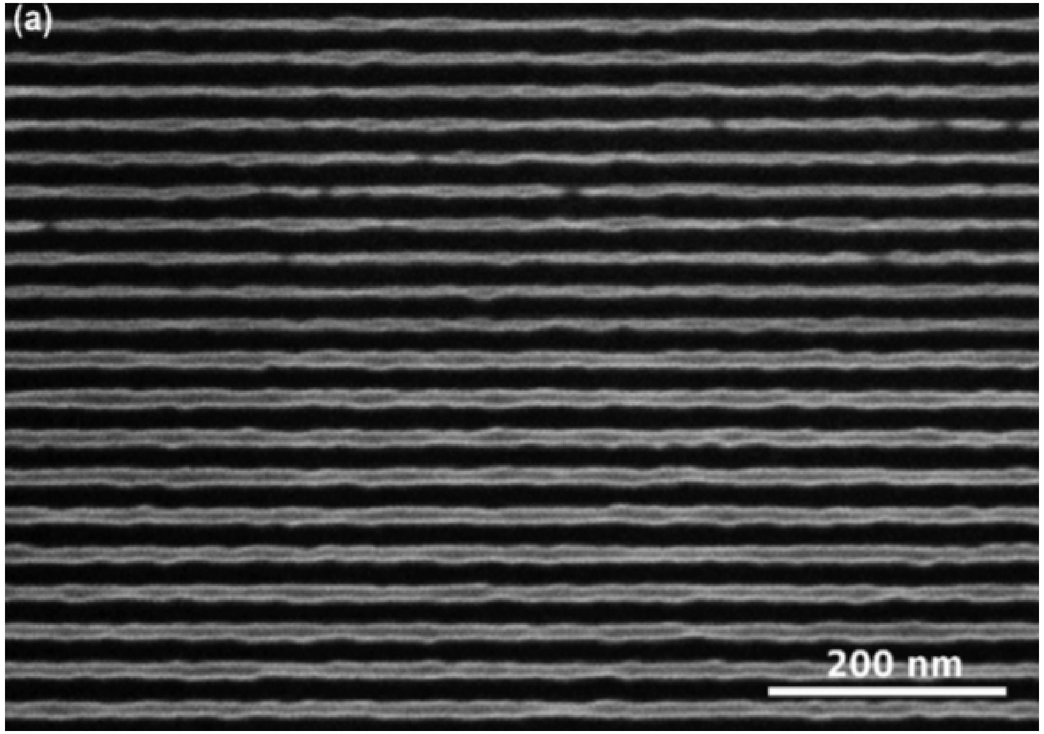


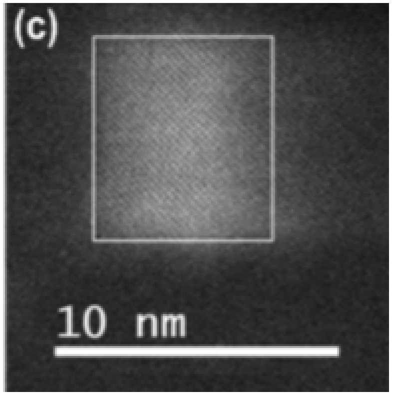
Science 328, 732–735 (2010).

Sub-10 nm features in Si via pattern transfer

Thin lines in polyphthalaldehyde (PPA) layer, then transferred into Si. The best pattern geometry is obtained at a heater temperature of ∼600 °C, which is below or close to the transition from mechanical indentation to thermal evaporation. For the 14 nm half-pitch lines in silicon, a line edge roughness of 2.6 nm (3σ), and a feature size of the patterned walls of 7 nm (12 nm thick Si).



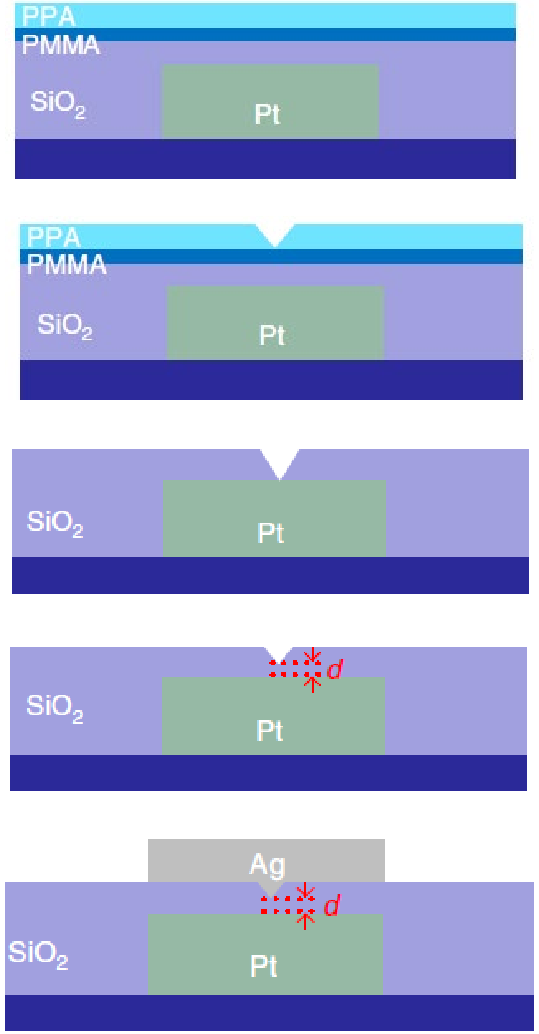




ACS Nano 2017, 11, 11890–11897

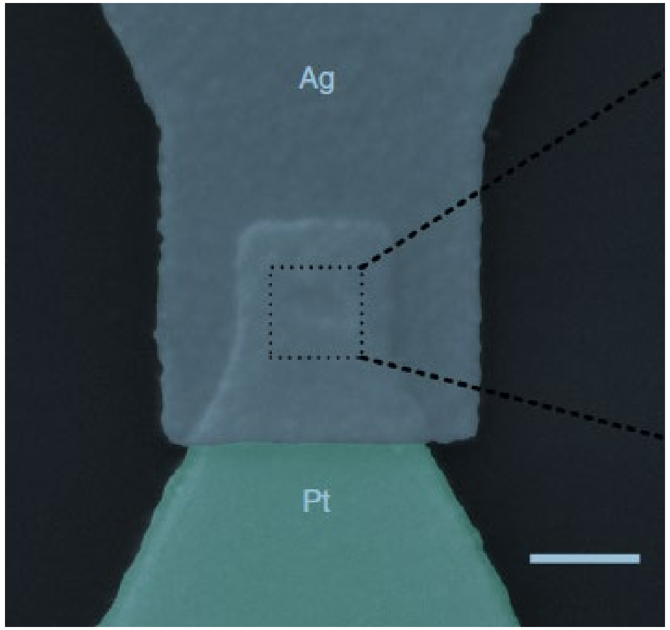
Atomic scale memristor fabrication

Fabrication process

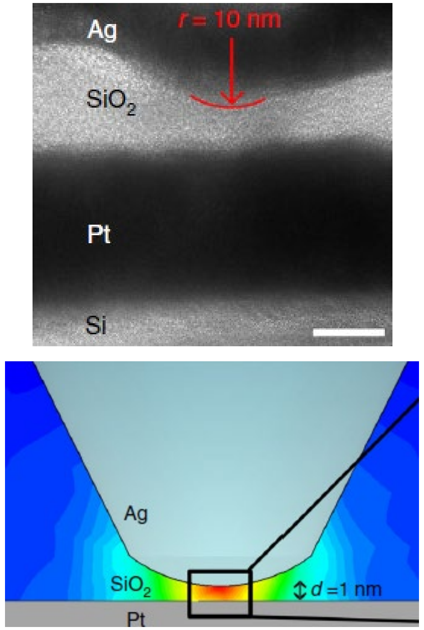


Tip-shaped structure patterned via t-SPL. Highly confined electric field at nanometer size and feature low switching voltage around 100 mV, operation speed in the nanosecond range, extinction resistance ratio as high as 6 × 105, reliable operations despite its atomic scale dimensions, and the possibility to a achieve multi-level behavior.

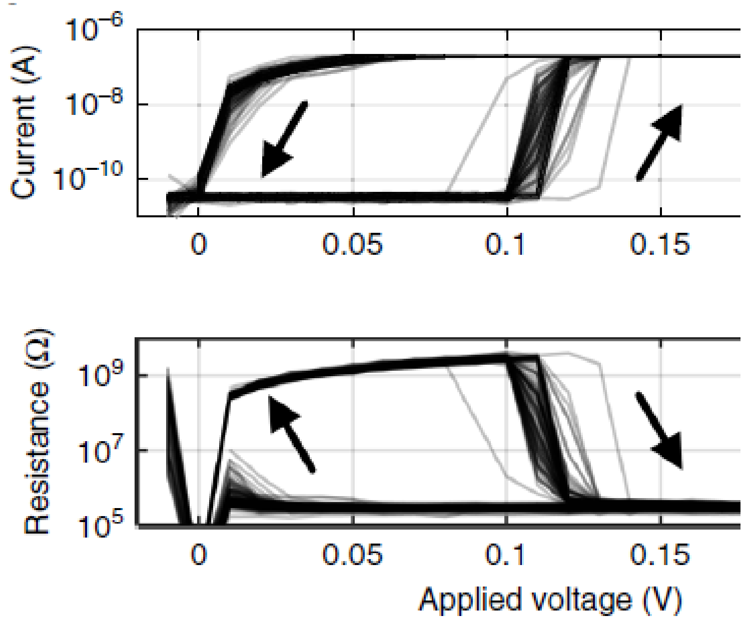
SEM top view



TEM cross section



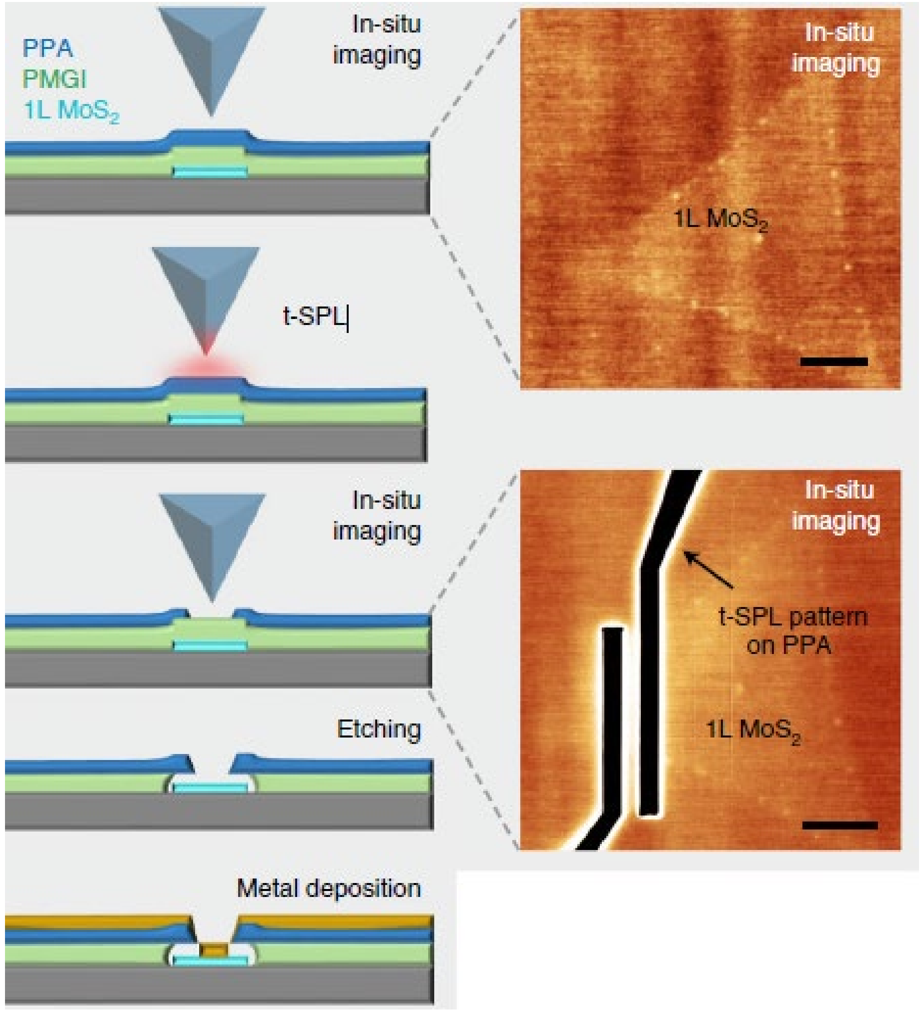
Switching characteristics



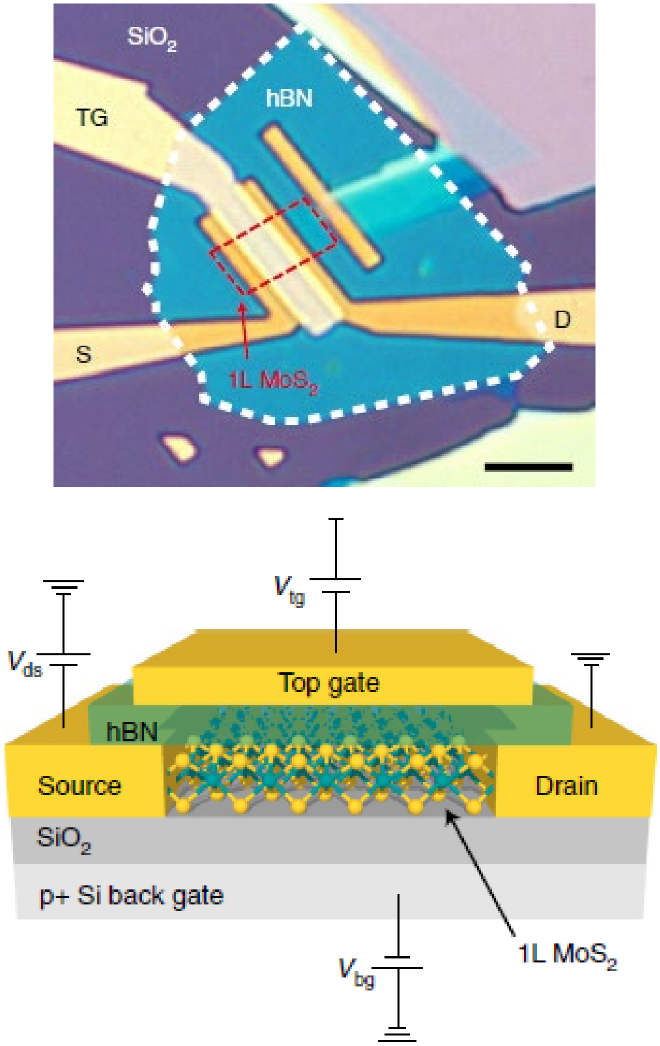
Commun. Phys. 2, 28 (2019)

Field effect transistors based on MoS_2

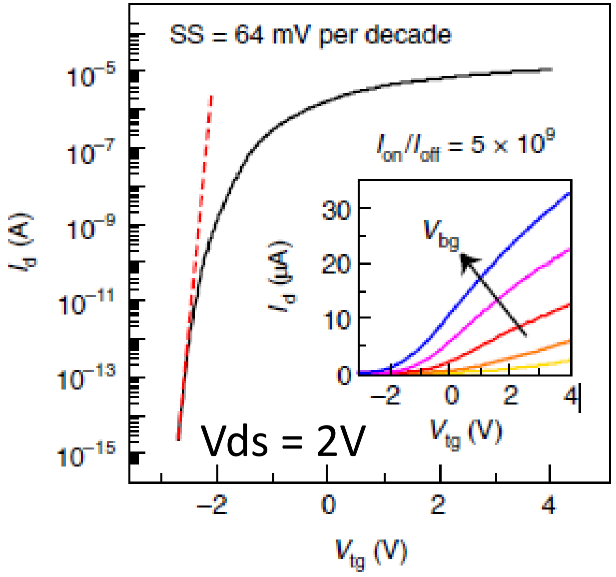
Fabrication process



Top gate FET



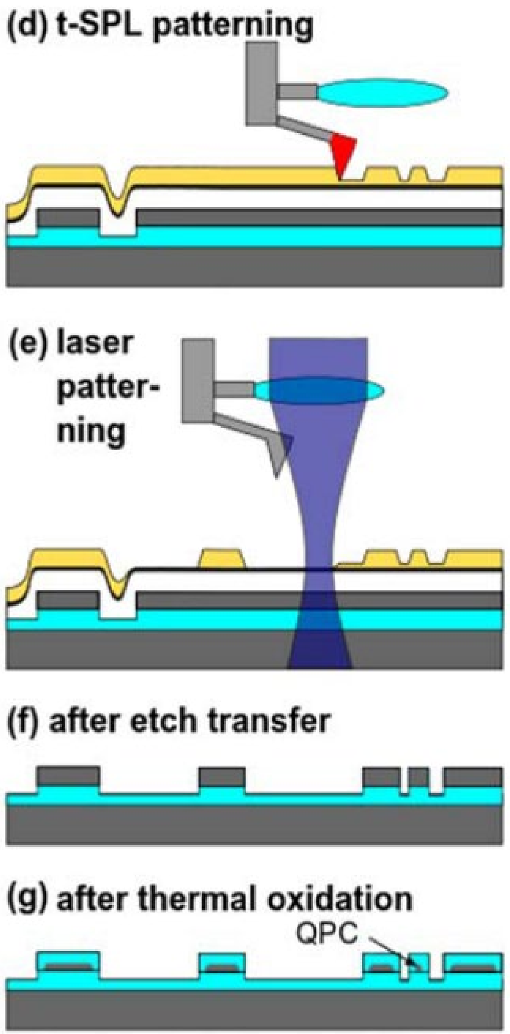
Transfer curve



X. Zheng.. EA et al. Nat. Electron. 2, 17–25 (2019)

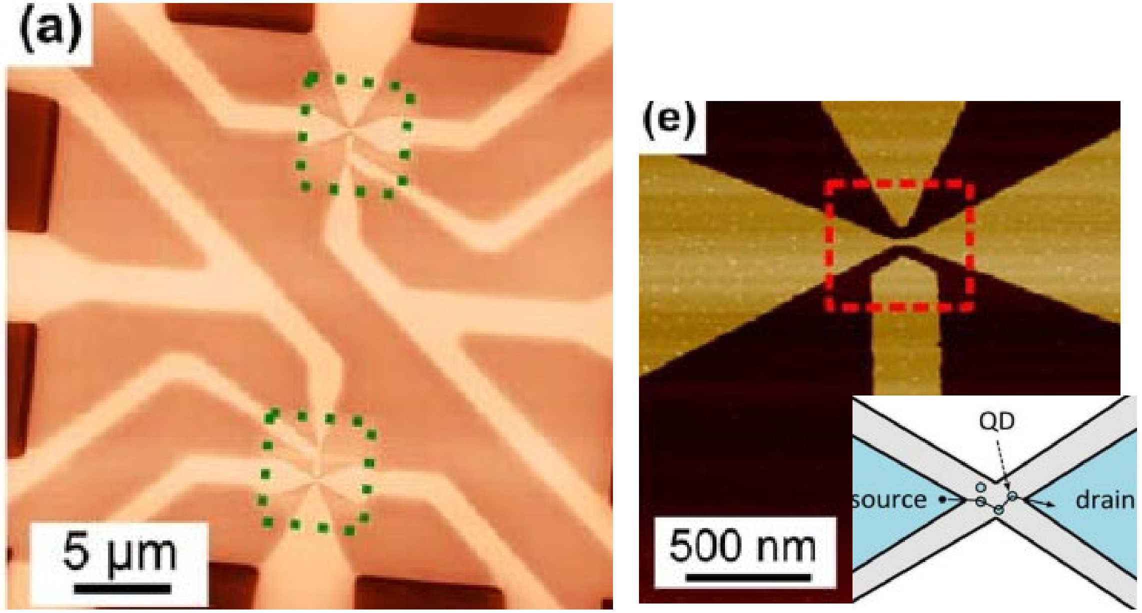
Quantum Dot Transistors via Hybrid t-SPL / laser writing

Fabrication process

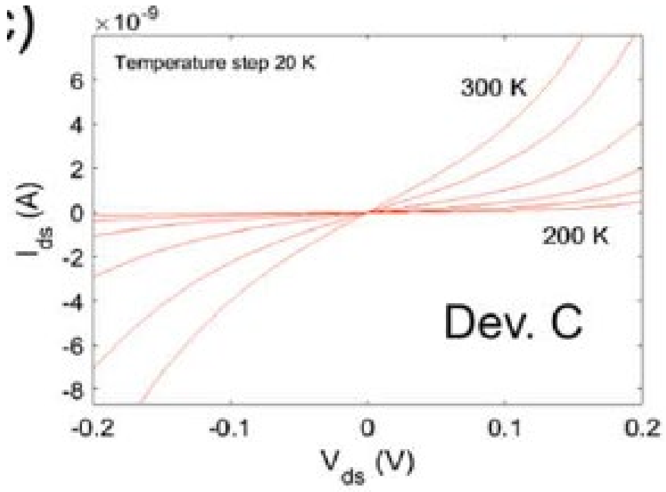


Room temperature (RT) single electron transistors (SETs) based on point-contact tunnel junctions. Electron localization within nanocrystals or phosphorous atoms embedded within the SiO2 allowed to reach tunneling behavior at RT.

