Litho etc

MICRO-331
Microfabrication
technologies

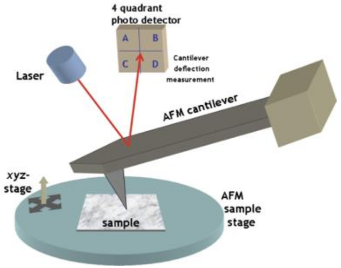
2025 edition

Litho - recap

- From CAD to device
- From micro to nano
- From writing to projection/replication
- Resolution limit: Diffraction – scattering – probe interaction
- Role of resist?
- Lift-off
- → stencil
- T-SPL
- (self-assembly, CAPA)

Three types of instruments to view nanoscale

A microscope is a tool that ‘probes’ a surface or material and the interaction with it provides some information. Often microscopes are surface instruments, but not only, depending how deep the ‘probe’ can penetrate into the material and re-exit to be detected by a monitoring system (eye, detector, sensor). The ‘probe’ may also alter the specimen.

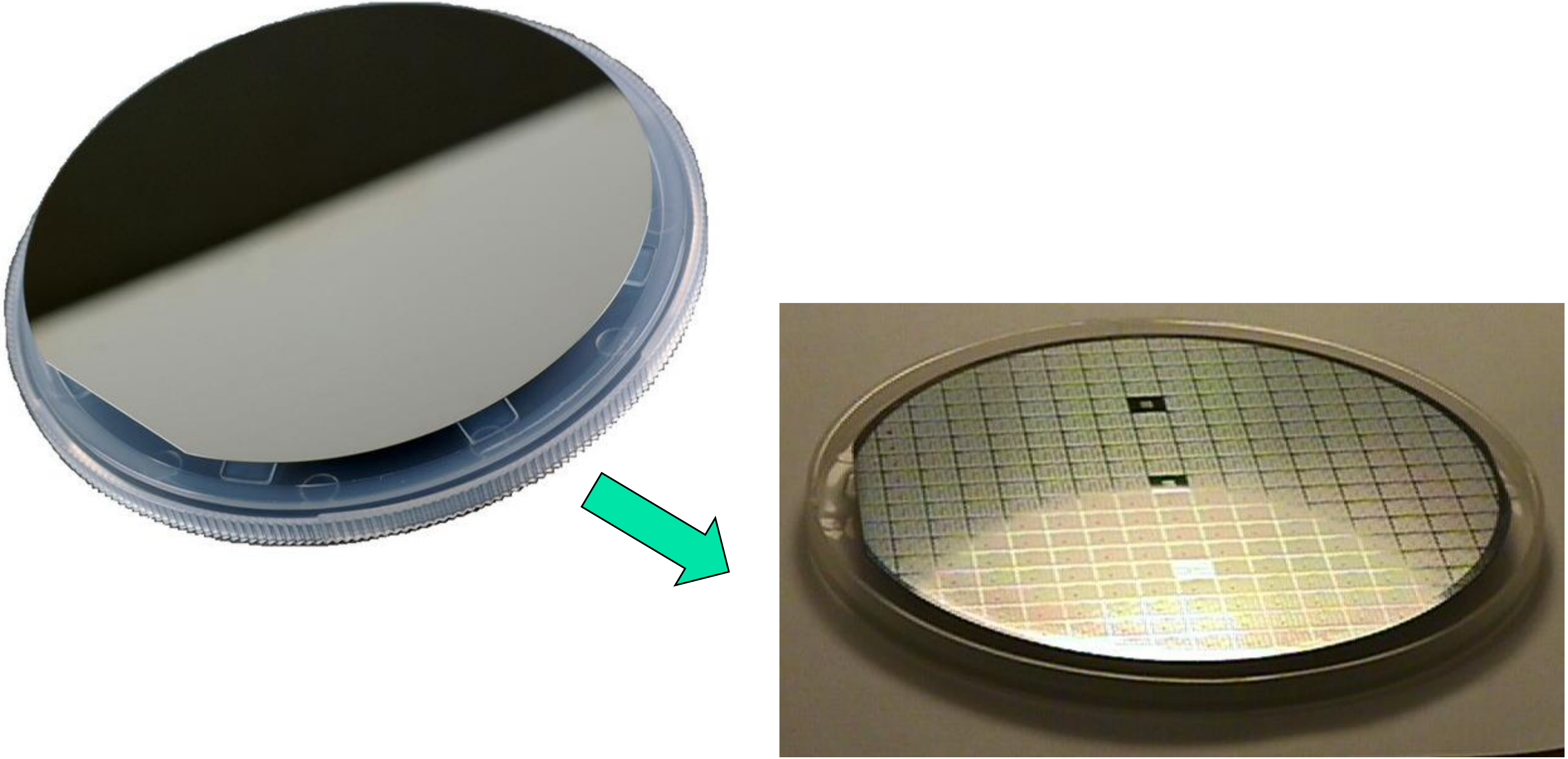


Optical (“light”) microscope ‘Probe’: Light that is reflected from or transmitted through sample.