Hybrid Laser + t-SPL patterns



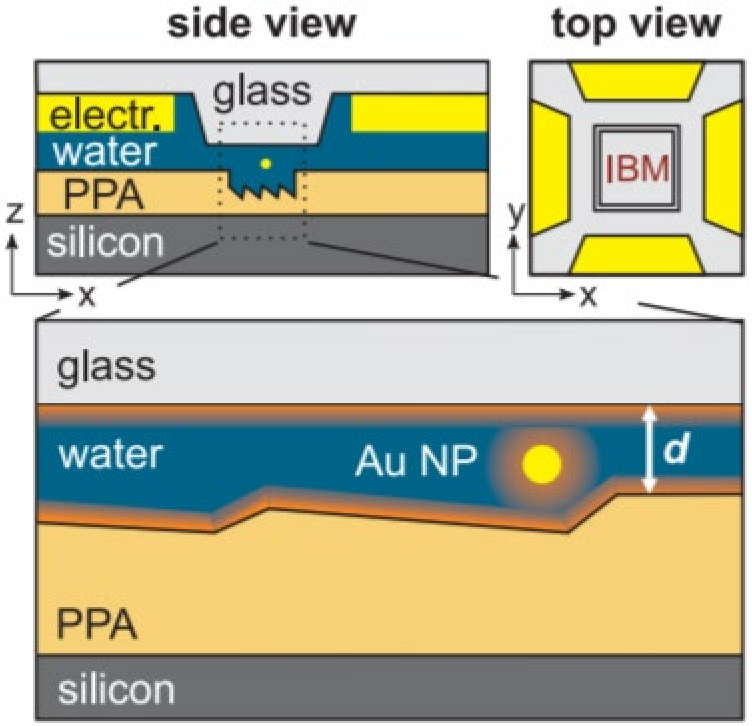
Tunnel dominated conduction at RT

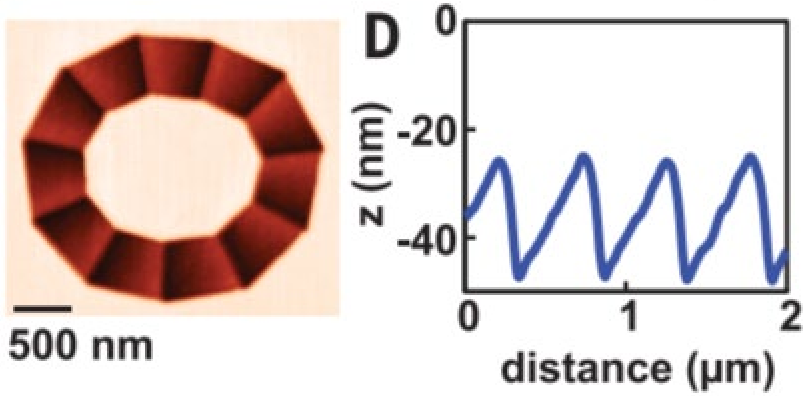


Nanotechnology 29, 505302 (2018).

Nanofluidic Rocking Brownian motors for nanoparticle manipulation

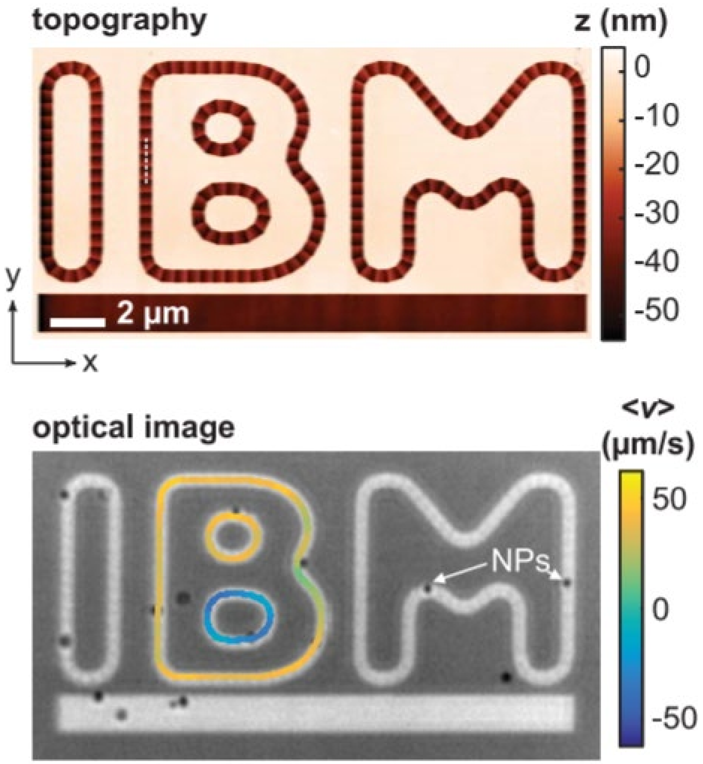
Concept / fabrication



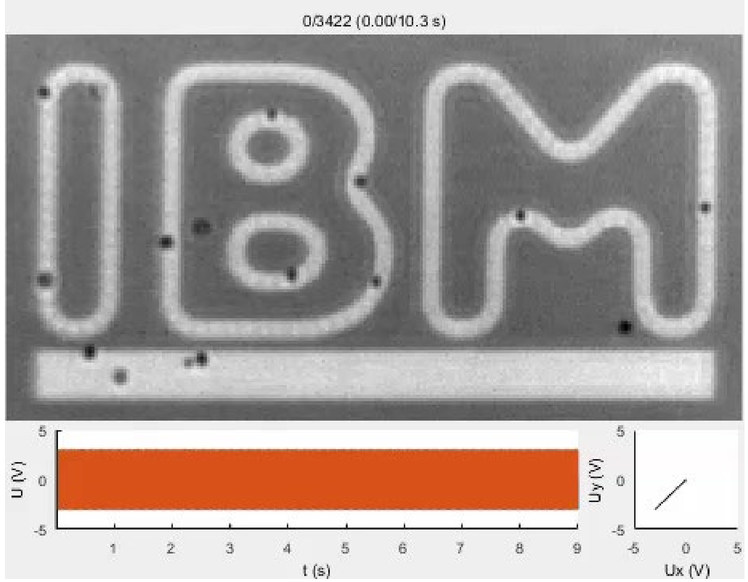


Energy landscapes for nanoparticles by accurately shaping the geometry of a nanofluidic slit and exploiting the electrostatic interaction between like-charged particles and walls. Directed transport was performed by combining asymmetric potentials with an oscillating electric field to achieve a rocking Brownian motor.

Nanoparticle Path



Directed transport via rotating E field

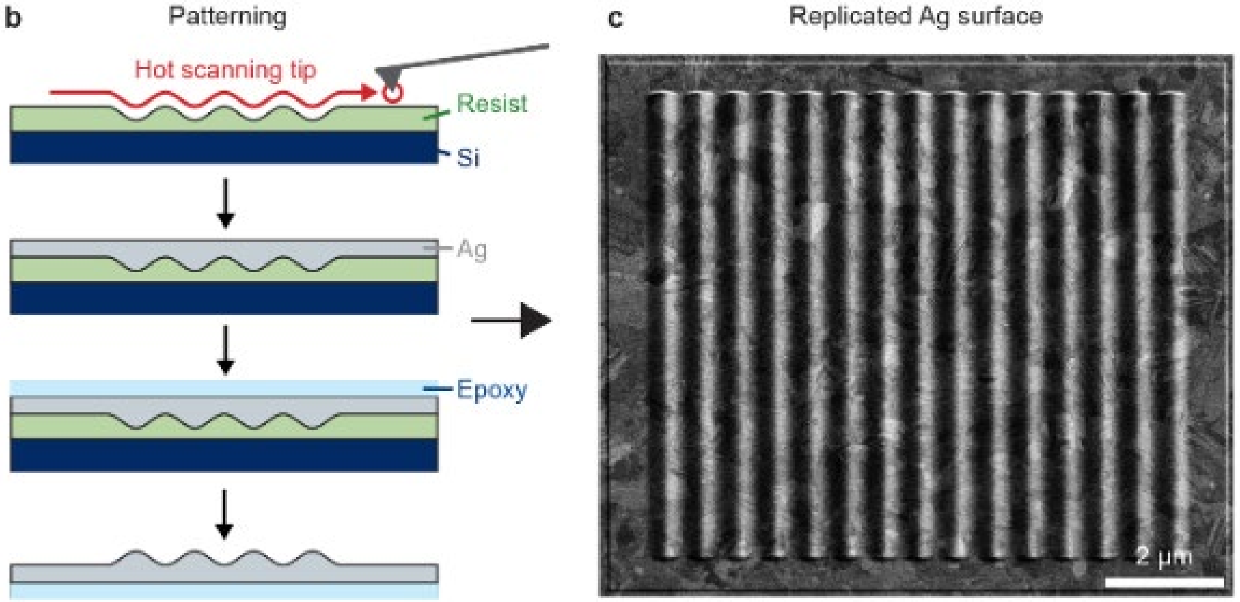


Science 359, 1505–1508 (2018).

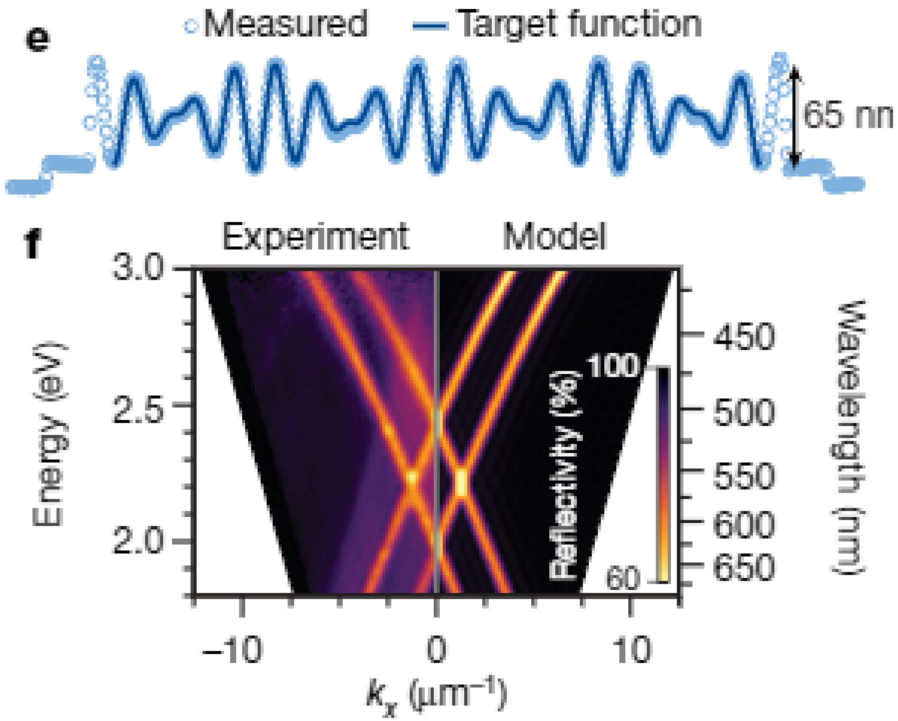
Optical Fourier Surfaces: 3D optical metasurfaces

The surface pattern generates a desired diffracted output through its Fourier transform. To shape the optical wavefront, **the ideal surface profile should contain a precise sum of sinusoidal waves**, each with a well defined amplitude, spatial frequency and phase.

Fabrication



Fourier Surface Model VS Experiment



Nature 582, 506–510 (2020)

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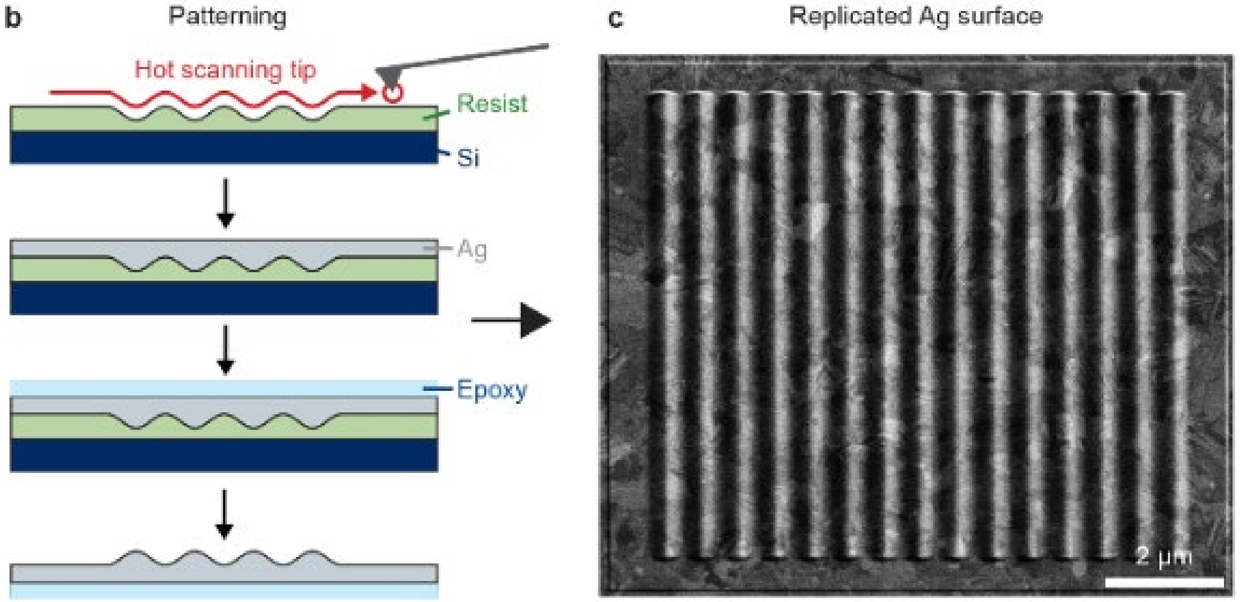
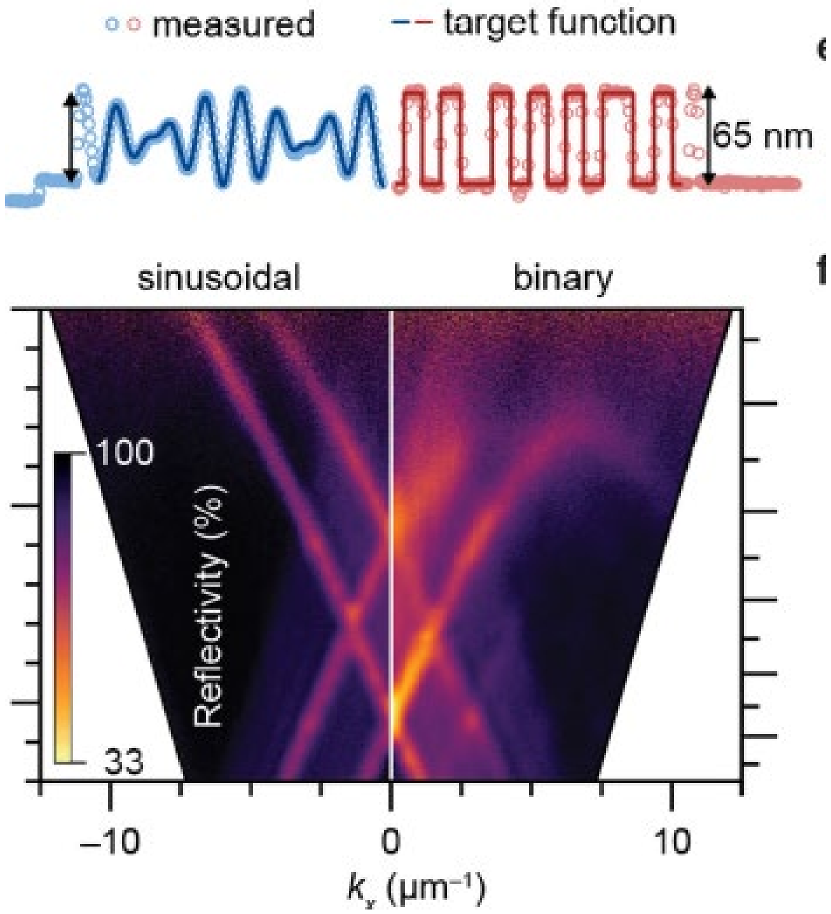


Sinusoidal VS binary



Nature 582, 506–510 (2020)

Outlook

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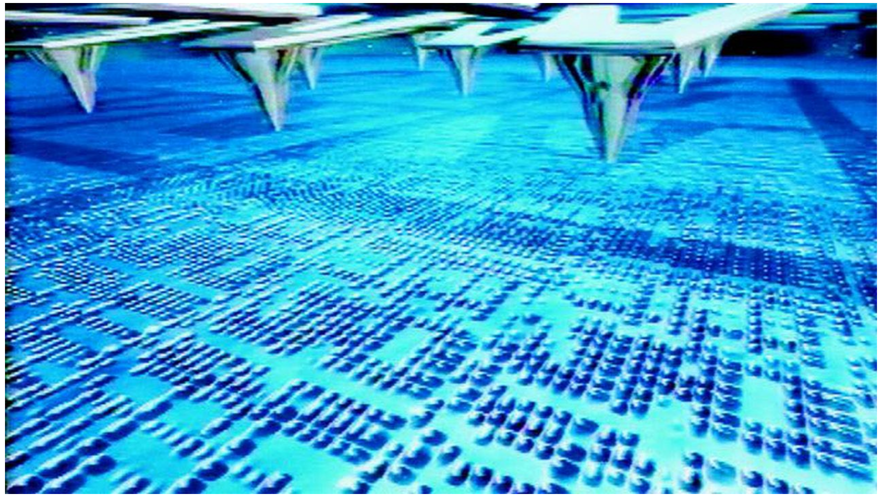
- *Experimental: features and limitations of t-SPL*



- ***Applications:***

1) *REMOVAL Direct sublimation of organic resists / lithography*
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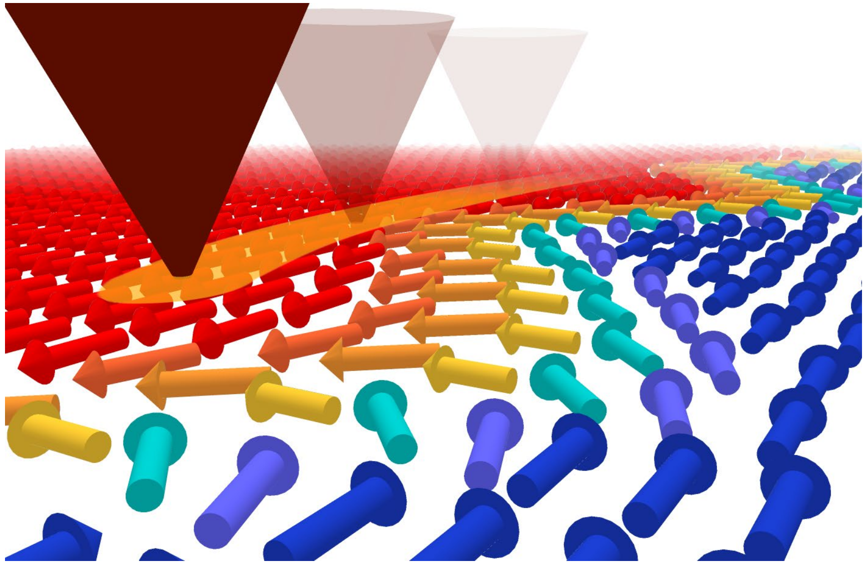
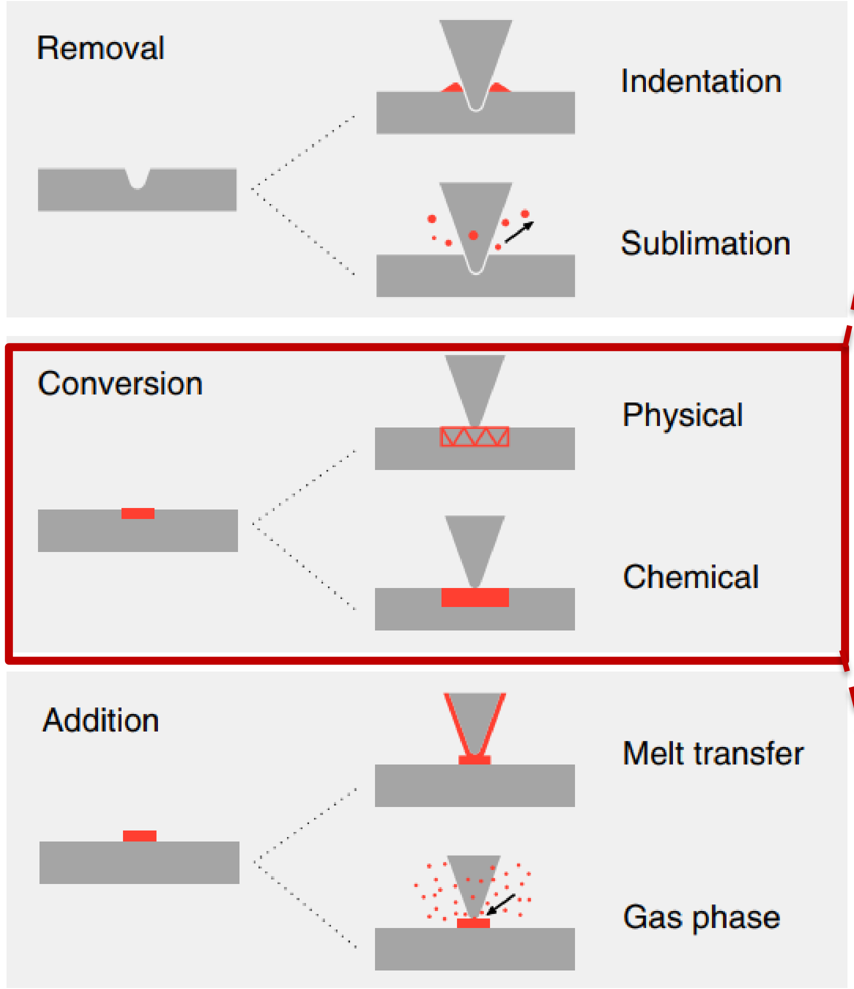
3) *«PHYSICAL conversion»: t-SPL for magnetism*