Electron microscope ‘Probe’: Electrons (shorter wavelength) that are re-emitted from or transmitted through sample.

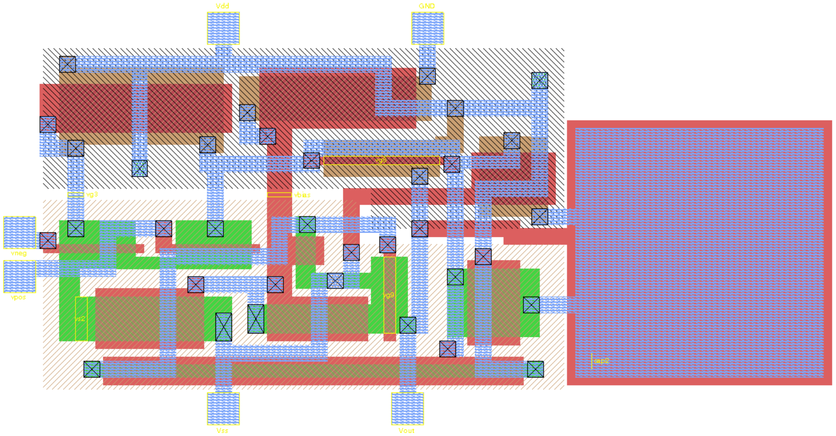
Scanning Probe microscope ‘Probe’: tip that interacts locally with surface (forces, electrons, photons)

From a bare silicon substrate to integrated circuits (chips, dies…)



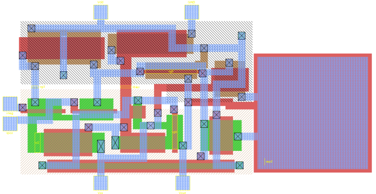
In-class question

- Q: How do you get from a circuit design on a computer (CAD) to a physical layer?



Wikipedia

From design to a micro/nanodevice



Data of micro/nanostructure (CAD)

Electron beam writer / laser beam writer

Mask for contact, proximity or projection lithography

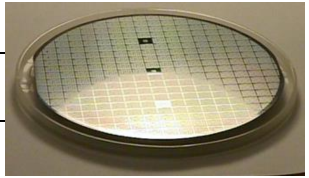
- UV: 365-436nm
- DUV 157-250nm
- EUV 11-14nm
- X-ray <10nm
- Electron beam projection
- Ion beam projection

Direct writing

Resist coated substrate / develop

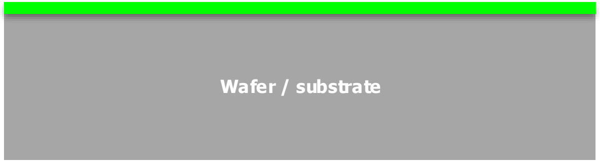
Wet/dry chemical etching

Micro/nanostructure on substrate



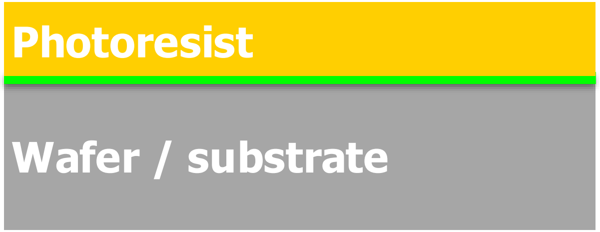
Lithography process flow

- Substrate preparation
- Resist coating and pre-baking
- Resist exposure
- Resist development
- Pattern transfer (etching, lift-off)
- Resist stripping



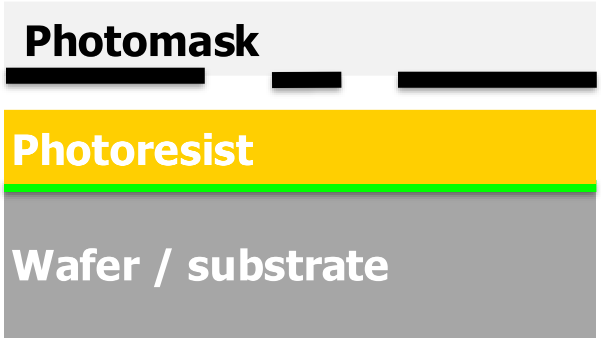
Lithography process flow

- Substrate preparation
- Resist coating and pre-baking
- Resist exposure
- Resist development
- Pattern transfer (etching, lift-off)
- Resist stripping