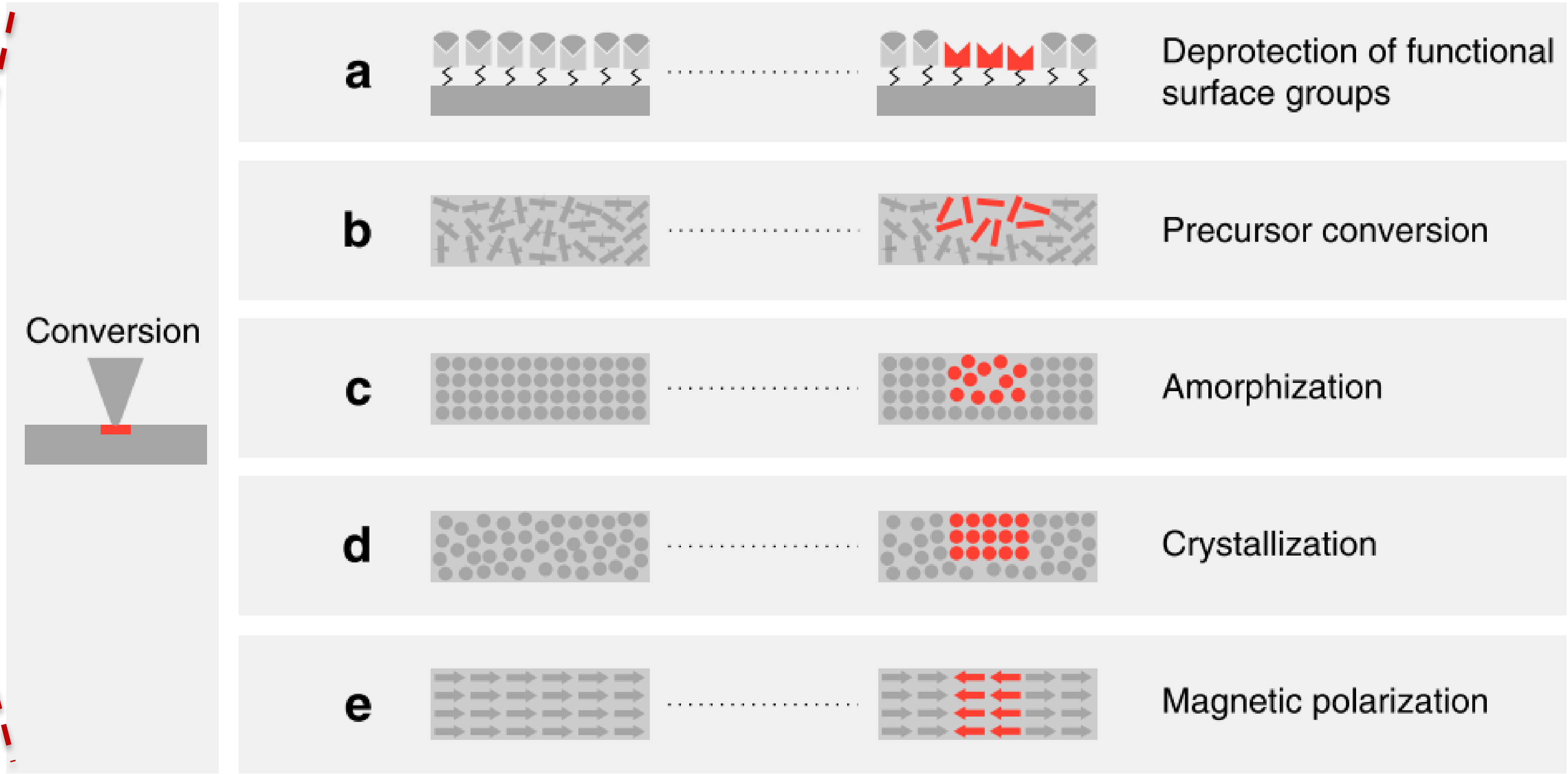
Direct material conversion

Heat as a universal stimulus



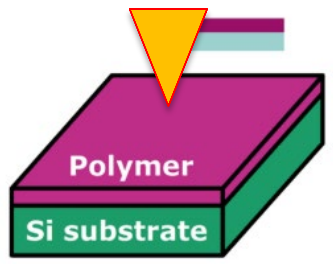
Howell et al. Microsystems & Nanoengineering (2020) 6:21

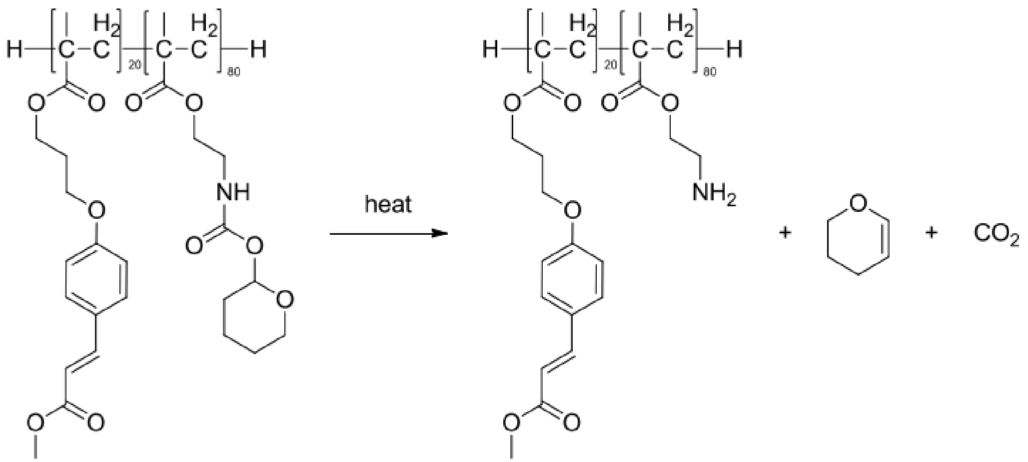
Conversion processes (not exaustive)



Controlled deprotection of functional groups

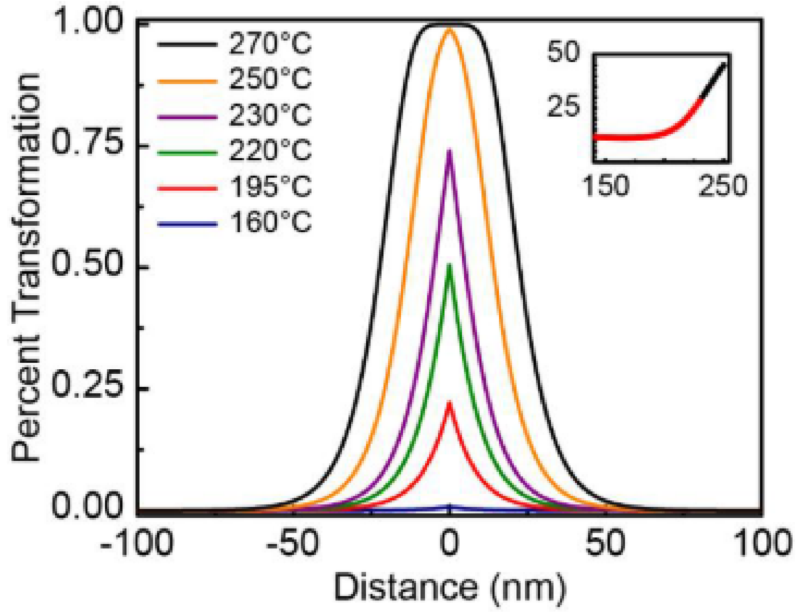
Thermally-induced deprotection of reactive amines



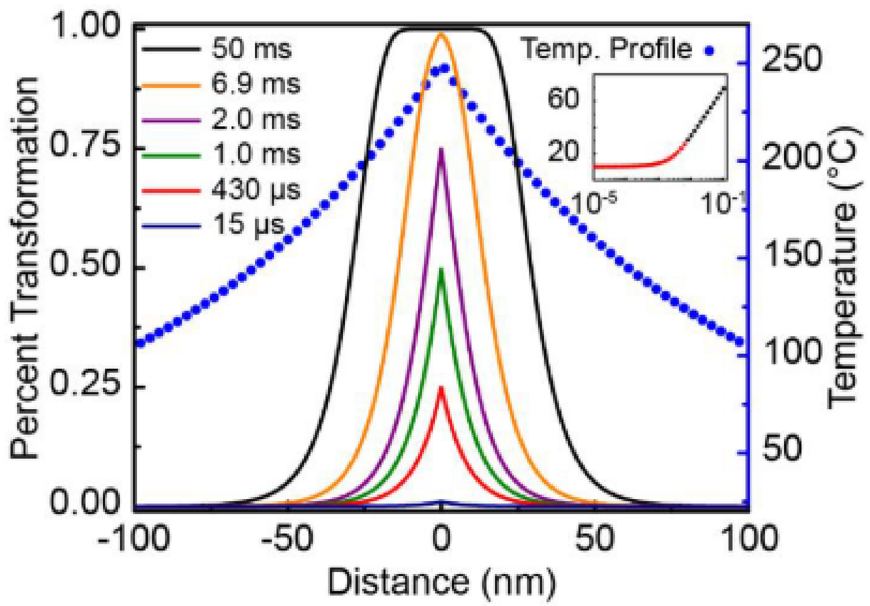


$$\frac{[P]}{[P_{tot}]} = 1 - e^{-k\cdot t} = 1 - e^{-A\cdot t\cdot e^{\frac{-E_a}{R\cdot T}}}$$

Model: Temperature dependence



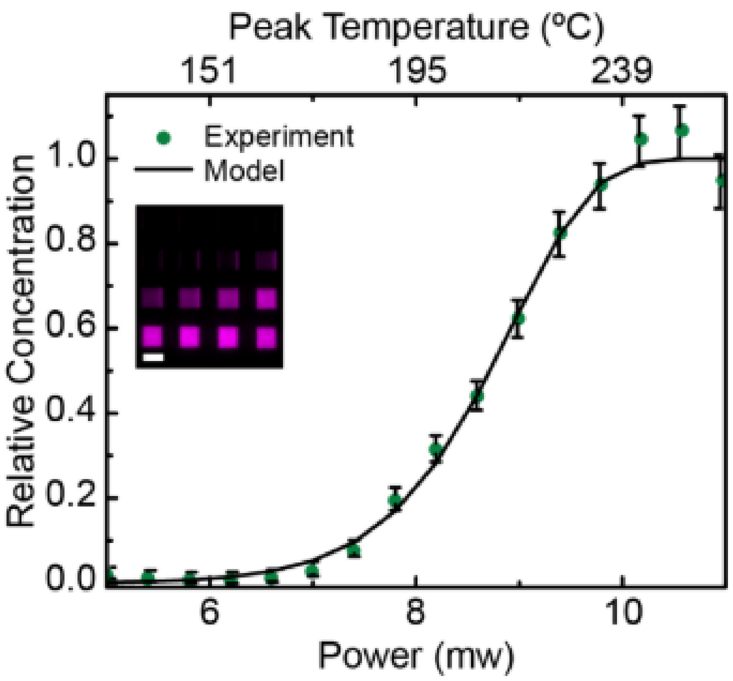
Model: Time-dependence

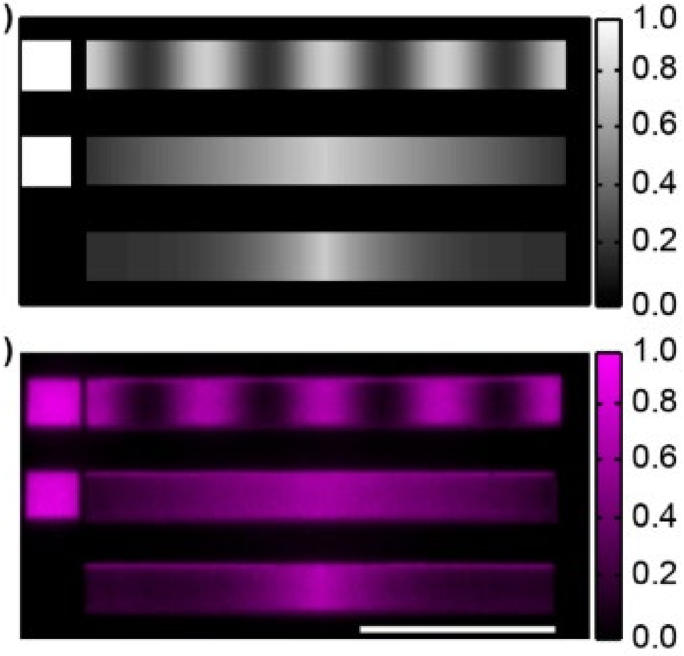


Carroll K M et al Langmuir 29 8675–82 (2013)

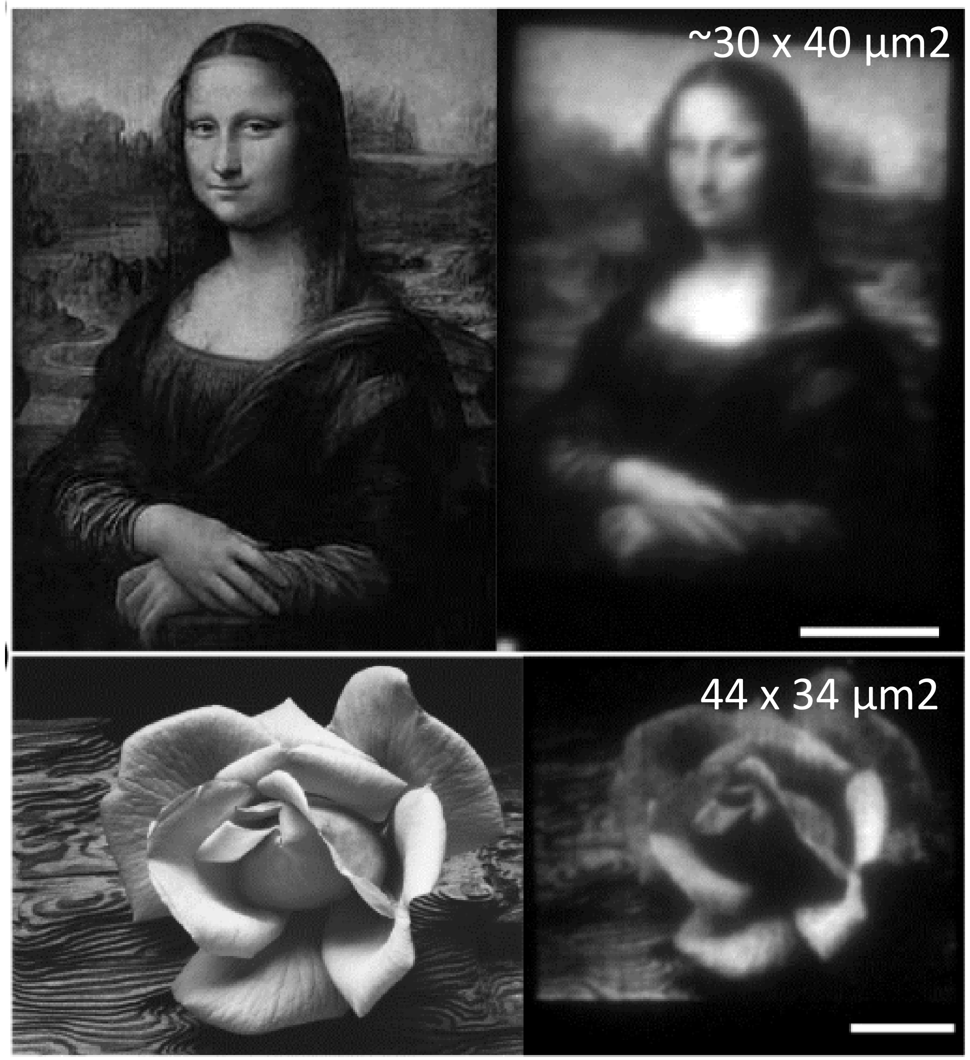
Controlled deprotection of functional groups

Exp: Controlled amine gradients





Grayscale map of amine concentration

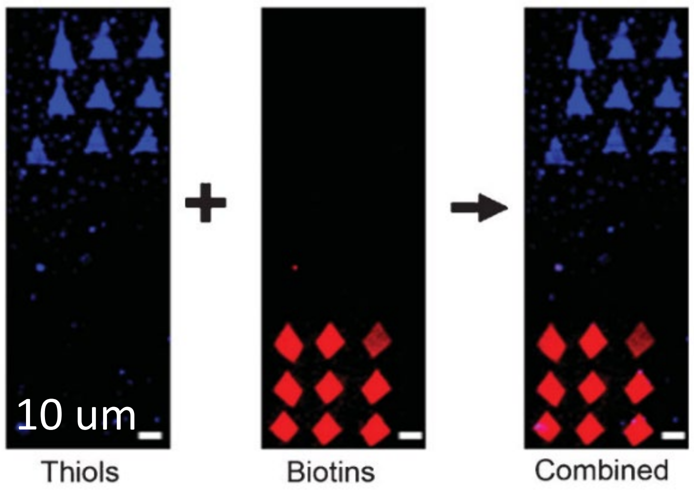


Carroll K M et al Langmuir 29 8675–82 (2013)

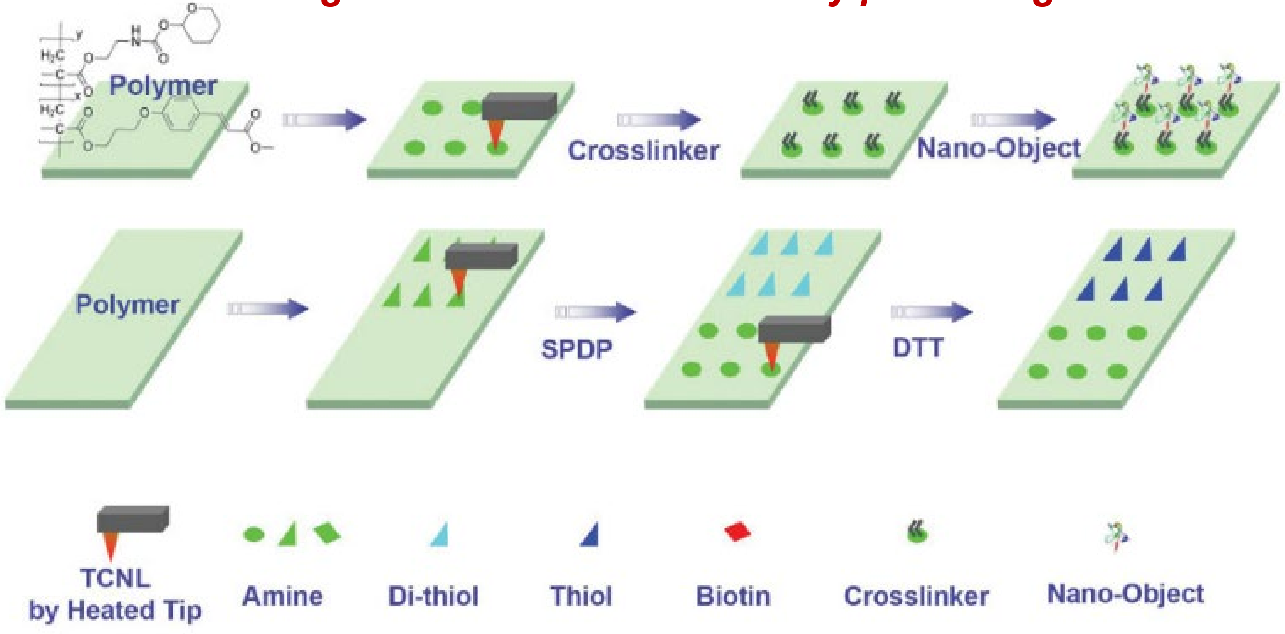
Controlled immobilization of multiple nano-objects

Nanoscale chemical patterning of different chemical species (amine, thiol, aldehyde, and biotin) in independent nanopatterns is achieved by the iterative application of thermochemical nanolithography (TCNL) and control the surface positioning of patterns followed by their chemical conversion to other functional groups.

Fluorescence image

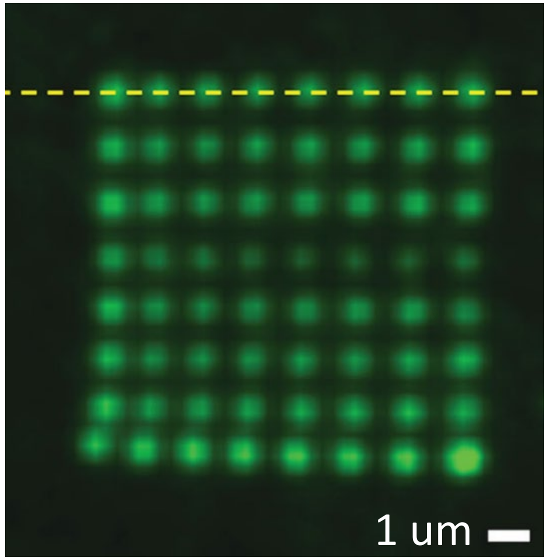


Single and double functionality patterning



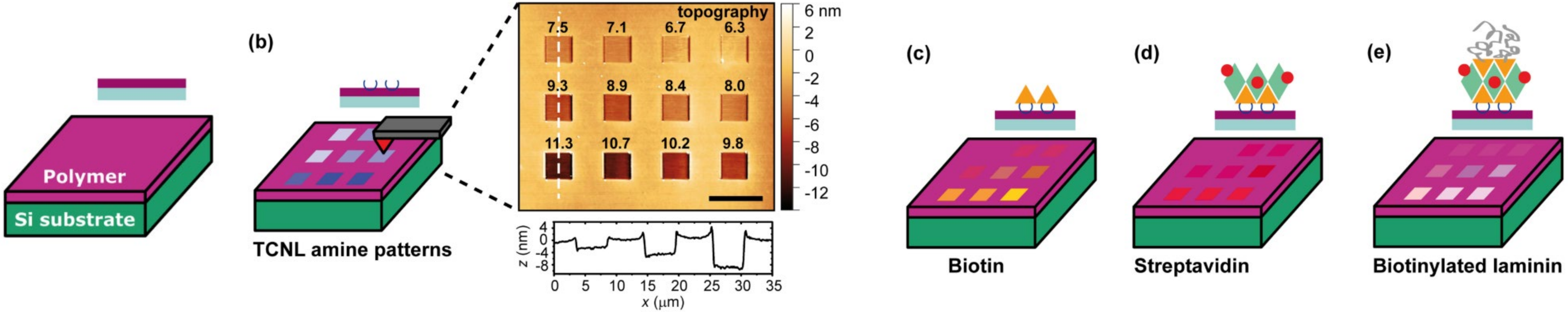
Wang et al. Adv. Funct. Mater. 19 3696–702 (2009)

Nanopatterning fibronectin arrays



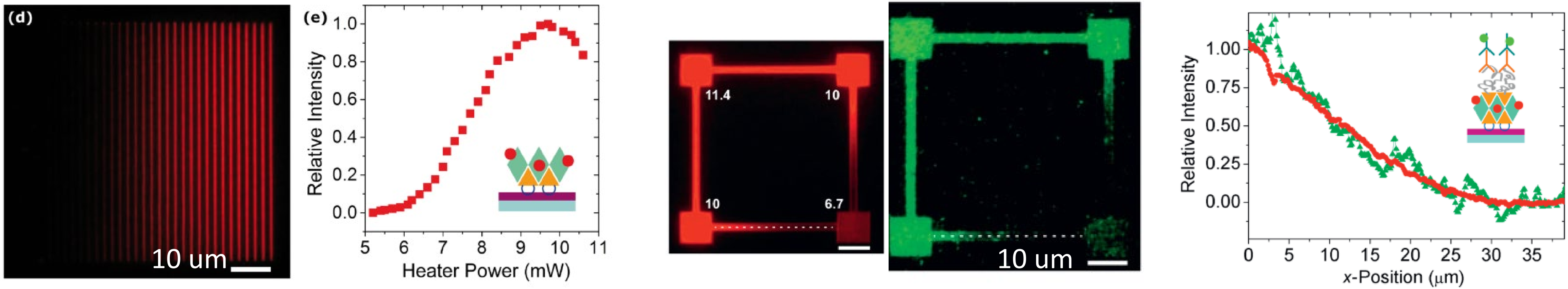
Immobilizing protein gradients with nanoscale resolution

Protein immobilization process



Fluo Streptavidin gradients

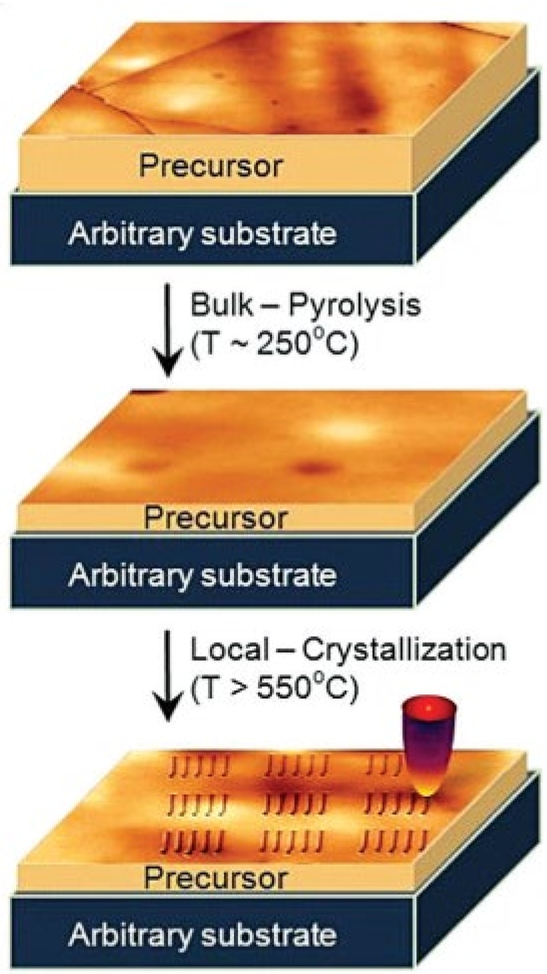
Fluo Streptavidin + Laminin gradients



EA et al. Nanotechnology 27 315302 (2016)

Direct nanofabrication of ferroelectric nanostructures

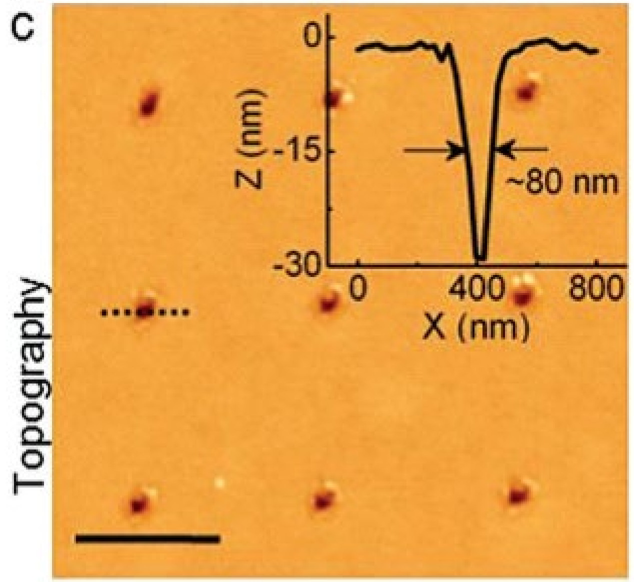
Fabrication process in PTO and PZT



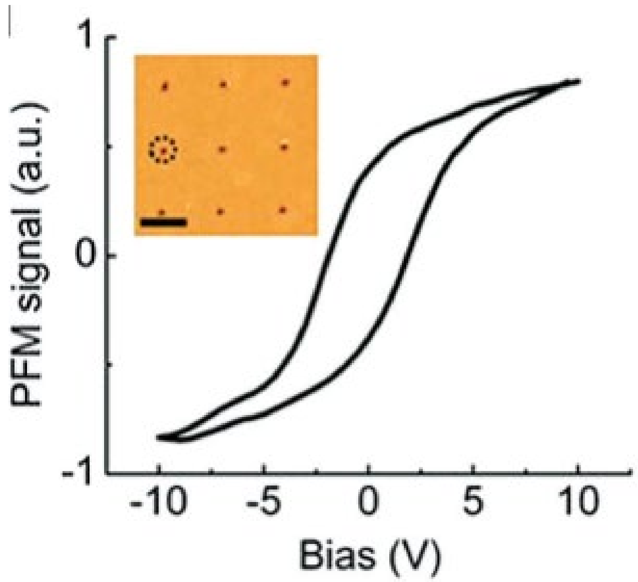
Kim S. Adv. Mater. 23 3786–90 (2011)

After deposition of a sol-gel precursor film of PZT and PTO and baking for removing the solvent, t-SPL is perform in order to locally crystallize the film into PZT or PTO. Tcryst > 550°C. The piezoelectric properties of the directly written nanostructures are measured via PFM.

Topography of FE patterns



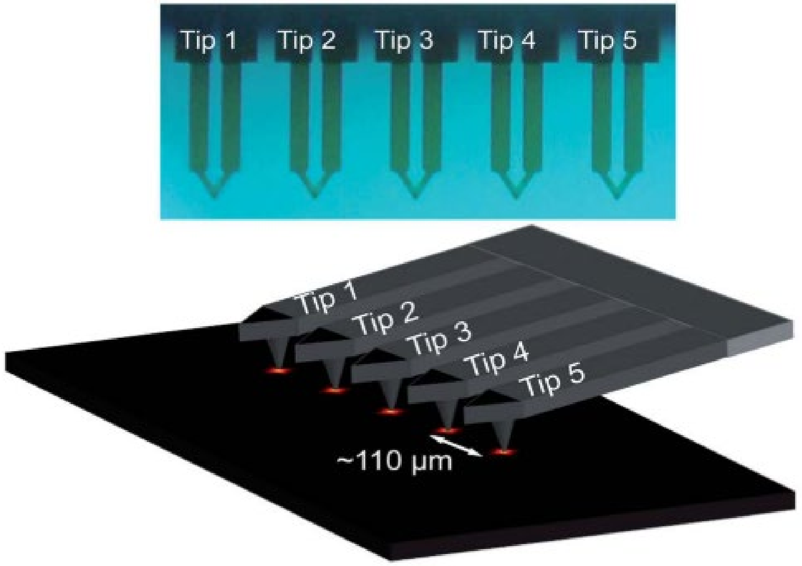
PFM hysteresis loop



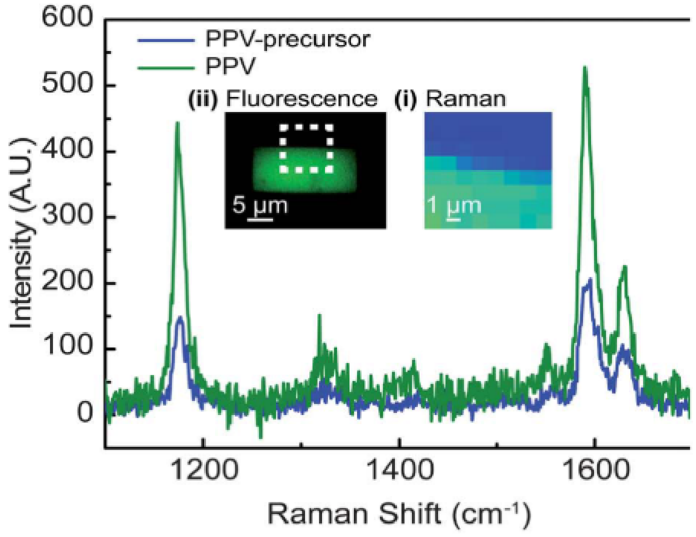
Parallelization via tip array: direct patterning of PPV nanostructures

An array of 5 tips independently addressable was used for the fabrication of conjugated polymer nanostructures. A precursor film is locally heated and converted in PPV, which is a photo-luminescent semi-conducting organic polymer. The photoluminescence is controlled by the degree of conversion, related to temperature.

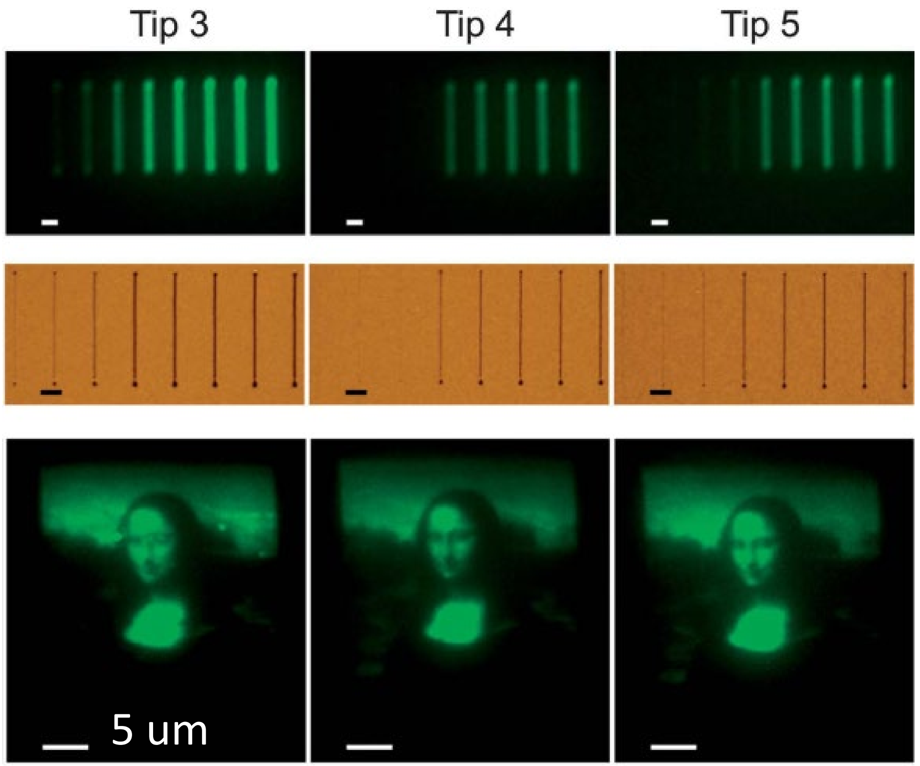
Leveled tip array



Micro Raman PPV fingerprints



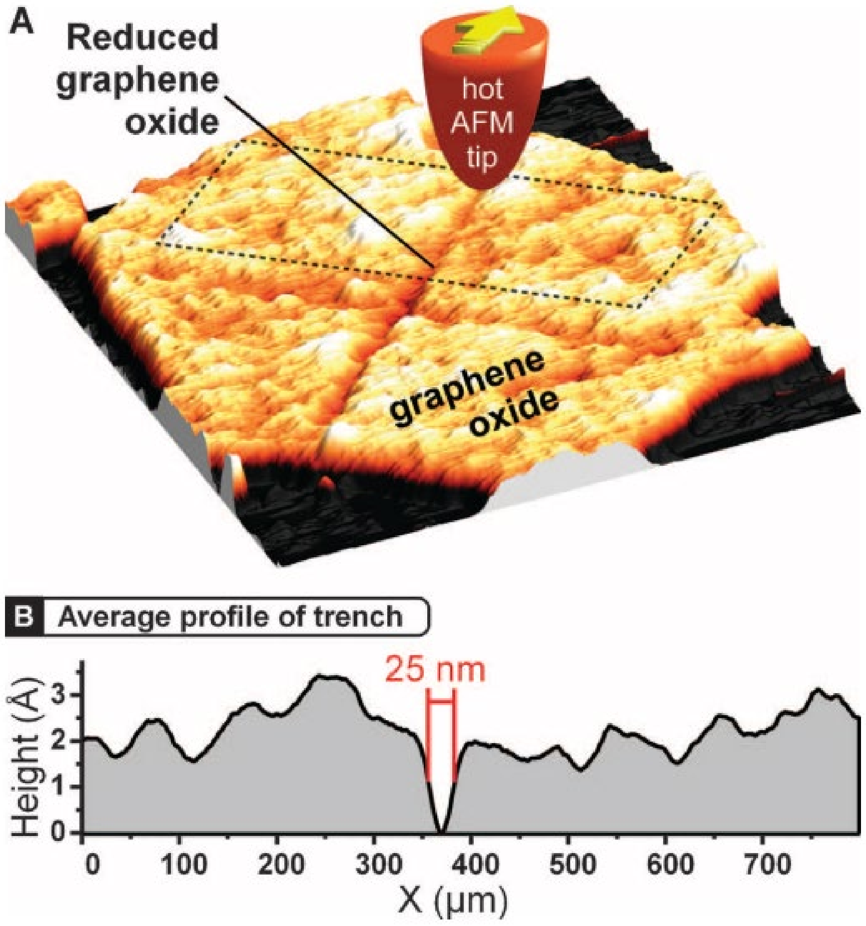
Photoluminescent graded patterns



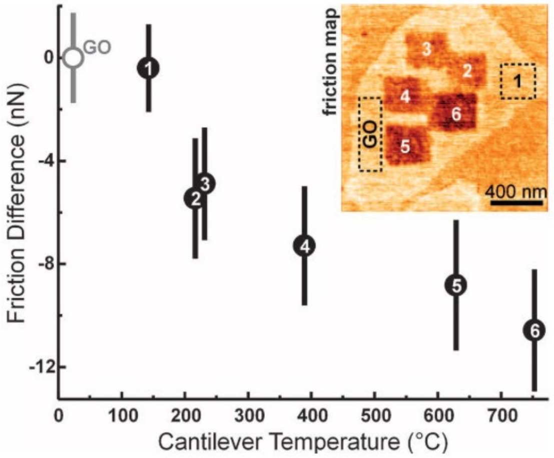
Keith M. Carroll, Nanoscale,2014, 6,1299–1304

Tunable reduction of Graphene Oxide

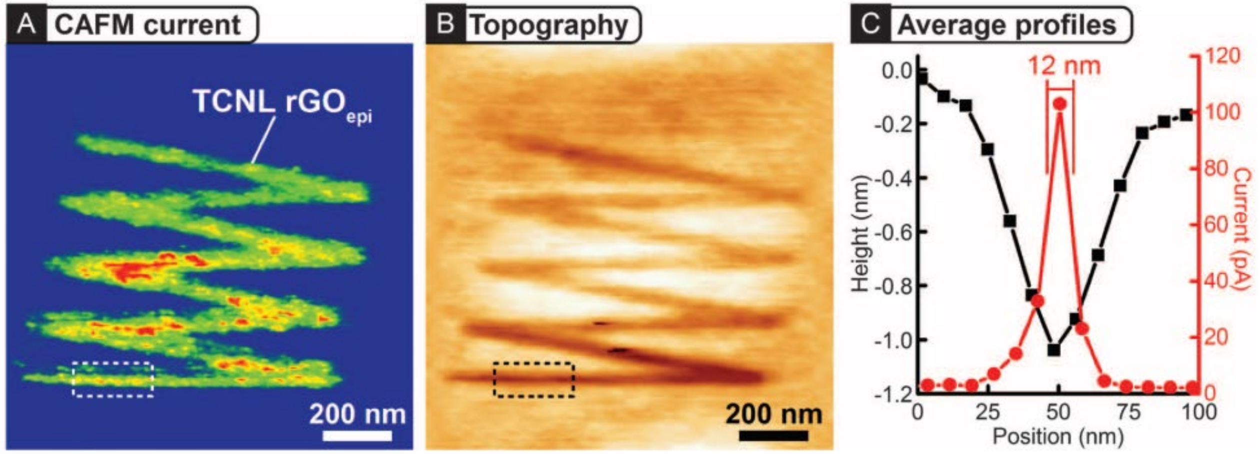
Topography of reduced grOX



Tunable friction with temperature



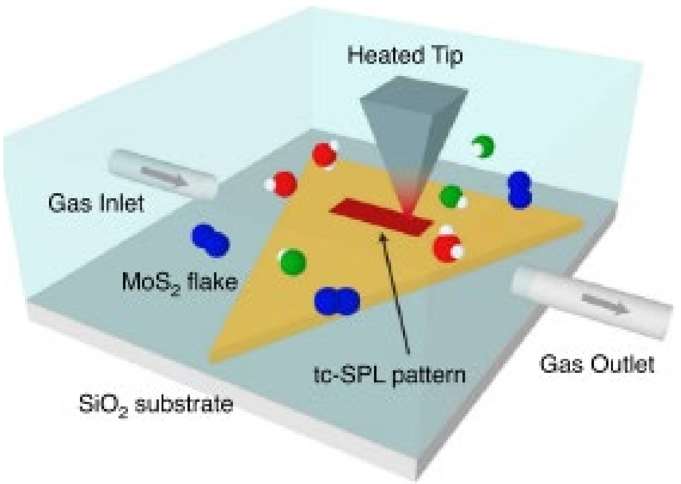
Nanoscale conductivity via C-AFM



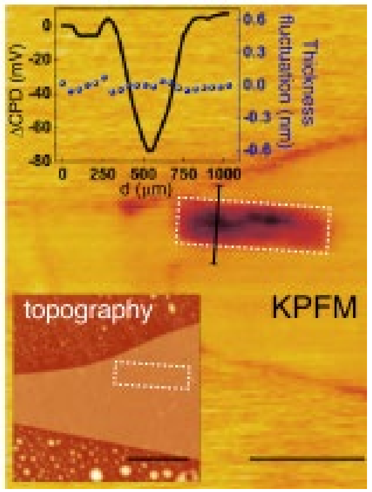
Wei Z, Science 328 1373–6 (2010)

Spatial defect nanoengineering in MoS2

t-SPL in a controlled atmosphere

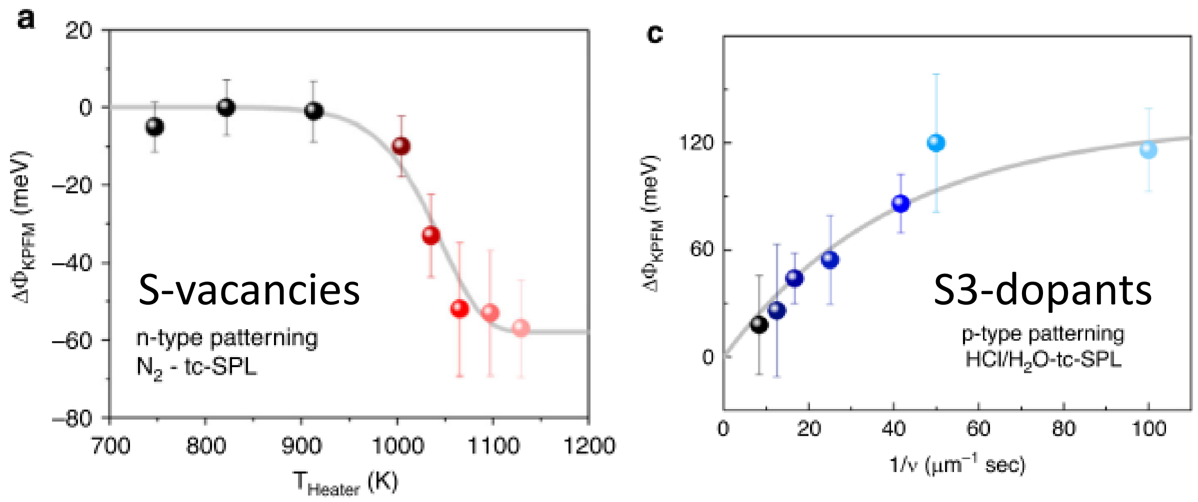


KPFM

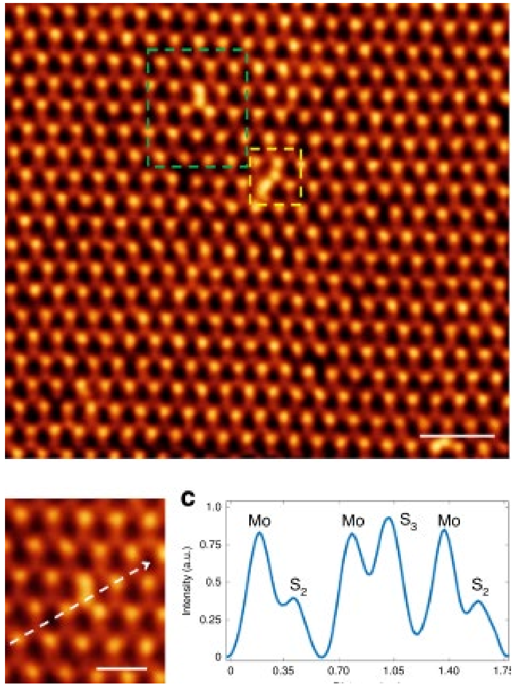


t-SPL in combination with a gas cell is used for generating defects in MoS2. Nanoscale control of defects in monolayer MoS2. The defects can present either p- or n-type doping on demand, depending on the gas used, allowing to realize p-n junctions.

n-type or p-type patterning



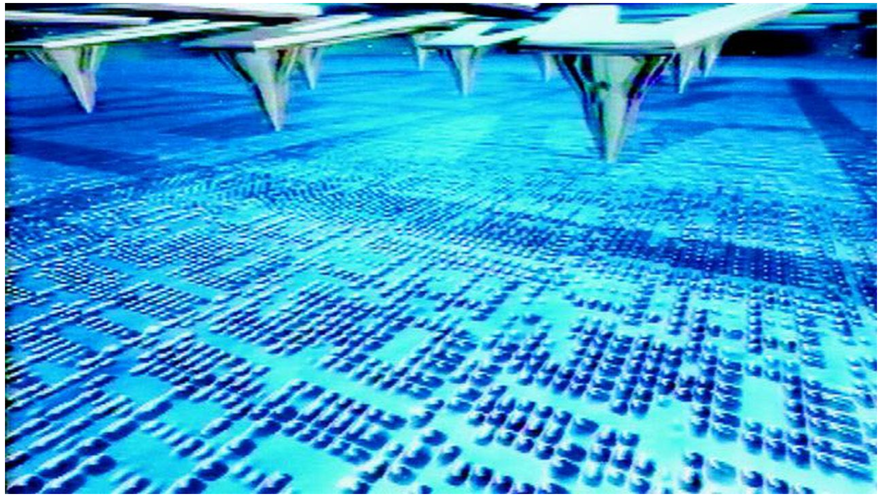
S3 dopants in HRTEM



Zheng X, EA, et al Nat. Commun. 11 1–12 (2020)