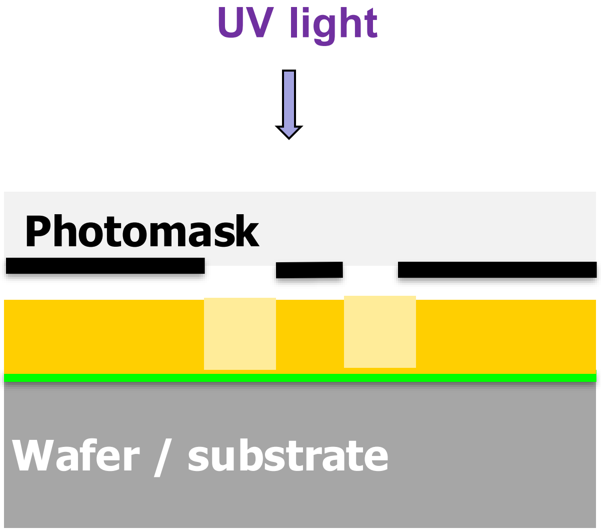
Lithography process flow

- Substrate preparation
- Resist coating and pre-baking
- Resist exposure
- Resist development
- Pattern transfer (etching, lift-off)
- Resist stripping



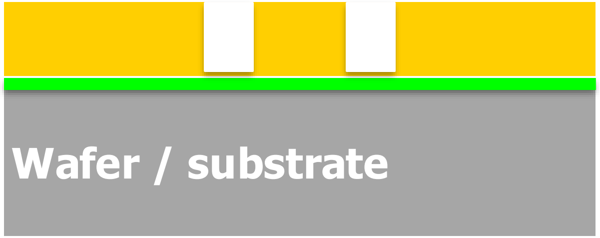
Lithography process flow

- Substrate preparation
- Resist coating and pre-baking
- Resist exposure
- Resist development
- Pattern transfer (etching, lift-off)
- Resist stripping



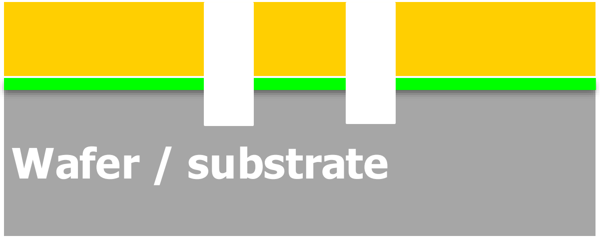
Lithography process flow

- Substrate preparation
- Resist coating and pre-baking
- Resist exposure
- Resist development
- Pattern transfer (etching, lift-off)
- Resist stripping



Lithography process flow

- Substrate preparation
- Resist coating and pre-baking
- Resist exposure
- Resist development
- Pattern transfer (etching, lift-off)
- Resist stripping



Lithography process flow

- Substrate preparation
- Resist coating and pre-baking
- Resist exposure
- Resist development
- Pattern transfer (etching, lift-off)
- Resist stripping

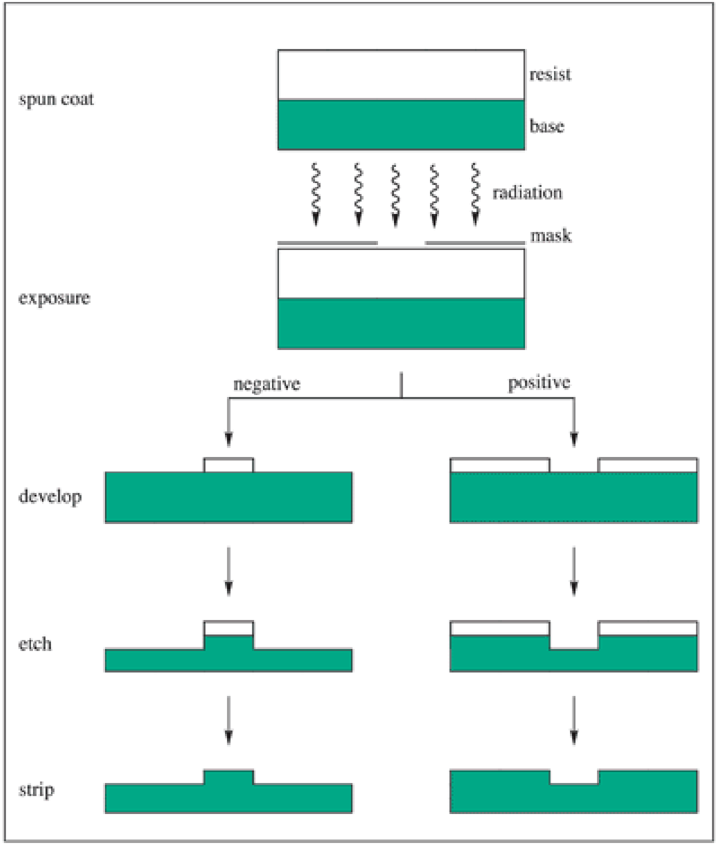
Lithography

From the Greek *lithos* (stone) and *graphy* (writing), lithography literally means writing on rocks.
In the context of micro- and nanotechnology, the method is widely employed by the semiconductor industry to pattern the surface of silicon wafers. Important parameters are:

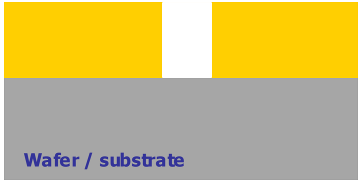
- Illumination (Light source, Optical system)
- Mask, reticle
- Resist (dose, development, etch selectivity)

A positive photolithography means that the exposed region is developed 'away'.
A negative photolithography means that the unexposed region is developed 'away'.

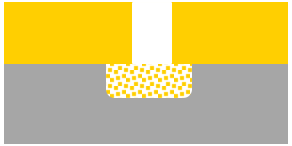
Hg-arc lamps: G-line (436 nm), H-line (405 nm), I-line (365 nm)
With typical k1 and NA values → ~ 400 nm resolution possible
Hg/Xe: wavelength λ = 248 nm, resolution ~ 300 nm
but low intensity
→ New light sources, high intensity, excimer laser (KrF, ArF, F2)
248nm, 193 nm



After lithography, what next? Pattern transfer



a) Ion Implantation
b) Isotropic etching (wet and dry)
c) Thin film etching
d) Molding
e) Anisotropic etching (wet and dry)
f) Electro-plating
g) PVD thin film coating (lift-off)

☐


☐


☐


☐

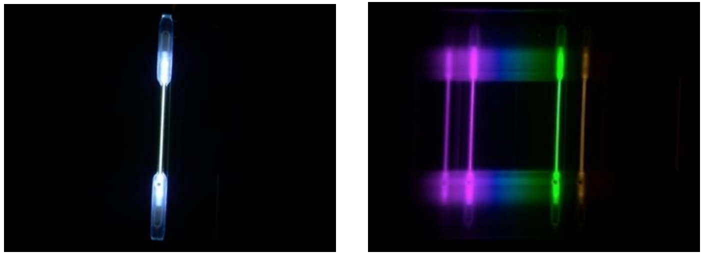

☐

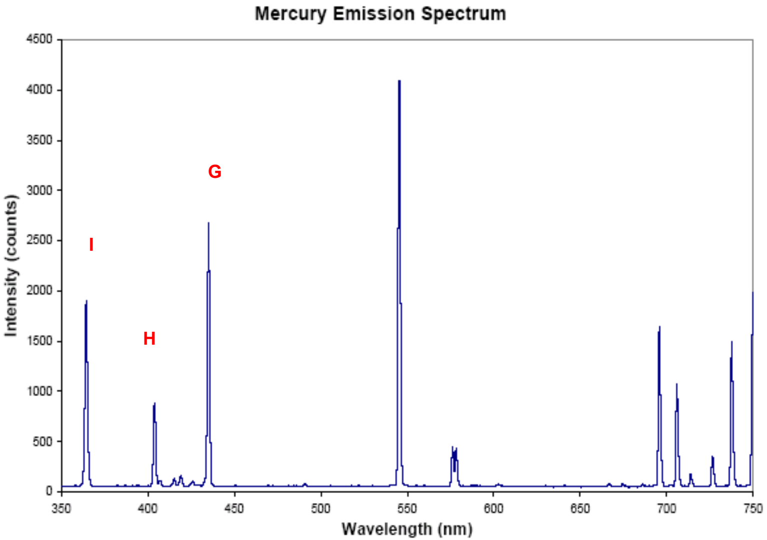

☐


☐


Exposure wavelength and light sources

Wavelength [nm]	Source	Range
436	Hg arc lamp	G-line
405	Hg arc lamp	H-line
365	Hg arc lamp	I-line
248	Hg/Xe arc lamp, KrF excimer laser	Deep UV (DUV)
193	ArF excimer laser	DUV
157	F2 laser	Vacuum UV (VUV)
~ 10	Laser-produces plasma sources	Extreme UV (EUV)
~ 1	X-ray tube, syncrotonon	X-Ray





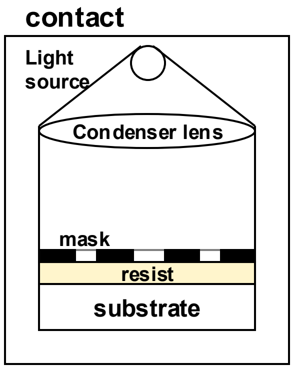
Illumination methods and resolution limits

- 3 methods:
    - Contact
    - Proximity
    - projection lithography

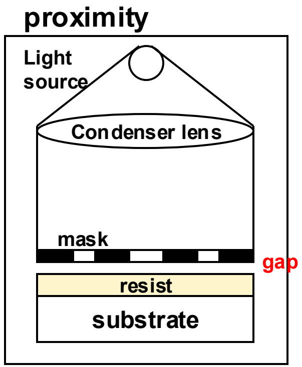
- Common point:
    - Condenser lens for parallel beam

- Key issue: minimum feature size (MFS)
    - Illumination method
    - Illumination wavelength
    - Materials of optical system
    - Resist used

contact



proximity



1:1 scale
Full wafer at once

contact

$$MFS = \sqrt{d \cdot \lambda}$$

$$d = thickness(resist)$$

$$\lambda = wavelength$$

proximity

$$MFS \approx \sqrt{(d+g) \cdot \lambda}$$

$$d = thickness(resist)$$

$$g = gap$$

$$\lambda = wavelength$$

Example:

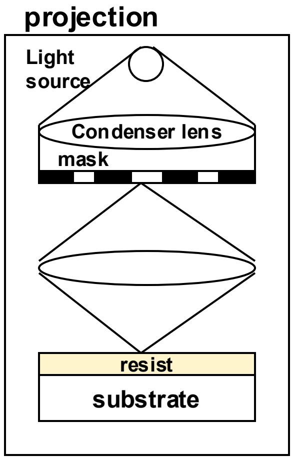
d = 1 μm
λ = 400 nm
MFS ?

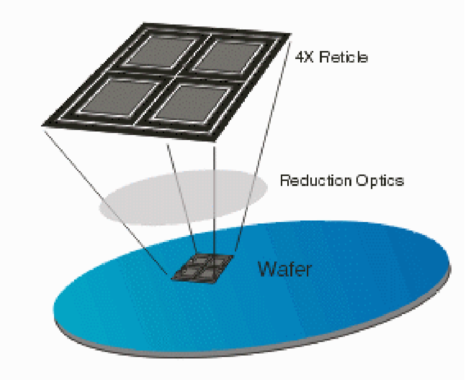
Example:

d = 1 μm
λ = 400 nm
g = 10 μm
MFS ?

Projection lithography

- Mainly used today for IC industry
- Not shadow projection
- Picture of the mask is projected
- No contact
- No deterioration
- Excellent resolution (reduction 4x, 5x)
- Reduction of errors
- Stepper, x-y movement, from field to field





$$MFS = \sqrt{d \cdot \lambda}$$

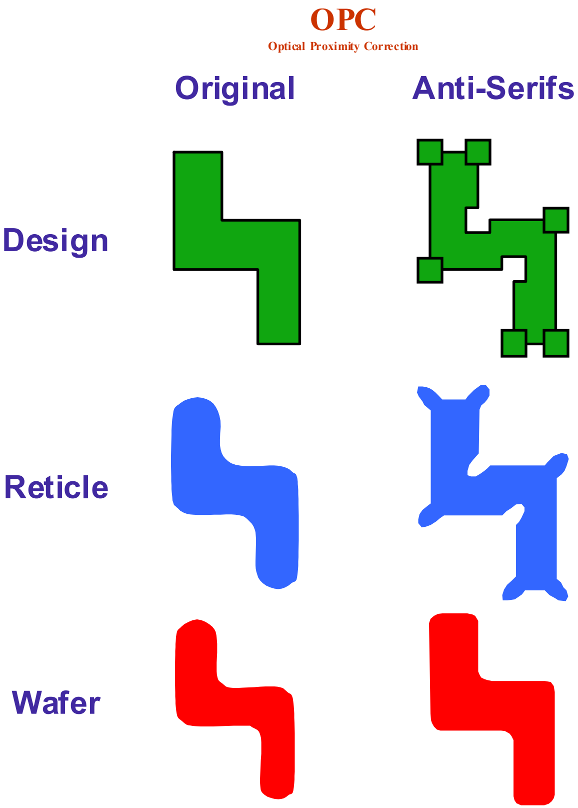
$$d = thickness(resist)$$

$$\lambda = wavelength$$

Rayleigh criterion says:
MFS=0.61*λ/NA

In microlithography:
MFS=k_1*λ/NA
k_1=technology constant (0.5-0.9)
Non-linear behavior of equipment
Lens error
Resist chemistry,
Exposure and processing,
shape, etc.