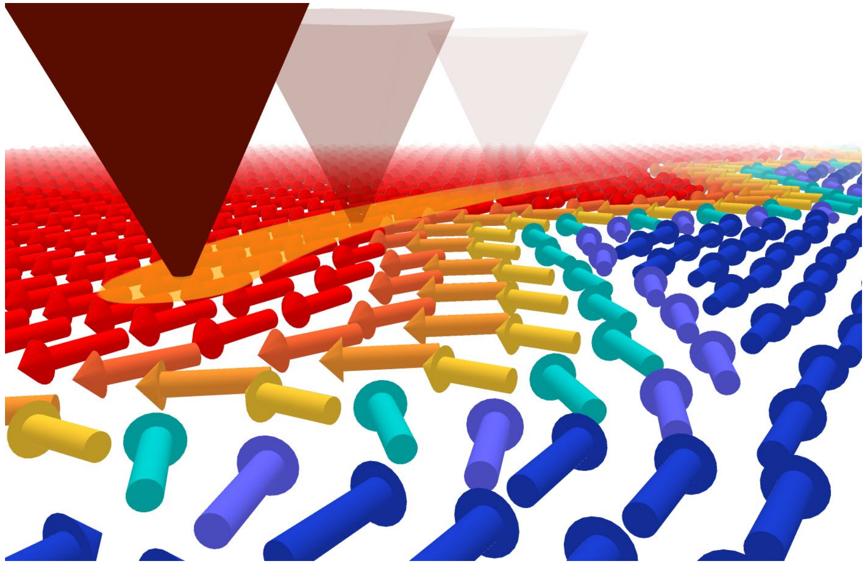
Outlook

- ► *Scanning Probe Microscopy / Lithography*
- ► *Brief history of t-SPL: from milli-pedes to nano-structures*
- ► *Experimental: features and limitations of t-SPL*



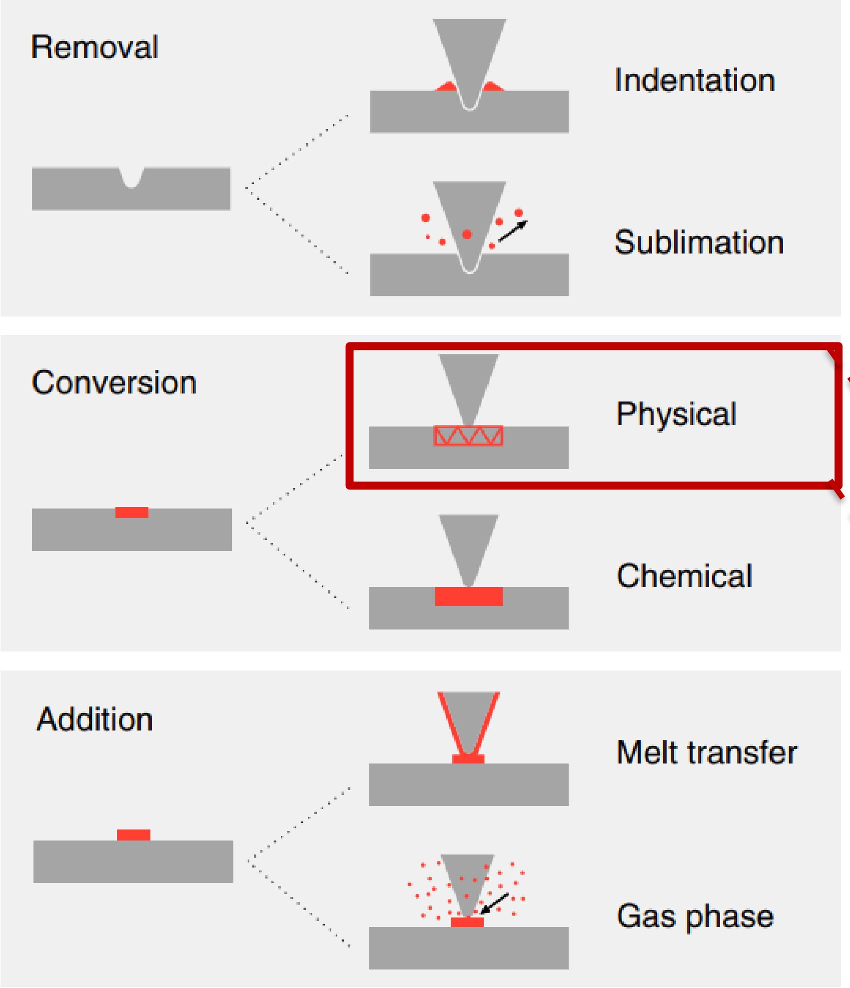
- ► ***Applications:***

1) *REMOVAL Direct sublimation of organic resists / lithography*
2) *«CHEMICAL conversion» at the nanoscale*
3) *«PHYSICAL conversion»: t-SPL for magnetism*



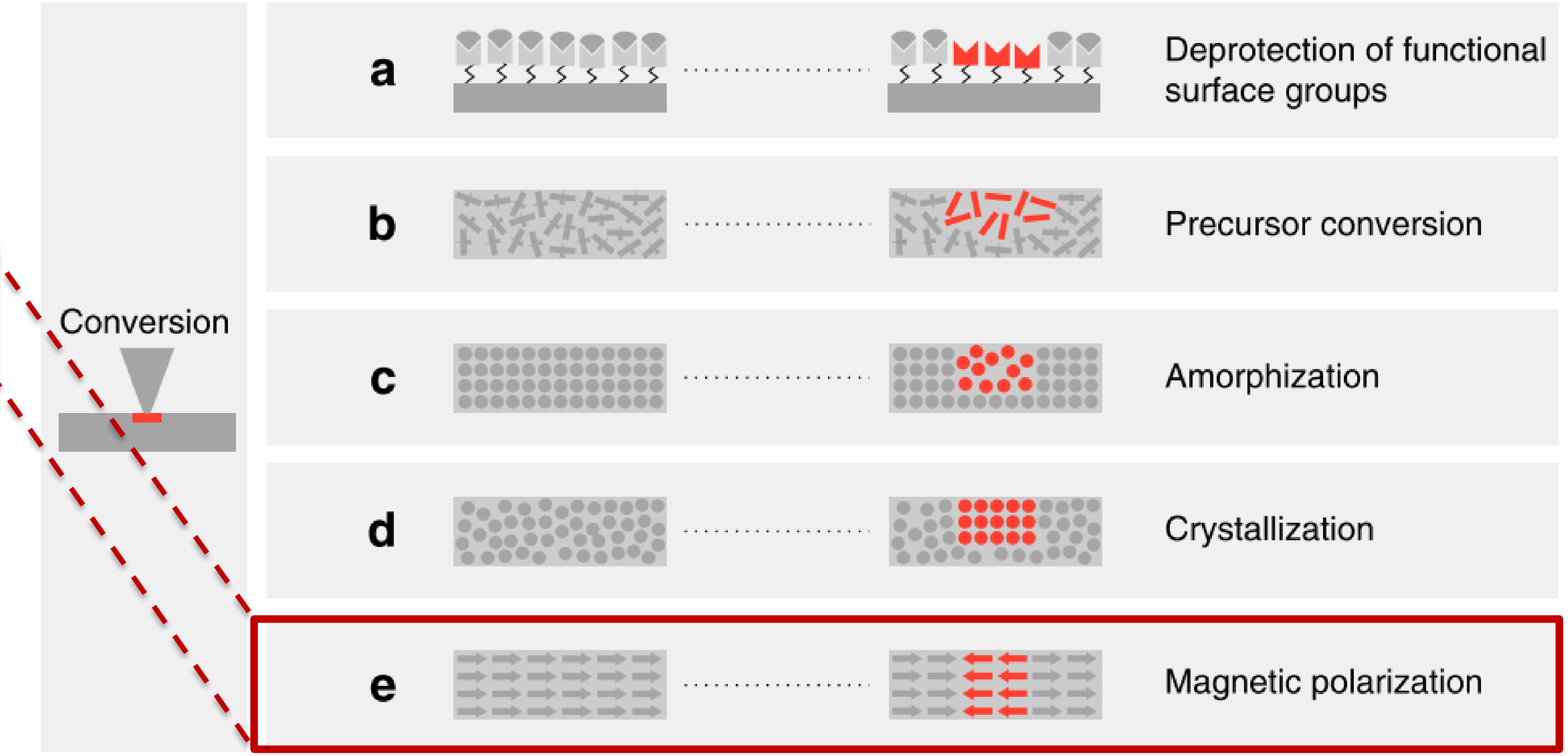
«Physical» material conversion: Nanopatterning Magnetism

Heat as a universal stimulus



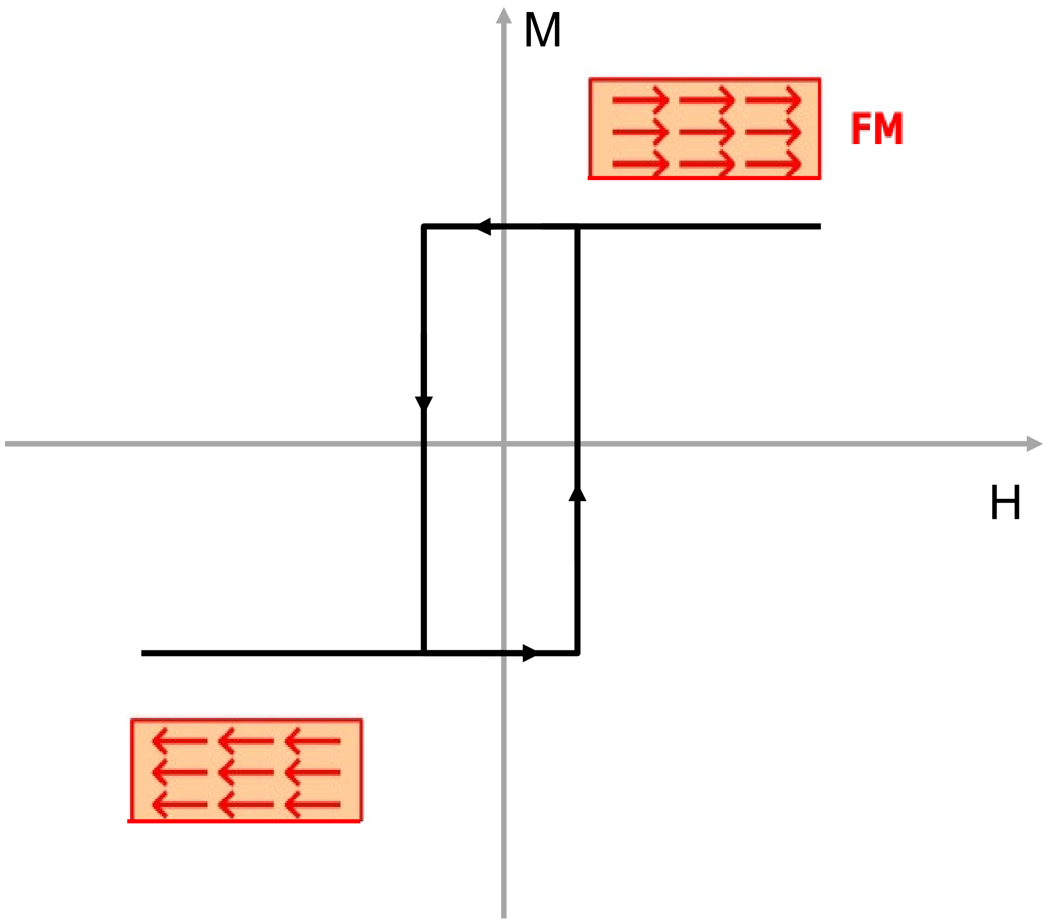
Howell et al. Microsystems & Nanoengineering (2020) 6:21

Conversion processes (not exaustive)

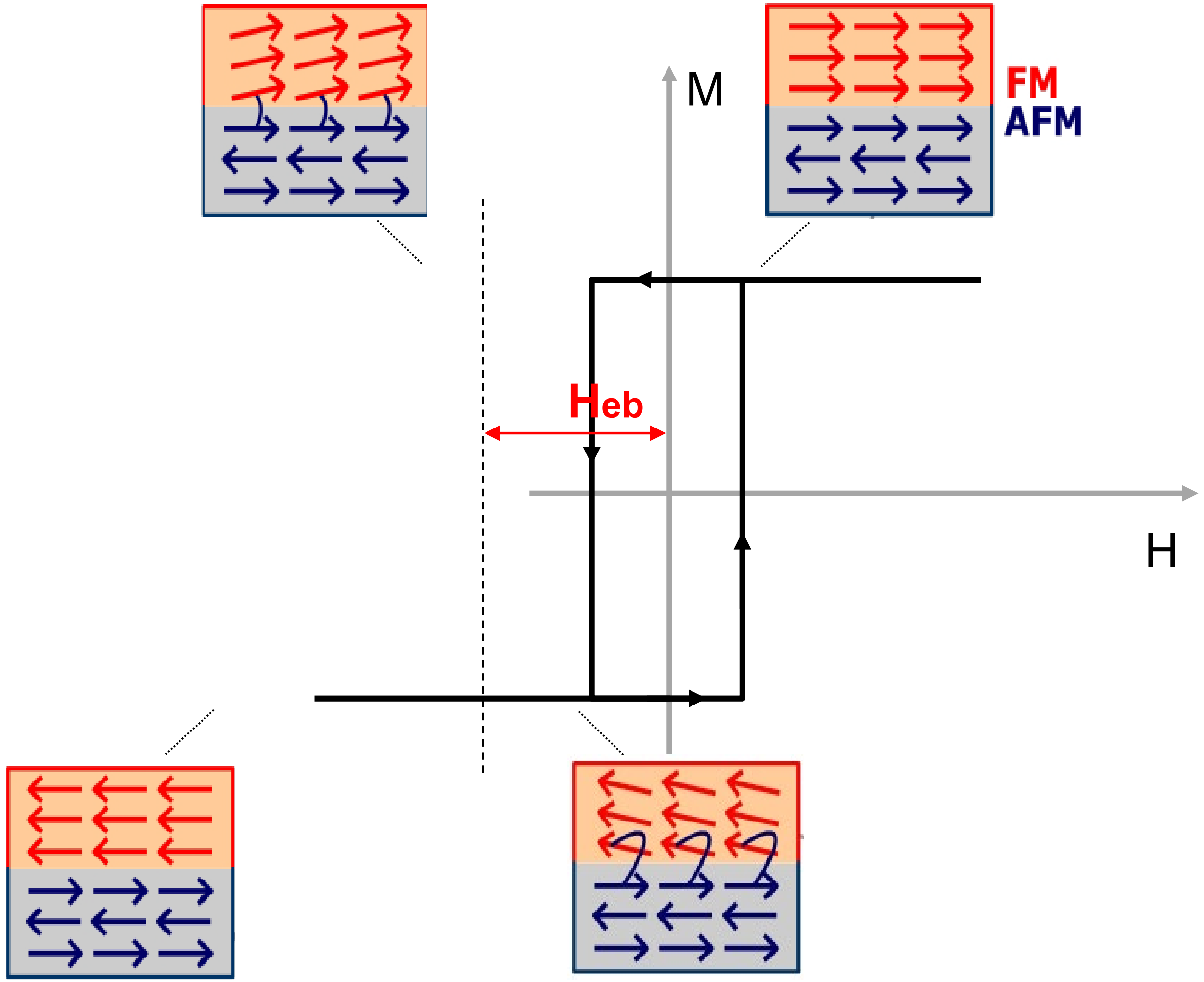


► ***t-SPL for magnetism***

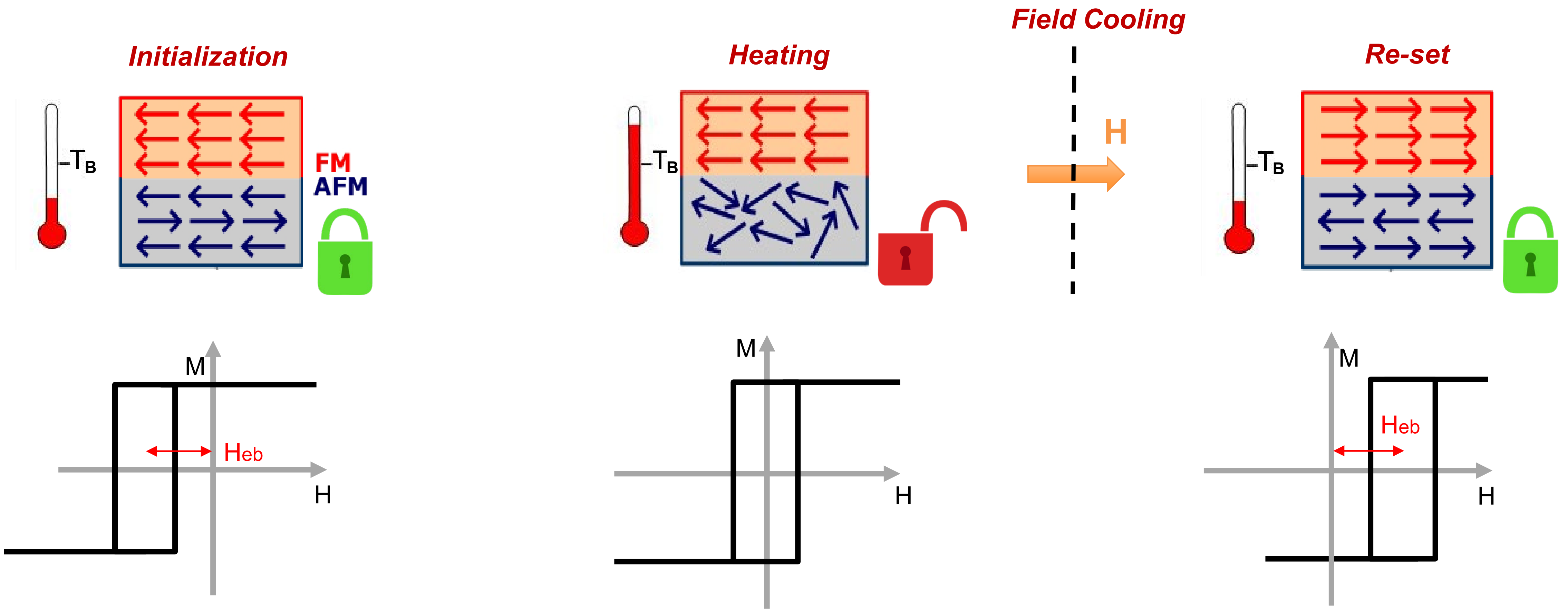
Exchange bias at the FM / AF interface



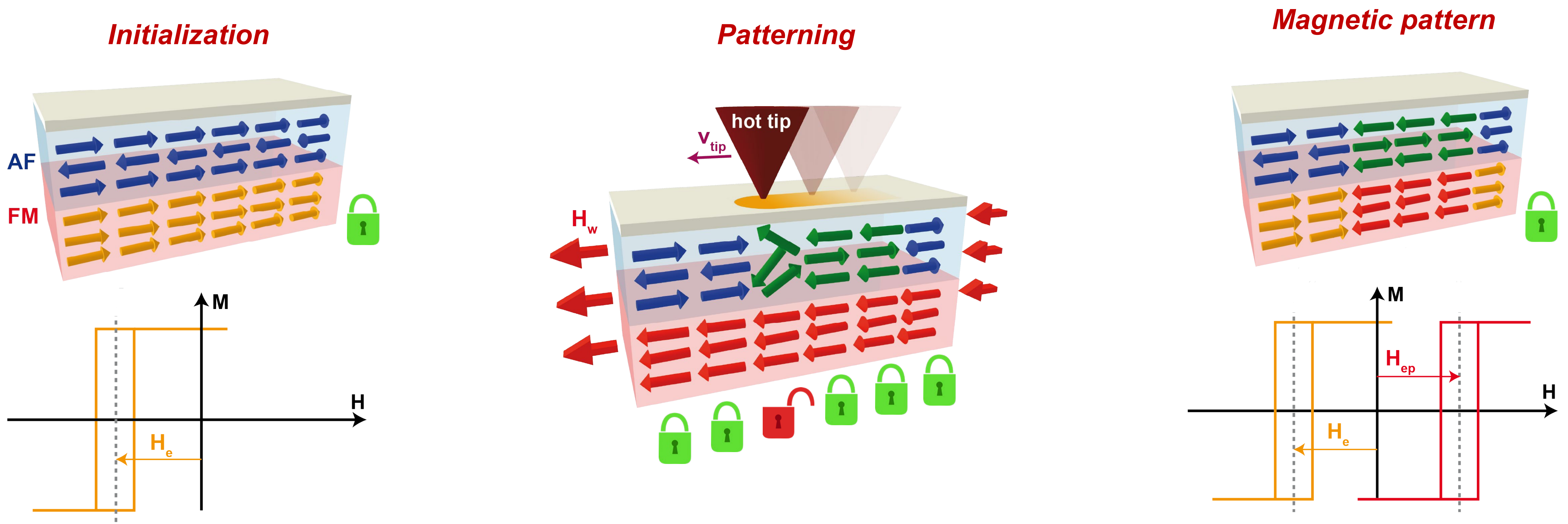
Exchange bias at the FM / AF interface



Setting the exchange bias with temperature



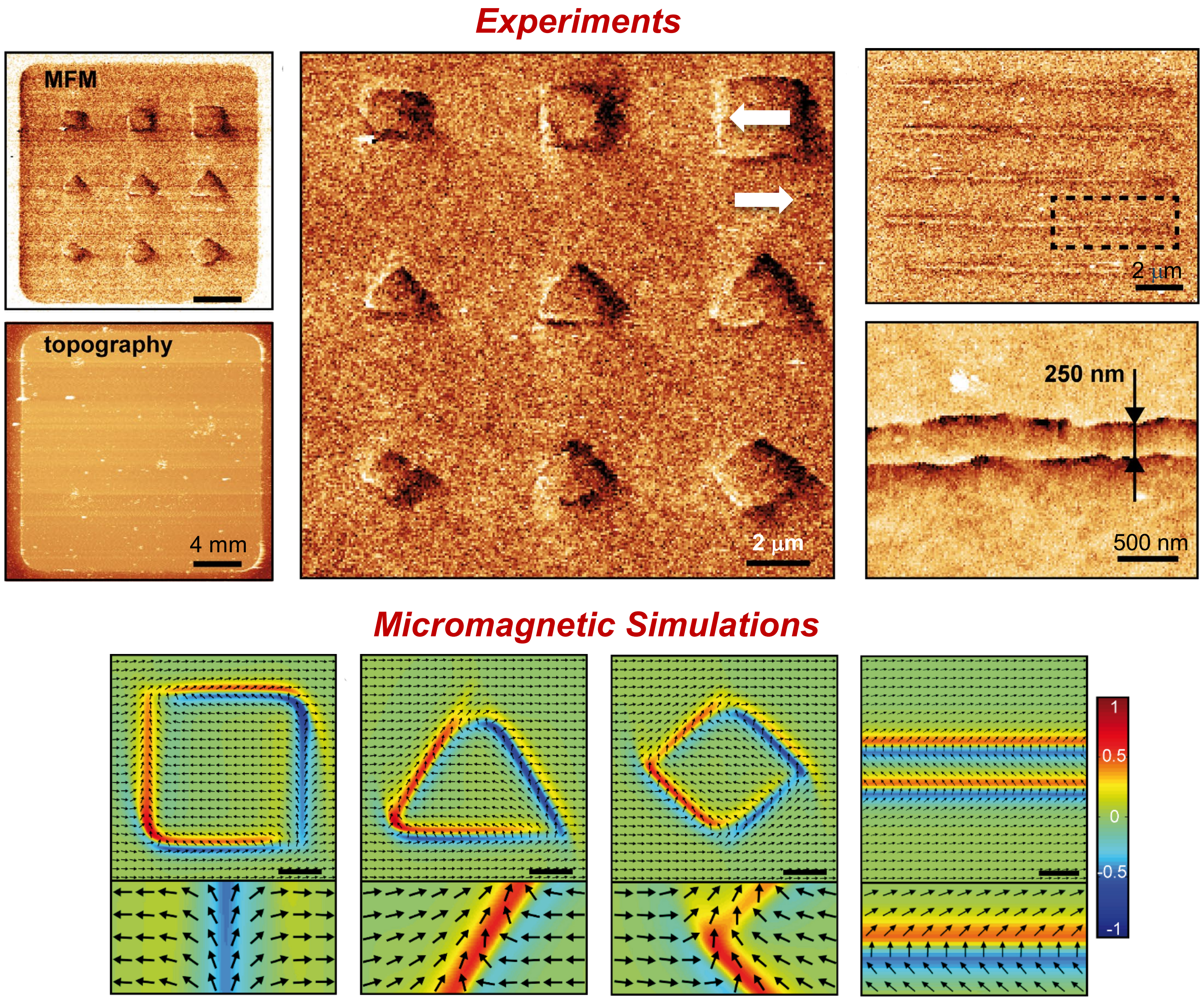
Thermally assisted magnetic Scanning Probe Lithography (tam-SPL)



- *Single step, non-destructive, ambient conditions*
- *Reconfigurable patterns (erase – rewrite)*
- *Robust vs external fields*
- *Finely tunable*

EA *et al.*, Nat. Nanotech. **11**, 545–551 (2016)

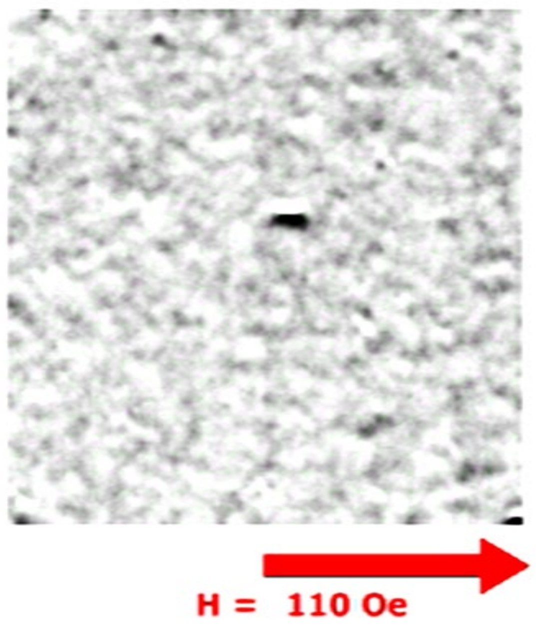
Patterning magnetic domains / domain walls

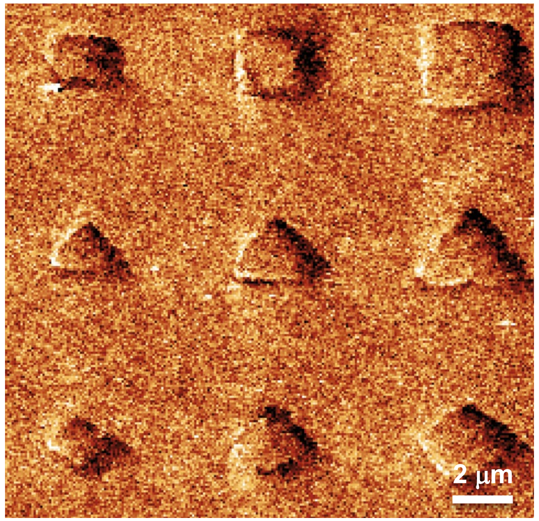


EA *et al.*, Nat. Nanotech. **11**, 545–551 (2016)

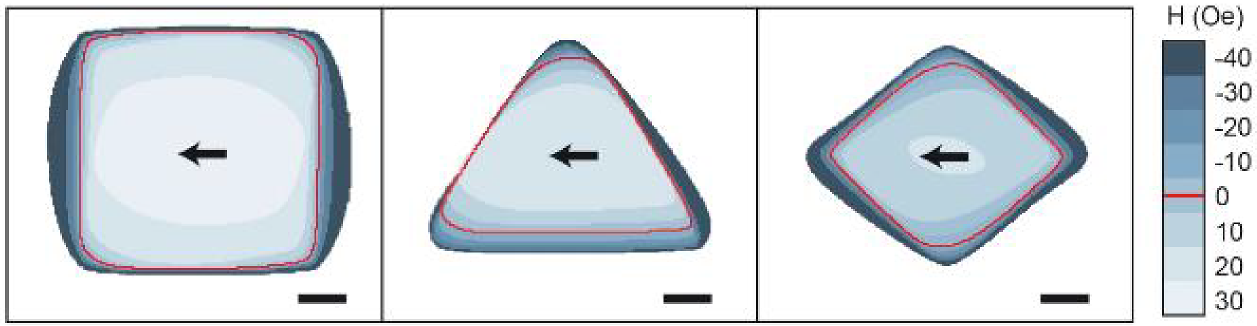
EA et al., J. Magn. Magn. Mater. **400** 230–235 (2016)

Spin-texture evolution with external field





Displacing domain walls with H, before switching

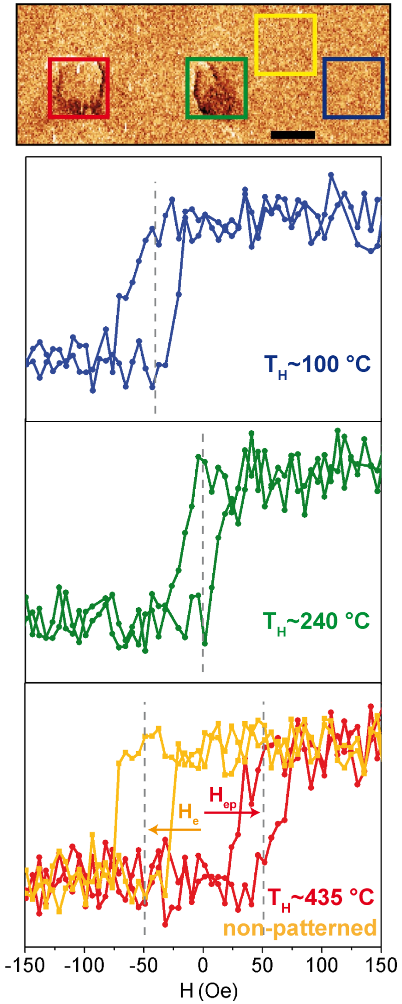


EA *et al.*, Nat. Nanotech. **11**, 545–551 (2016)

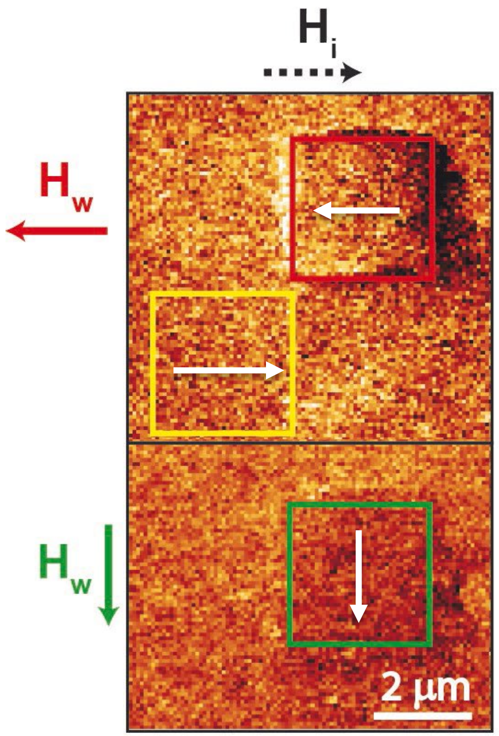
w/t M. Pancaldi, P. Vavassori, CIC Nanogune, Spain

Writing / rewriting on a magnetic blackboard

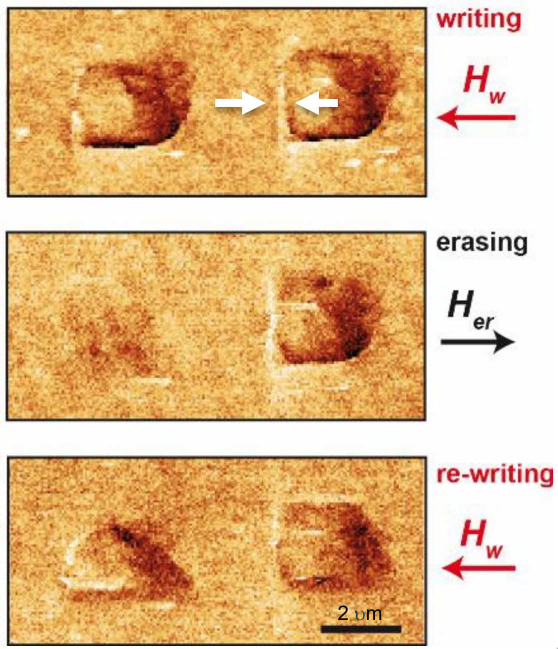
Tuning EB strength



Tuning magnetization direction



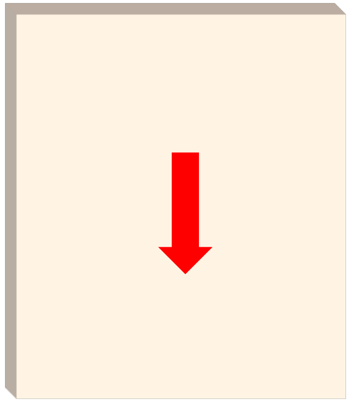
Writing, erasing, rewriting



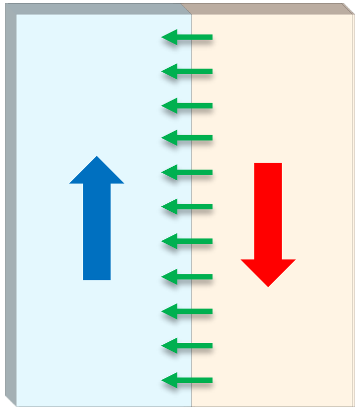
EA *et al.*, Nat. Nanotech. **11**, 545–551 (2016)

From 2D domains to 1D domain walls, to 0D topological solitons

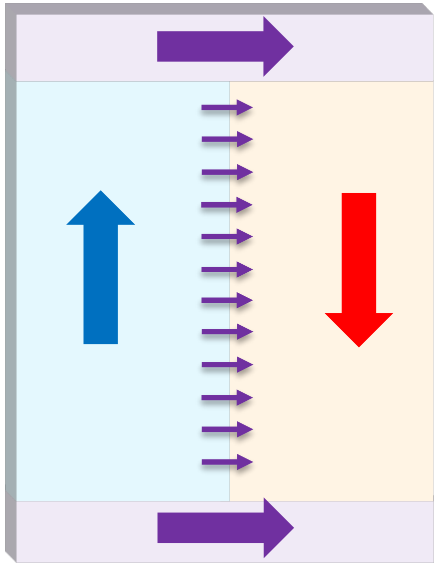
Uniform domain



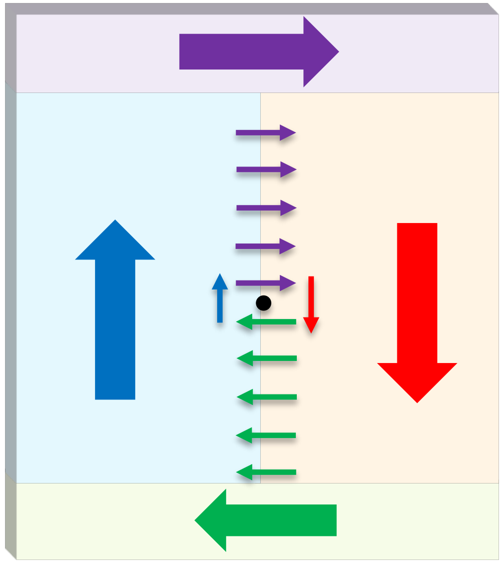
Néel wall



Néel wall with fixed chirality



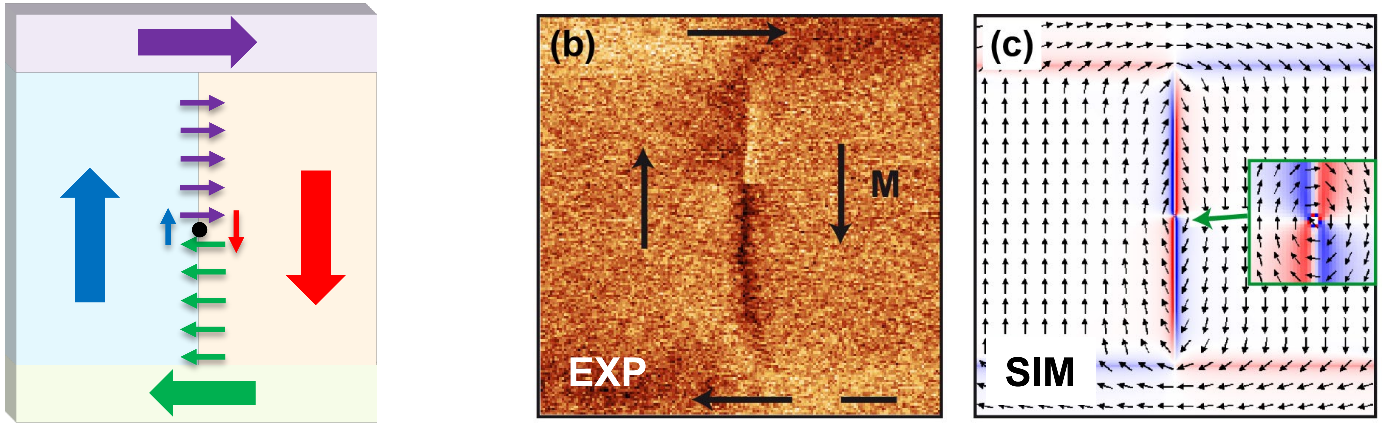
Néel wall with Vortex Bloch Line



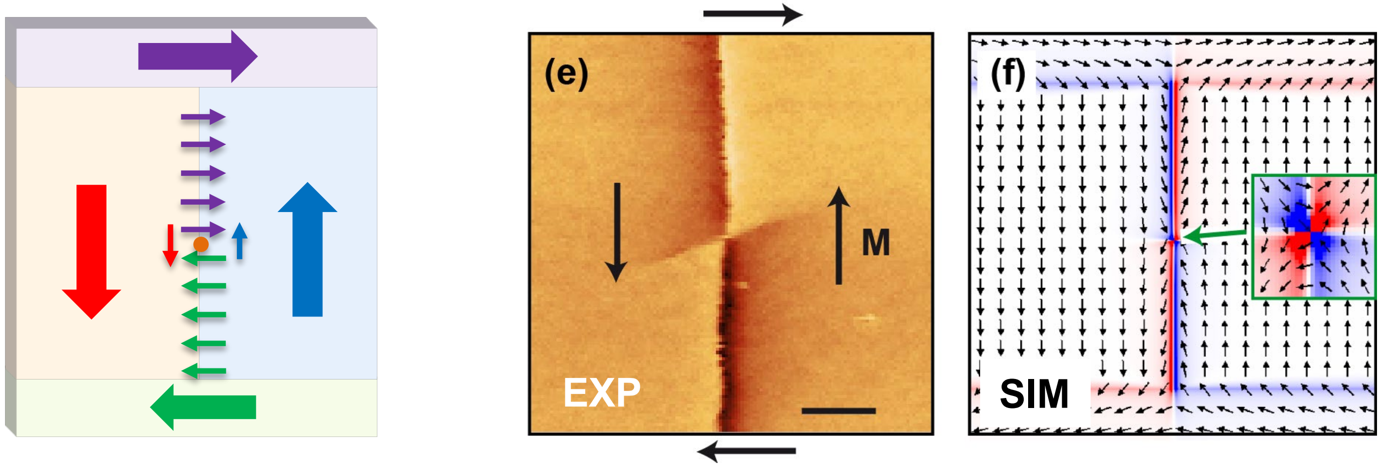
EA *et al.*, Appl. Phys. Lett. 113, 162401 (2018)

Deterministic control on position, vorticity and circularity

Vortex Bloch Line within Néel wall (CW)



Anti-Vortex Bloch Line within Néel wall

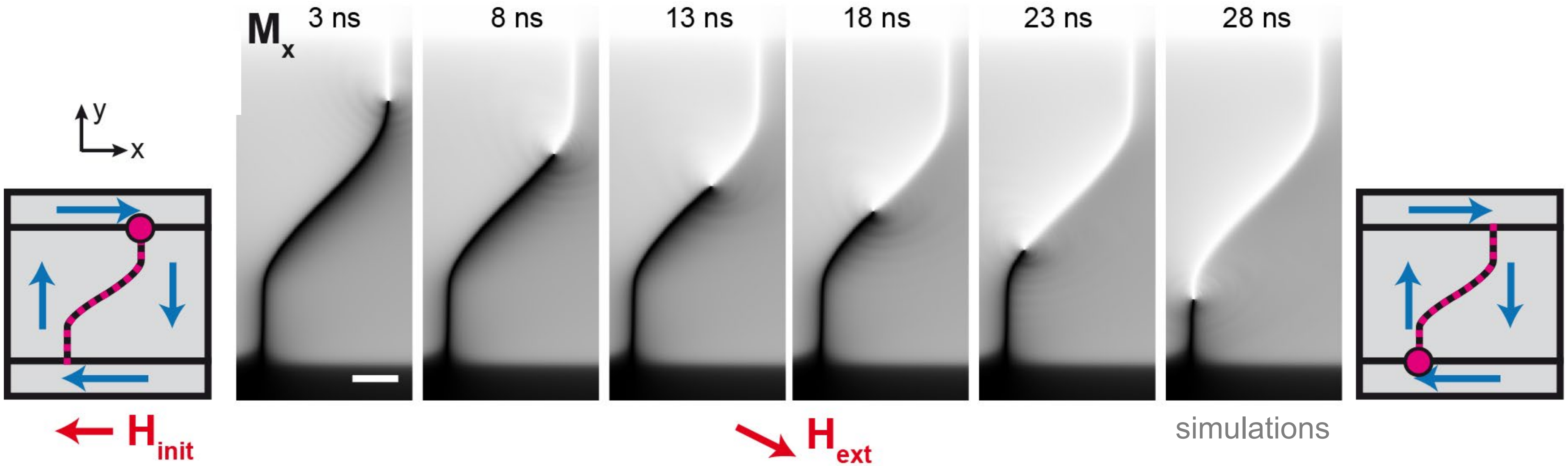


EA et al., Appl. Phys. Lett. 113, 162401 (2018)

► ***Deterministic topology***

Manipulation of magnetic solitons within tam-SPL DWs

Vortex displacement along arbitrarily- shaped Néel wall

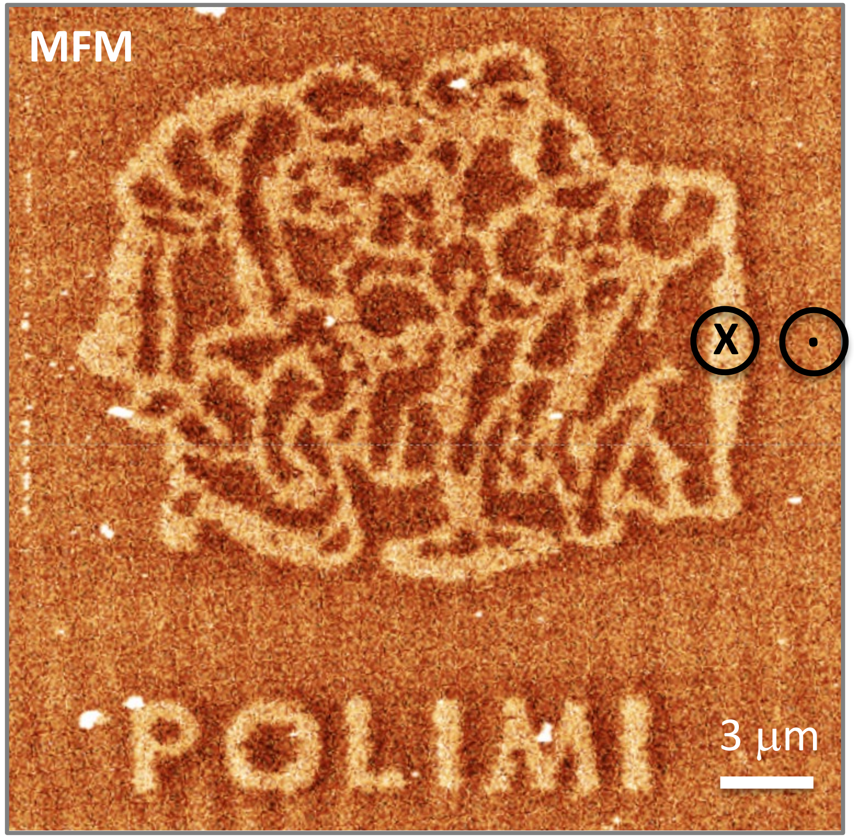


► ***DWs as reconfigurable racetracks***

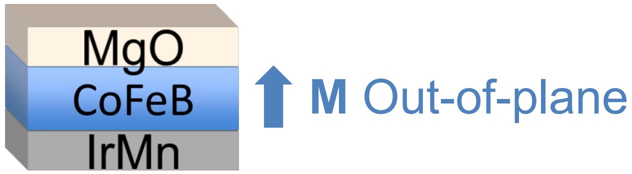
EA et al., Appl. Phys. Lett. 113, 162401 (2018)

Patterning out-of-plane EB, magnetization (..and skyrmion phase)