Optical proximity correction



Optical proximity correction (OPC) is a photolithography enhancement technique commonly used to compensate for image errors due to diffraction or process effects.

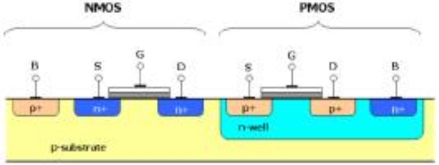
Optical Proximity Correction corrects errors by moving edges or adding extra polygons to the pattern written on the photomask.

This may be driven by pre-computed look-up tables based on width and spacing between features (known as rule based OPC) or by using compact models to dynamically simulate the final pattern and thereby drive the movement of edges, typically broken into sections, to find the best solution, (this is known as model based OPC).

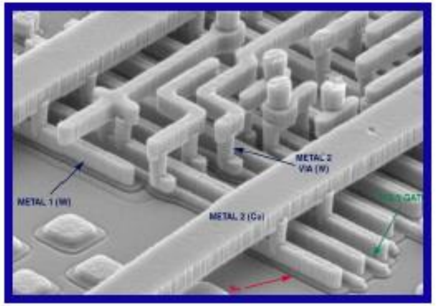
The objective is to reproduce, as well as possible, the original layout drawn by the designer in the silicon wafer.

From Silicon, to Transistors and ultimately to Integrated Circuits (IC)

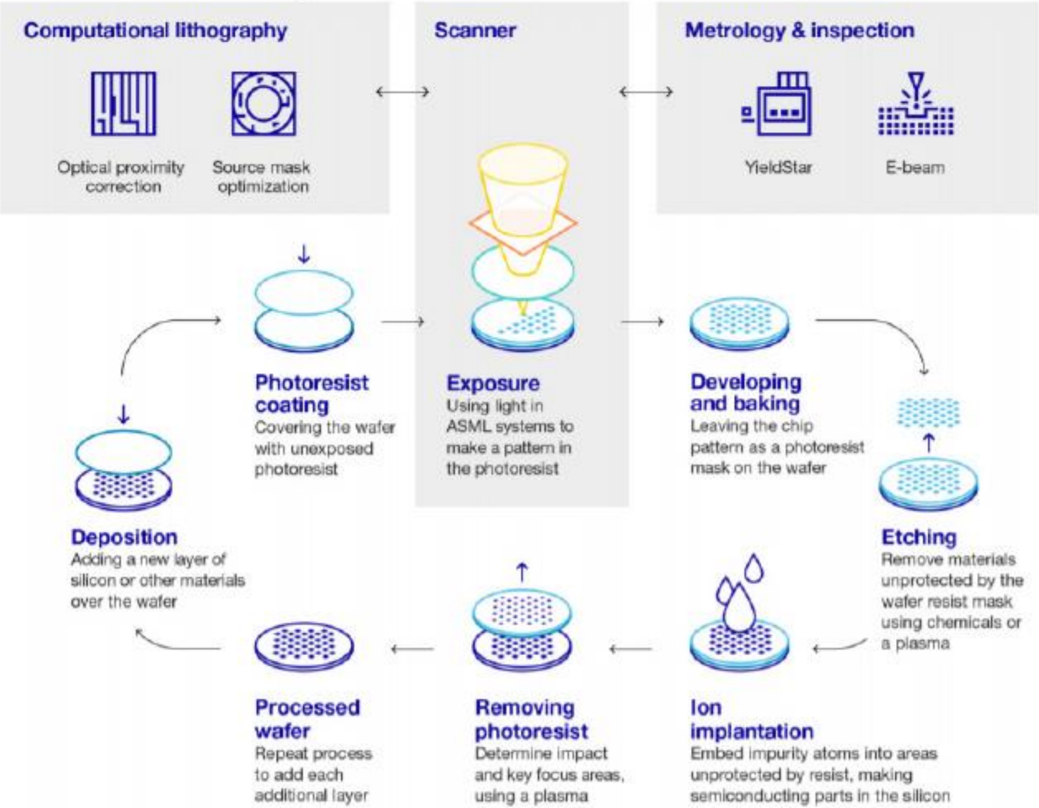
the (MOS-FET) Transistor



Interconnecting the transistors



Semiconductor processes / Manufacturing loop



Computational lithography

Optical proximity correction

Source mask optimization

Scanner

Metrology & inspection

YieldStar

E-beam

Photoresist coating
Covering the wafer with unexposed photoresist

Exposure
Using light in ASML systems to make a pattern in the photoresist

Developing and baking
Leaving the chip pattern as a photoresist mask on the wafer