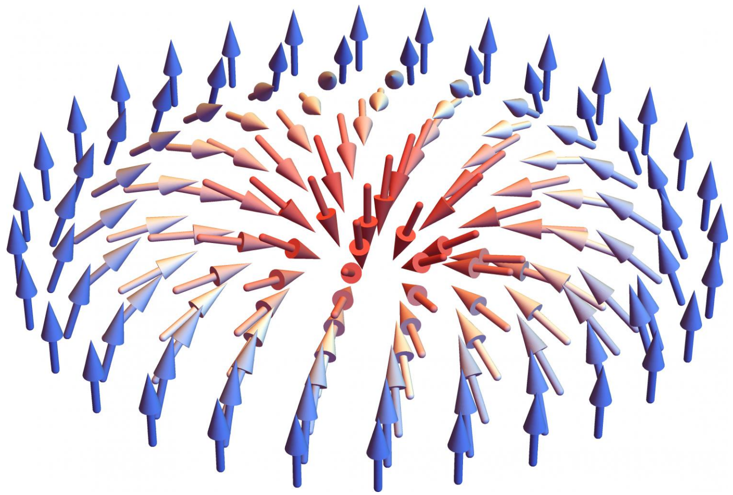
OOP complex domains



EA et al., *unpublished*

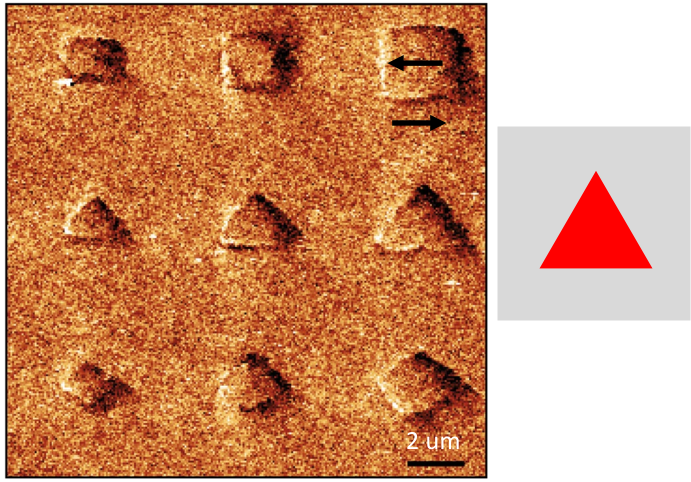


Topological textures e.g. Nèel Skyrmions

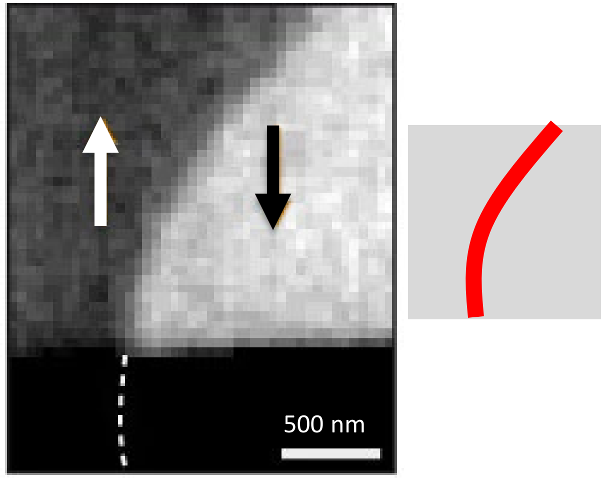


Summary: nanopatterning rewritable multidimensional spin-textures

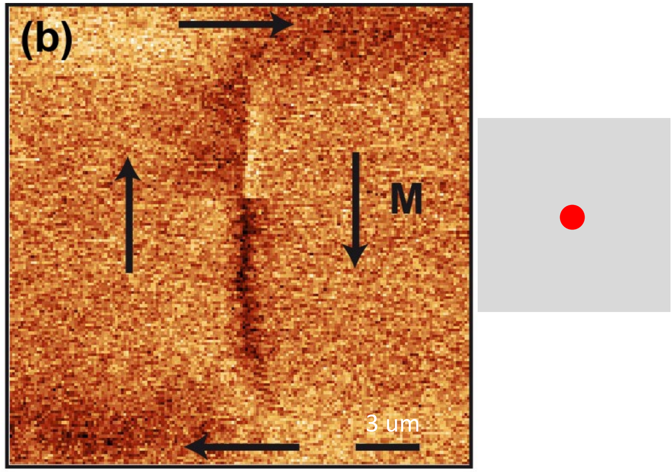
2D Magnetic domains



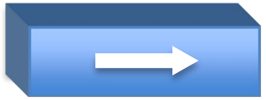
1D Domain walls



0D Topological solitons

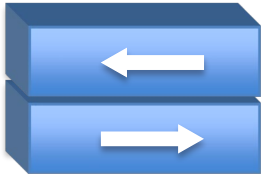


In plane



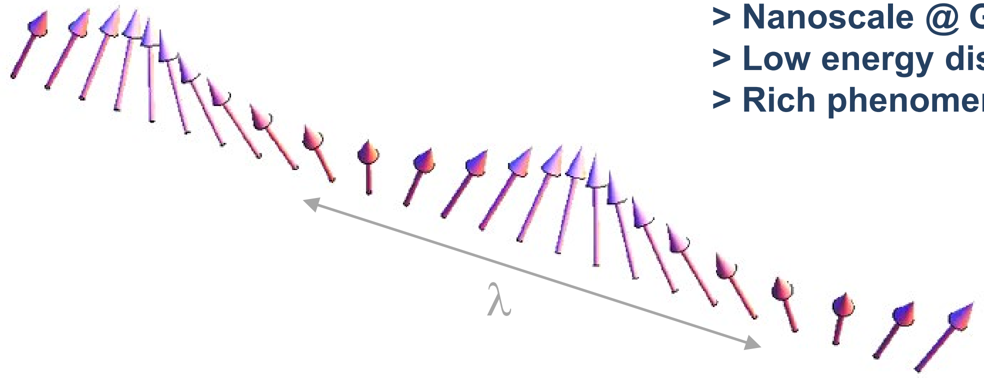
Out-of-plane

Synthetic AFs



Applications of tam-SPL: manipulating spin-waves

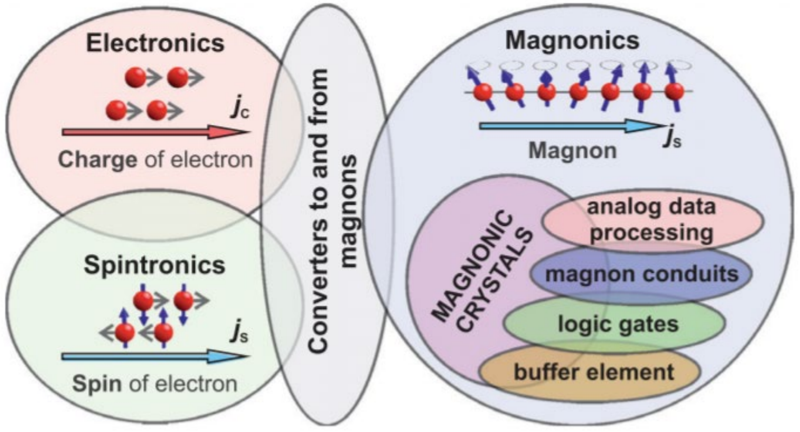
Spin-waves



> Nanoscale @ GHz/THz
> Low energy dissipation
> Rich phenomenology

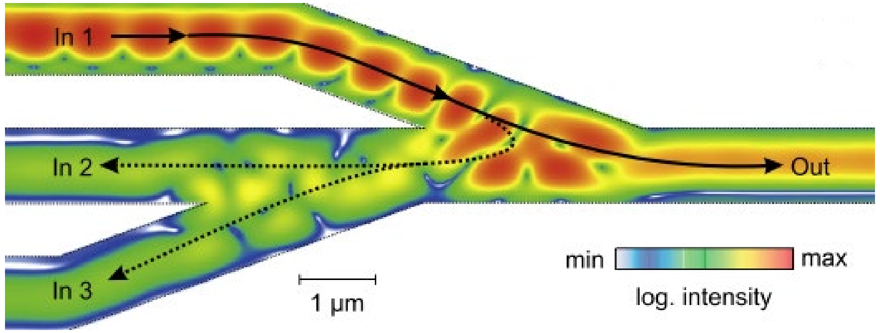
https://www.youtube.com/watch?v=pWQ3r-2Xjeo

Magnonics

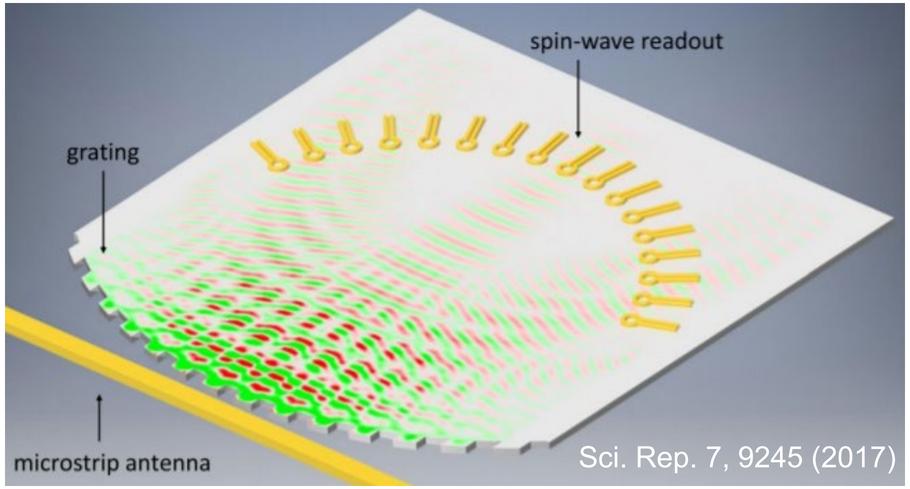


J. Phys. D: Appl. Phys. 50 (2017) 244001

Computing with spin-waves (digital / analog)



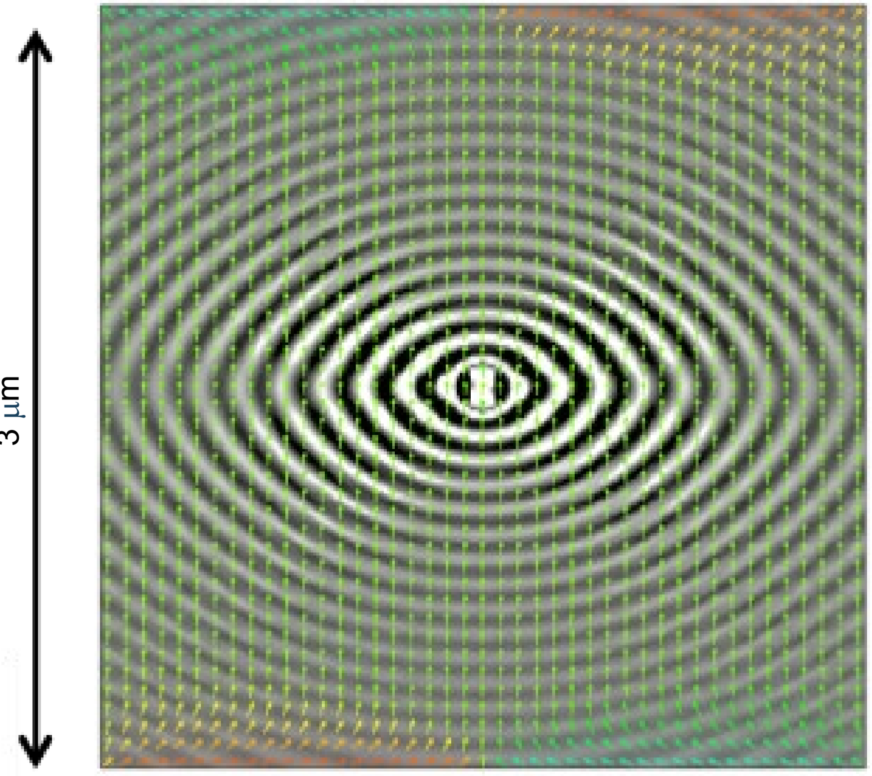
Physics Letters A 381 (2017) 1471–1476



Sci. Rep. 7, 9245 (2017)

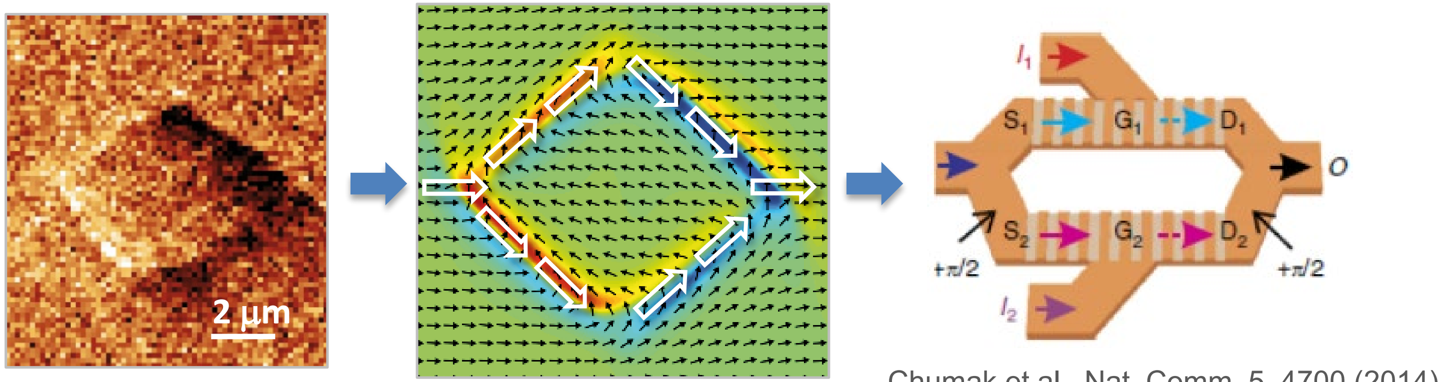
Manipulating spin-waves with tam-SPL spin-textures

Anisotropic excitation / propagation



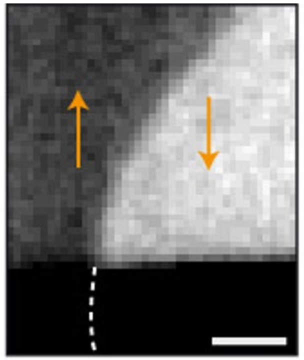
Point source @ 10 GHz

«Magnonics in-a-domain»



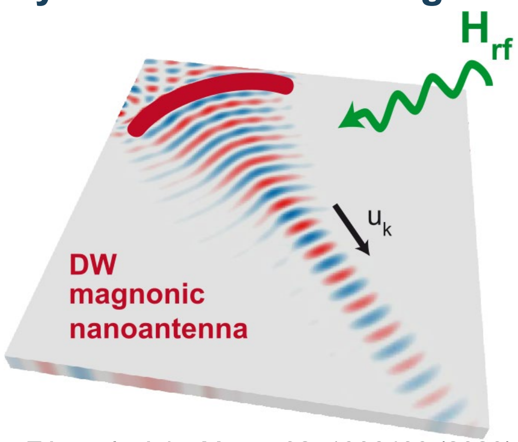
Chumak et al., Nat. Comm. 5, 4700 (2014)

Waveguides for SWs
domain walls



EA et al., Comms. Phys., 1, 56 (2018)

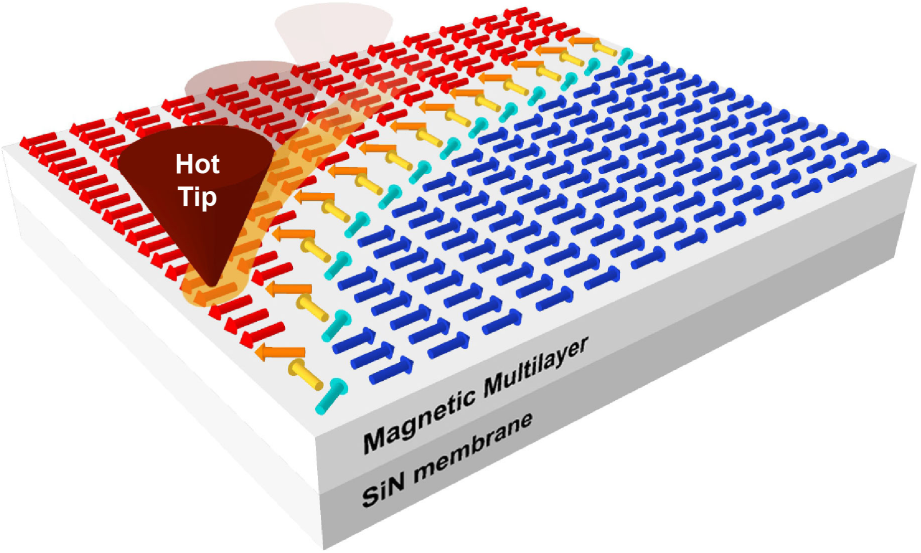
Nanoantennas for SWs
synthetic antiferromagnets



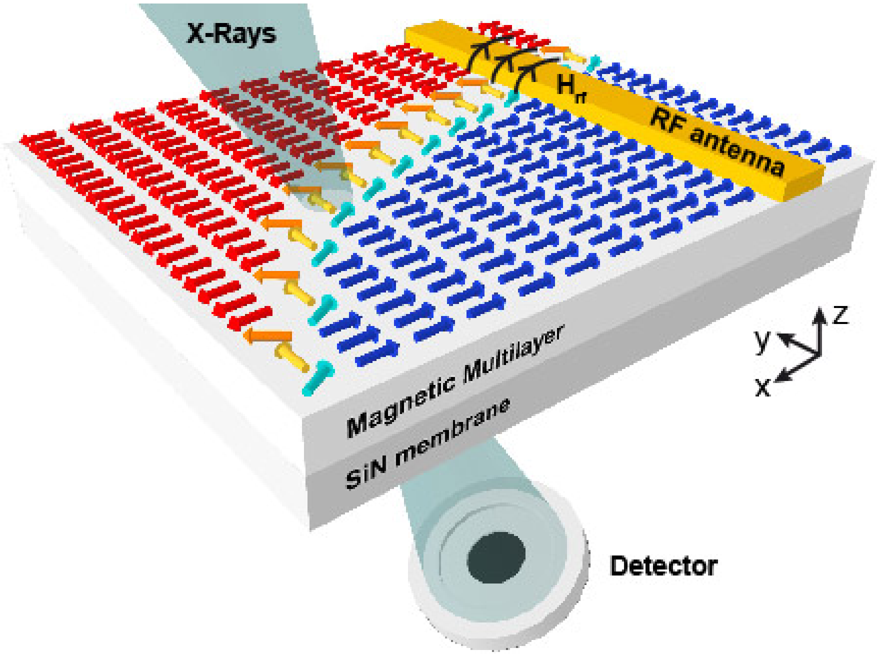
EA et al., Adv. Mater. 32, 1906439 (2020)

Nanoscale circuits for SWs based on domain walls

Patterning tailored domain walls



XMCD-STXM for SW visualization



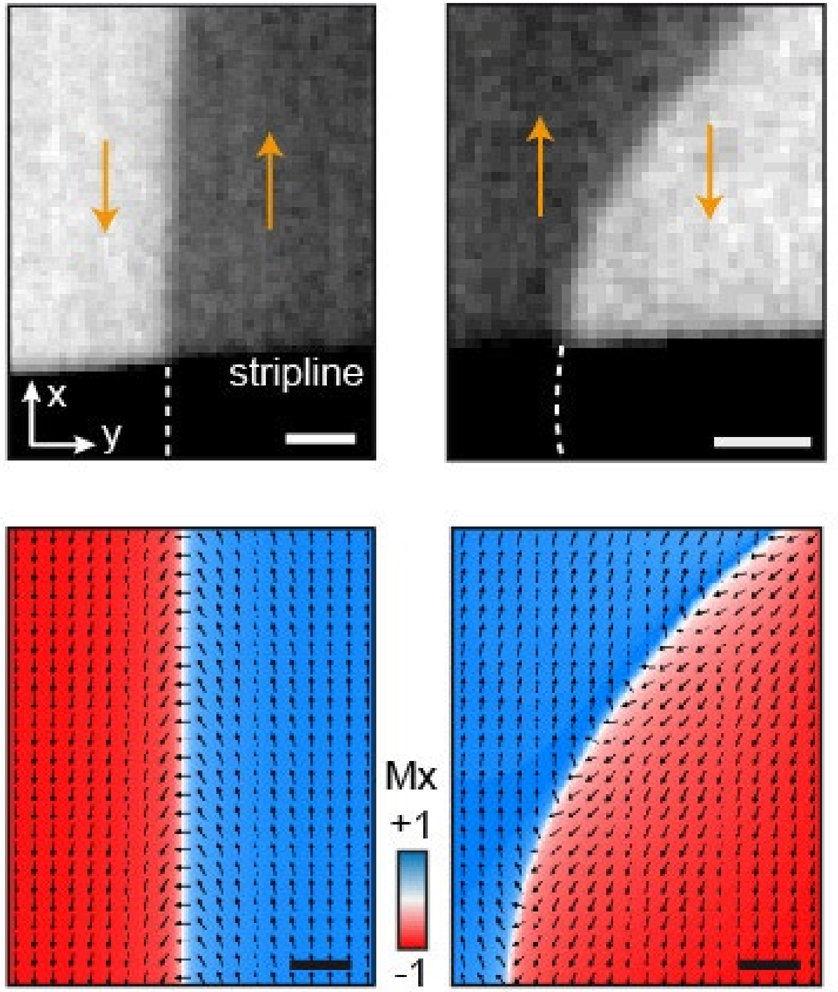
PolLUX beamline

EA et al., Comms. Phys., 1, 56 (2018)

w/t S. Finizio, S. Wintz, J. Raabe, SLS-PSI, Switzerland

Patterned spin-textures: static STXM

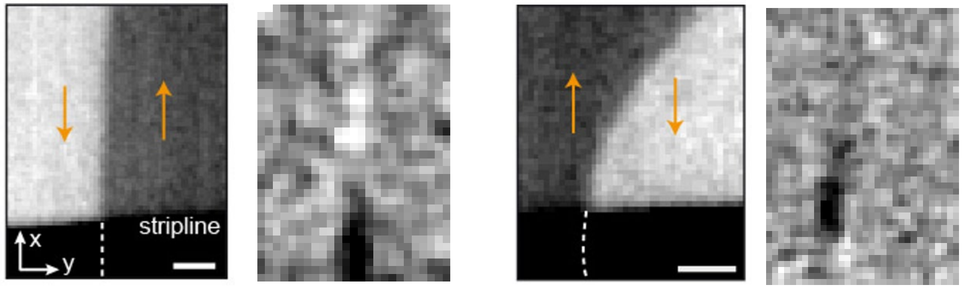
Straight Neél Wall ***Curved Neél Wall***



scale bars 500 nm

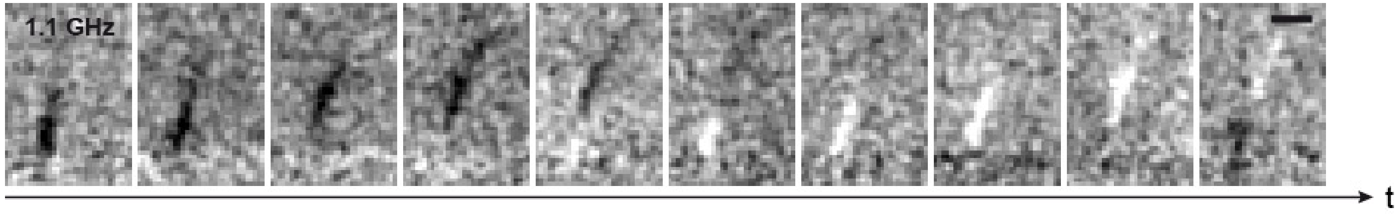
EA et al., Comms. Phys., 1, 56 (2018)