Etching
Remove materials unprotected by the wafer resist mask using chemicals or a plasma

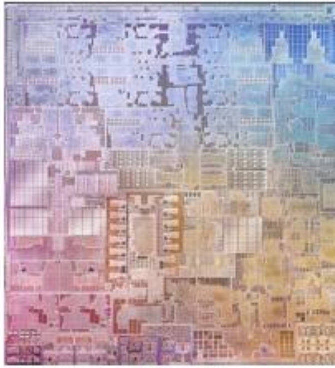
Ion implantation
Embed impurity atoms into areas unprotected by resist, making semiconducting parts in the silicon

Removing photoresist
Determine impact and key focus areas, using a plasma

Processed wafer
Repeat process to add each additional layer

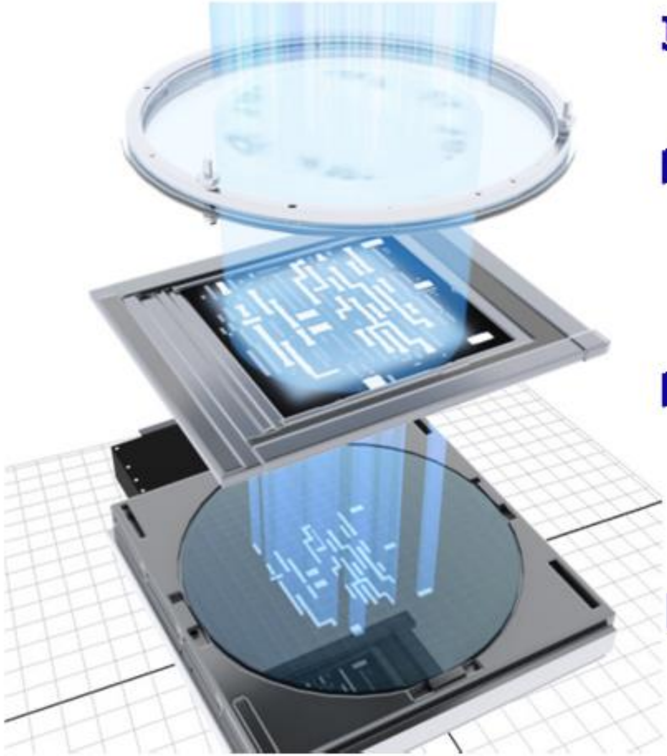
Deposition
Adding a new layer of silicon or other materials over the wafer

What comes out: the Integrated Circuit (IC



Lithography: Imaging the reticle on to the wafer

The key and most critical step in manufacturing Integrated Circuits



Light Source

Optics

Mask

Wafer

ASML EUV in action

https://www.youtube.com/watch?v=h_zgURwr6nA

In-class question

- Q: Remember the depth of focus in microscopy? Why is it very important in photolithography?

Litho - recap

- From CAD to device
- From micro to nano
- From writing to projection/replication
- Resolution limit: Diffraction – scattering – probe interaction
- Role of resist?
- Lift-off
- → stencil
- T-SPL
- self-assembly, CAPA