Guiding spin-waves with shaped walls

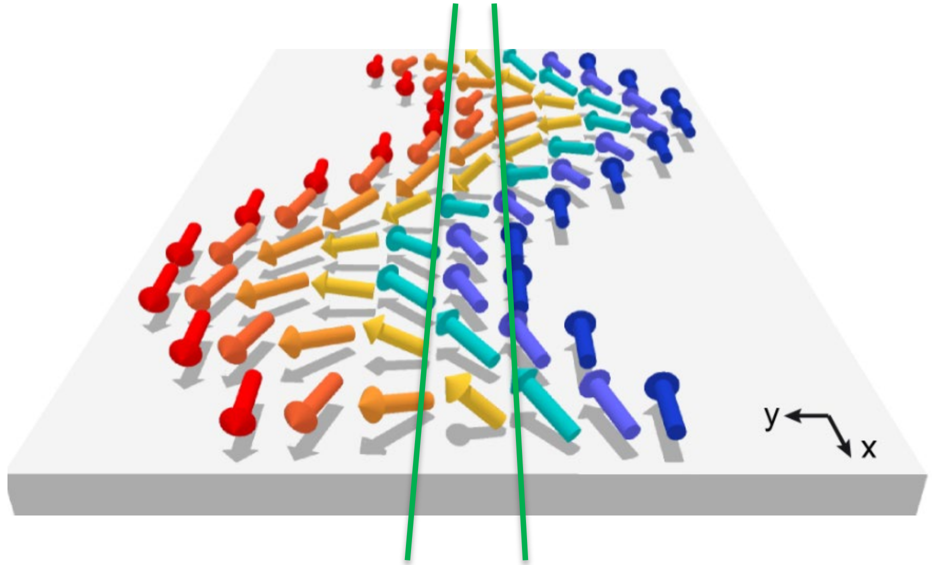


In-plane sensitivity

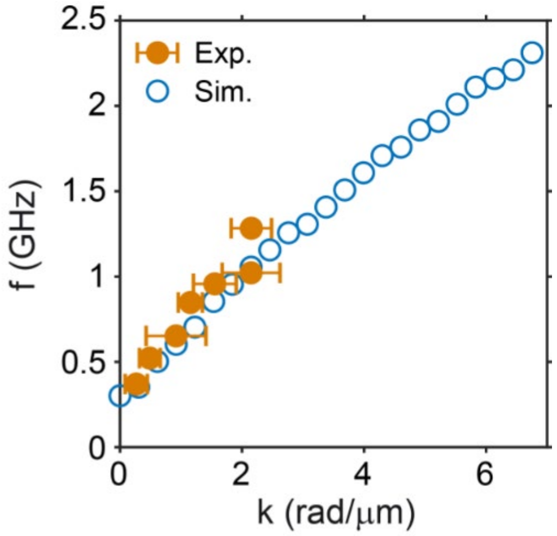
scale bars 500 nm



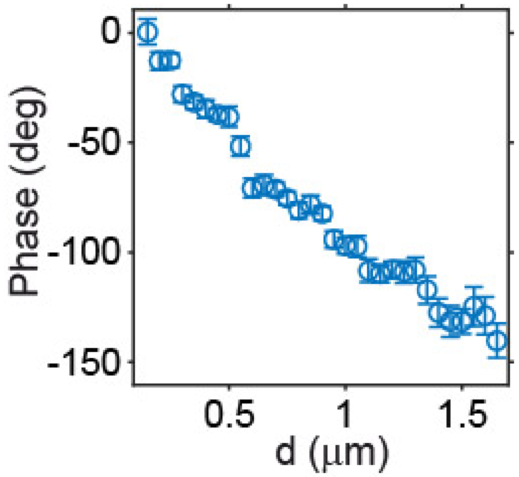
Winter modes



Dispersion



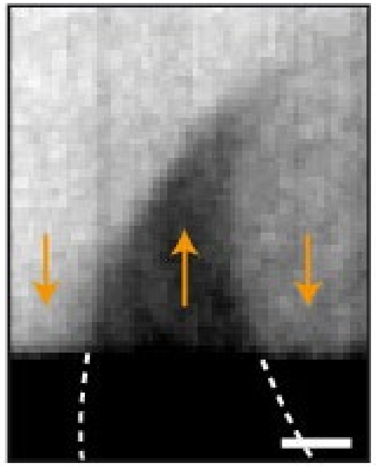
Propagating

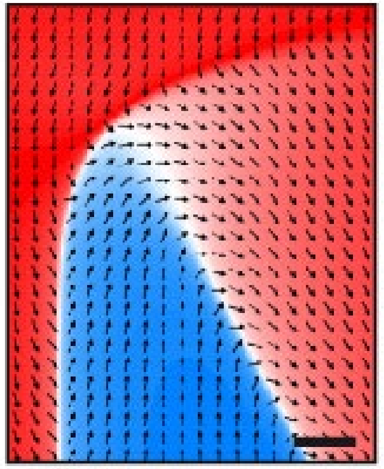


EA et al., Comms. Phys., 1, 56 (2018)

Domain wall-based spin wave circuit

2 Neel walls

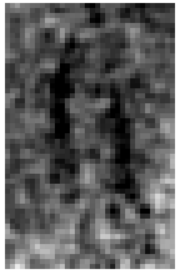


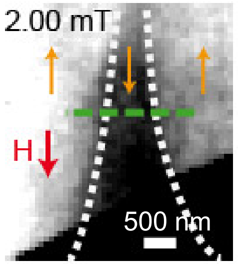


EA et al., Comms. Phys., 1, 56 (2018)

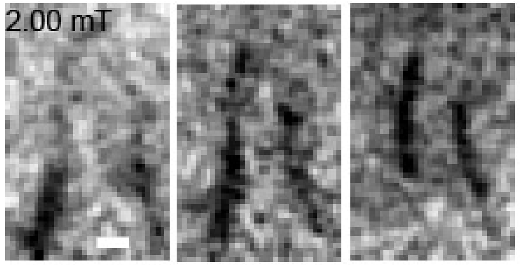
Tunable spatial superposition of guided modes

STXM videos

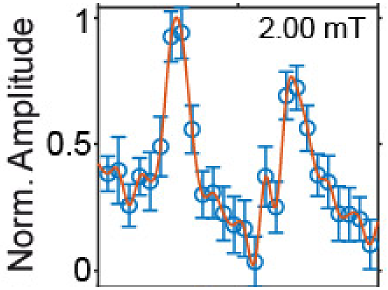




STXM frames



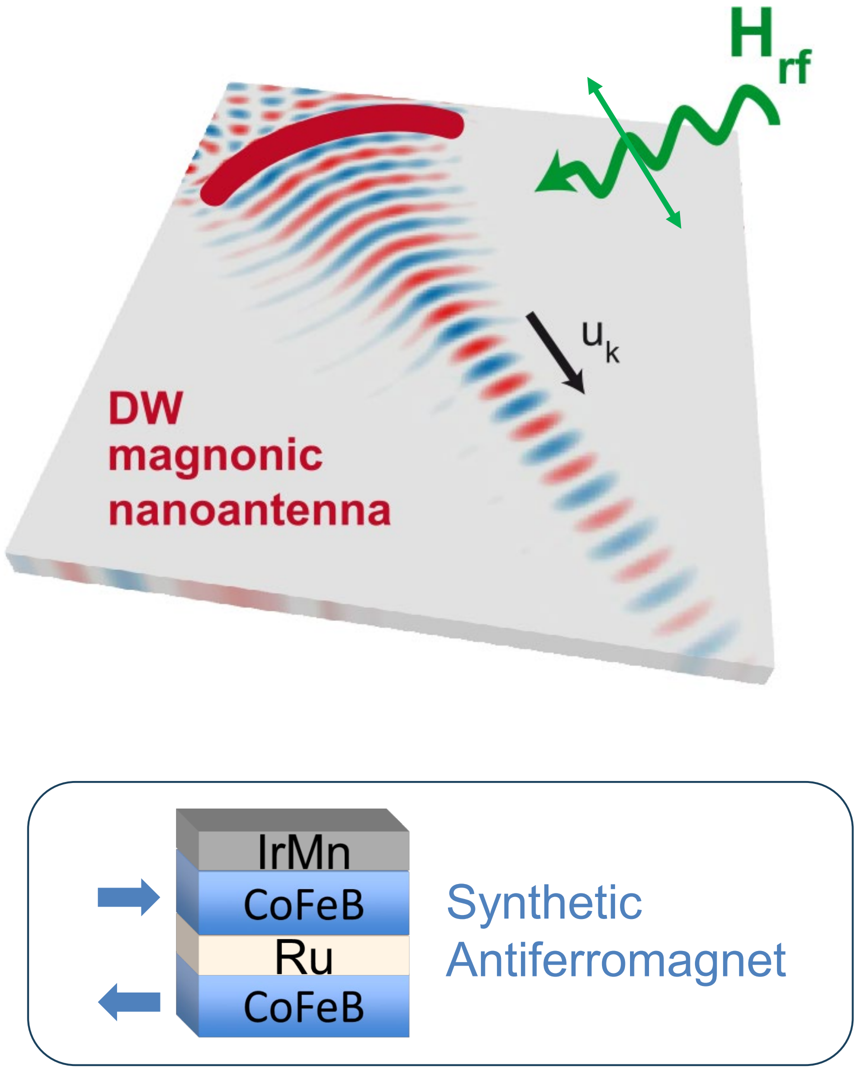
Amplitude profile (green line)



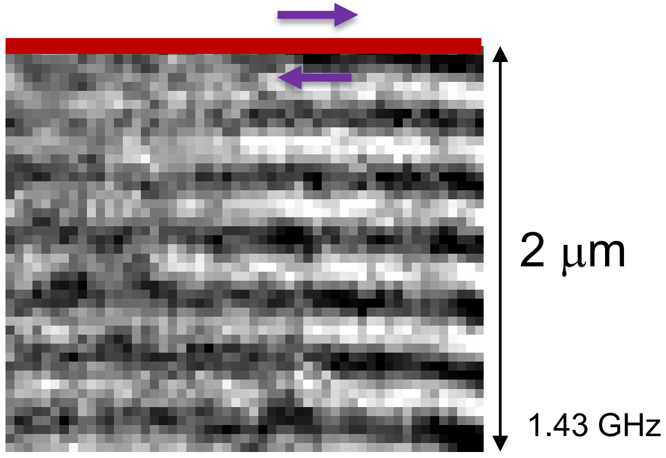
EA et al., Comms. Phys., 1, 56 (2018)

Spin-textures as nanoantennas for spin-waves

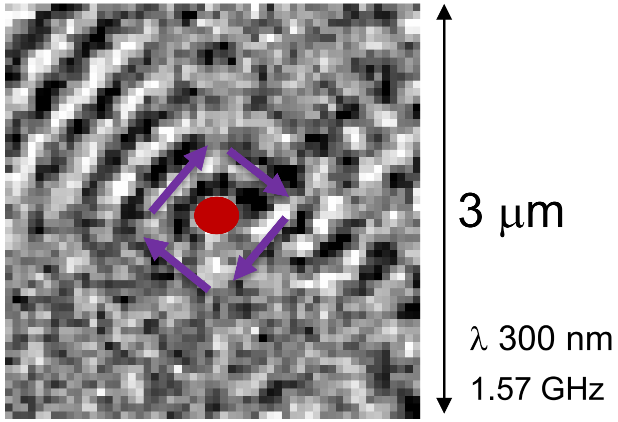
Launching magnons with nanoantennas



Straight wall: planar wavefront



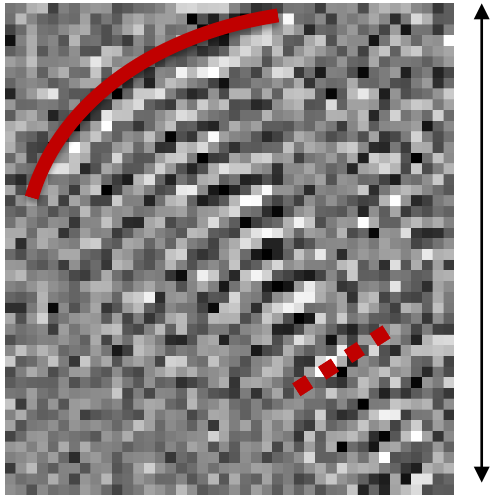
Vortex: radial wavefront



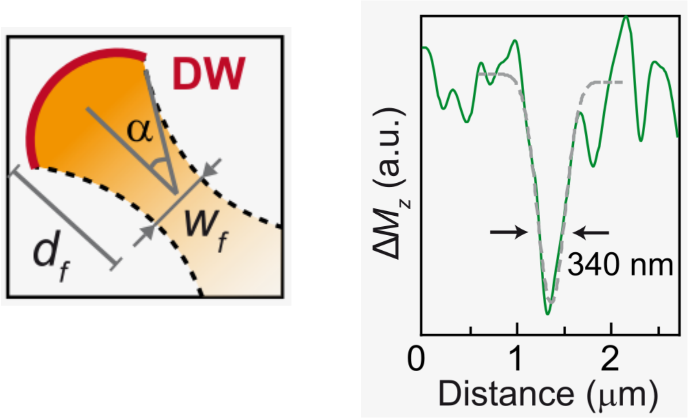
EA et al., Adv. Mater. 32, 1906439 (2020)

Spin-wave wavefront shaping with spin-texture emitters

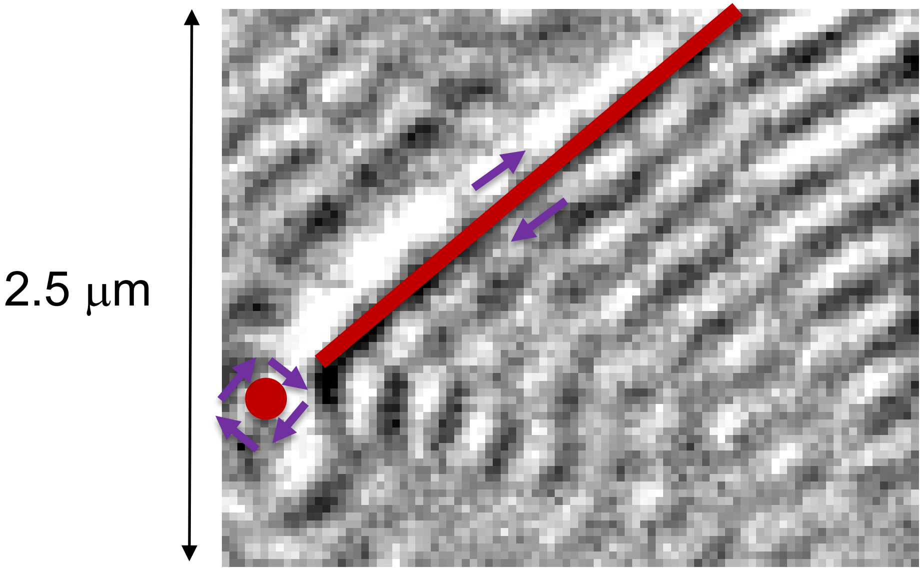
Focusing SWs



1.43 GHz



Interference pattern generation via multiple sources



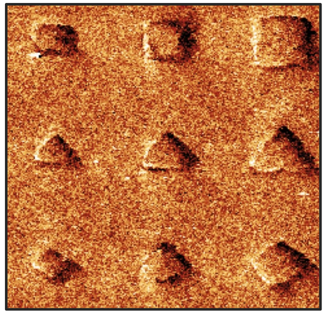
1.29 GHz

...Towards integrated analog processing using SW

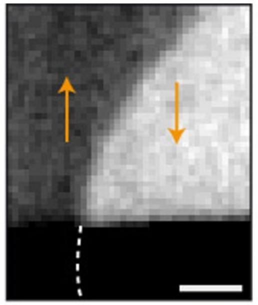
EA et al., Adv. Mater. 32, 1906439 (2020)

Summary: tam-SPL and applications

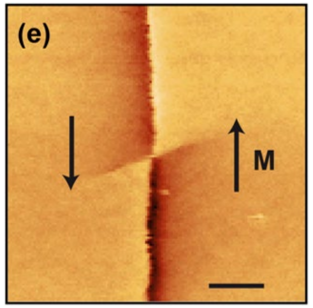
Tailored, deterministic 2D-1D-0D spin-textures



2D domains

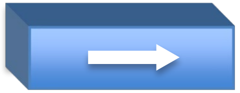


1D domain walls



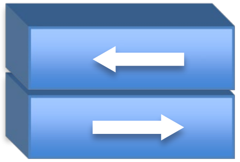
0D topological solitons

EB systems



In plane

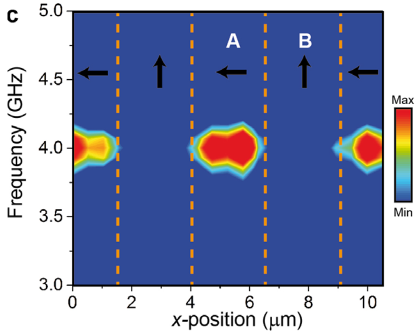
Out-of-plane



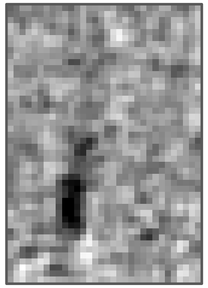
Synthetic Antiferromagnets

Nat. Nanotech. **11**, 545–551 (2016)
J. Magn. Magn. Mater. **400** 230–235 (2016)
AIP Advances 7, 055601 (2017)
Comms. Phys., 1, 56 (2018)
Appl. Phys. Lett. 113, 162401 (2018)
Adv. Mater. 32, 1906439 (2020)

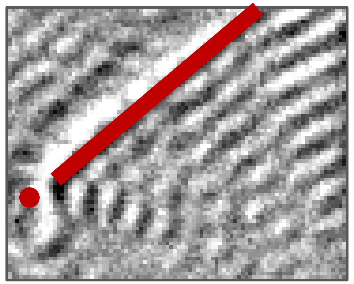
Manipulating spin-waves with patterned spin-textures



Spatial control in domains



Domain wall SW circuits



Optically-inspired magnonics

Thanks!

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M. Spiezer

M. Madami
S. Tacchi
R. Silvani
G. Carlotti

A. Papp
G. Csaba
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Beyond Nanofabrication via
Nanoscale phase-engineering of matter

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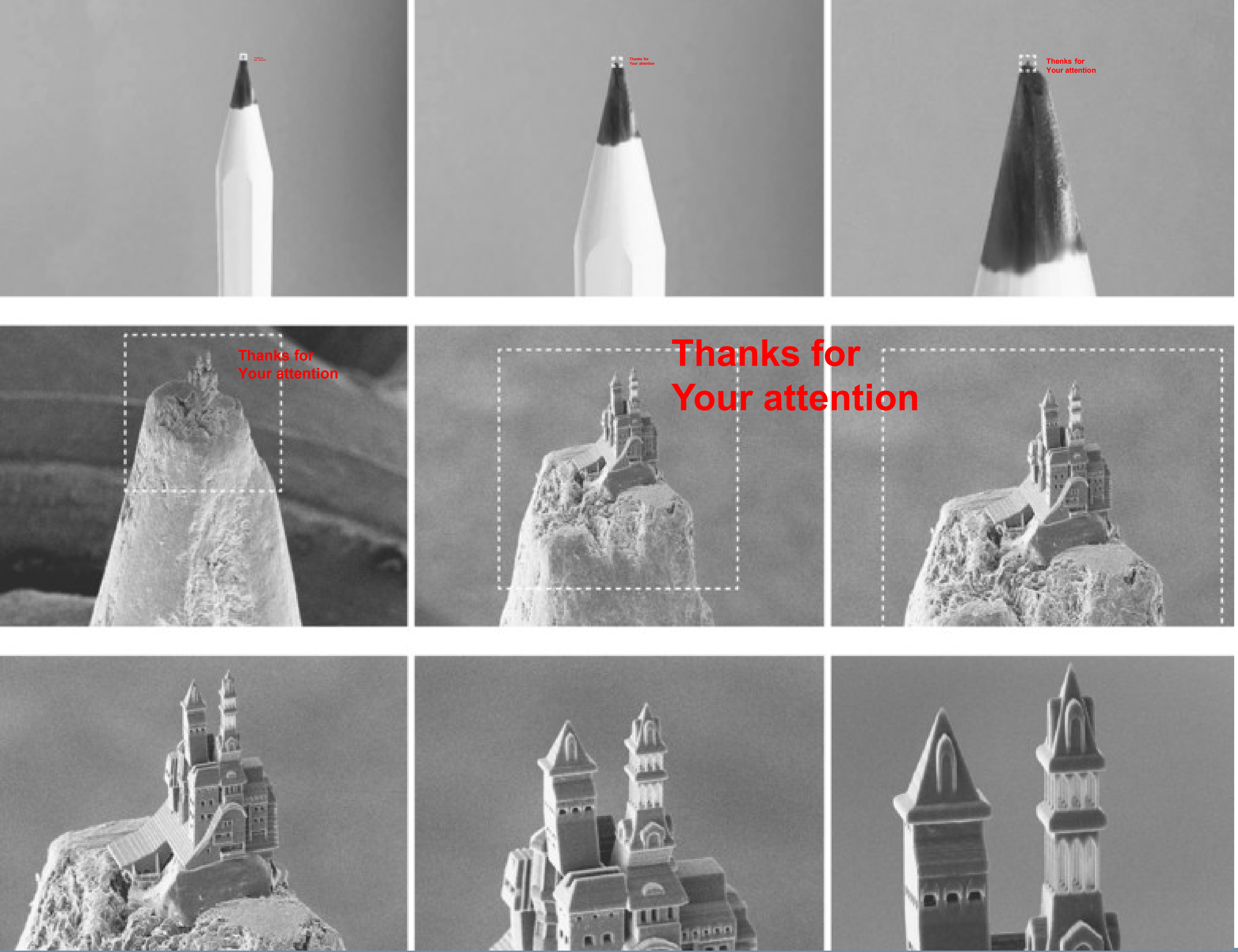

Thanks for your attention

Multiphoton Lithography: Techniques, Materials, and Applications, Wiley