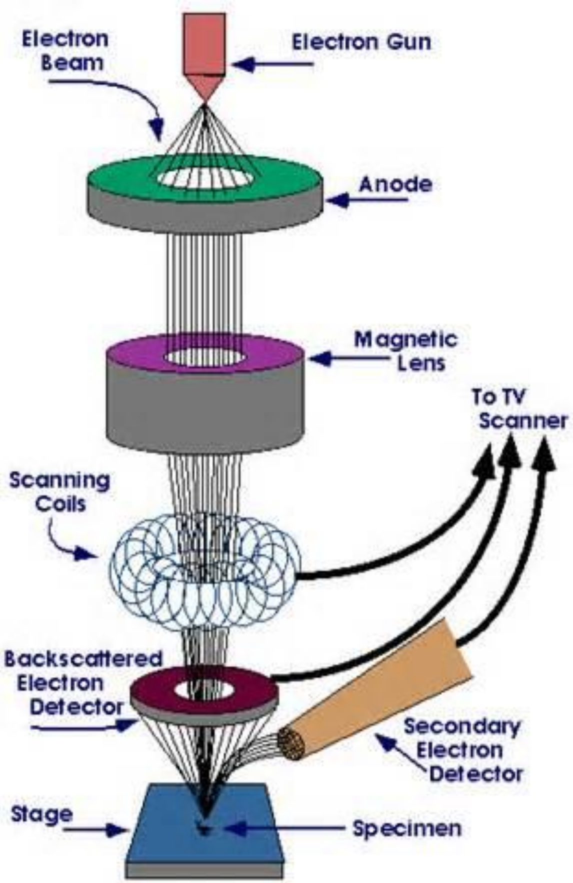
Charged beam techniques

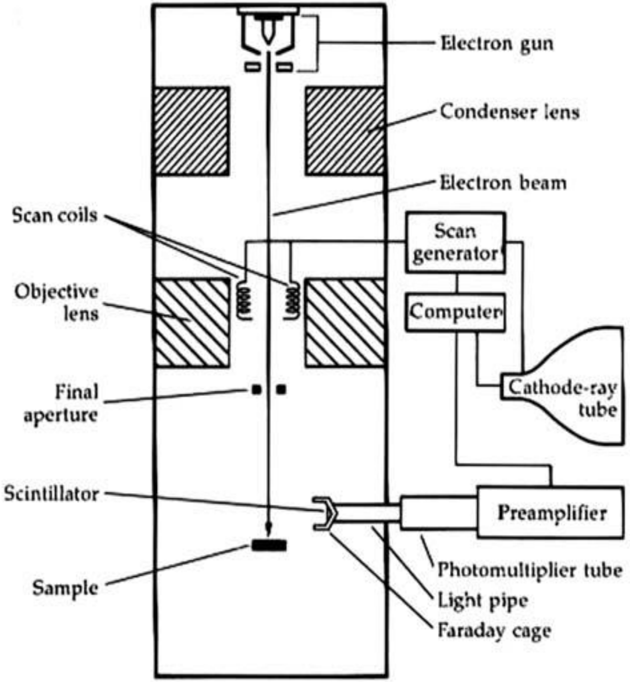
- Electron-based

(not photons, not limited by wave diffraction at the scale of interest)

  - Microscopy:
    - Scanning Electrong Microscope
    - Transmission Electron Microscope
  - Lithography:
    - Electron Beam Lithography

Schematics of a SEM





This simple schematic shows the principal elements of a classical SEM (nowadays, the acquisition is entirely digitalised).

Electrons – energy - wavelength

Electron wavelength (De Broglie relation)

The relation p = h / λ is one of the properties of the photon; De Broglie adapted it to a particle having a mass, in order to derive an equivalent wavelength.

$$\lambda = \frac{h}{p} = \frac{h}{m \cdot v} = \frac{h}{\sqrt{2m \cdot E}}$$

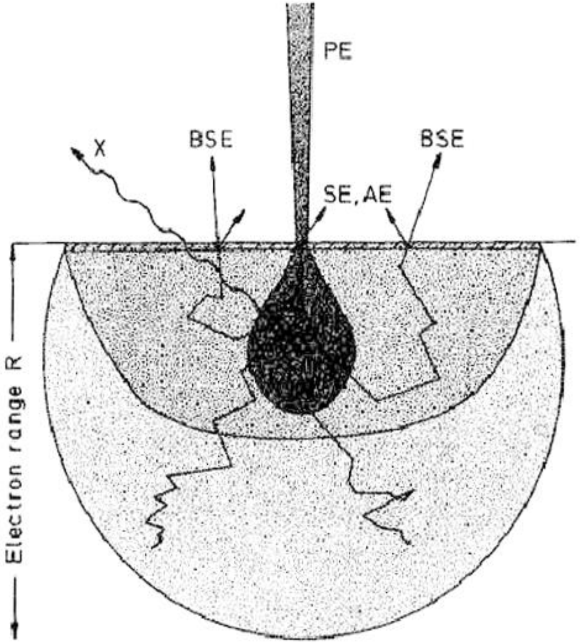
$$\lambda = \frac{h}{\sqrt{2m \cdot e \cdot U}}$$

e	**electron charge**	**$1.602 \cdot 10^{-19}$ C**
E	**kinetic energy**	
h	**Plank's constant**	
m	**electron mass**	**$9.1091 \cdot 10^{-31}$ kg**
p	**momentum**	
U	**acceleration voltage**	
v	**speed**	

U [V]	λ [pm]
1	1'220
10	387
10^2	122
10^3	39
10^4	12
10^5	4

Sample – electron beam interaction

Even with a very well focused beam, the resolution of the SEM is limited, by the size of the "interaction region" between the electrons and matter (the TEM uses thin slices and thus avoids this problem).



PE:	**primary electrons**
SE:	**secondary e$^-$ (0-50 eV)**
BSE:	**backscattered e$^-$**
AE:	**Auger e$^-$**
X:	**X - rays**

R: The electron range is the distance at which the electrons are stopped, depends of ρ, and Z of the material.

All can be detected individually for analysis !

Electron range @ 25 keV

Electron penetration into material decreases for heavy elements, and backscattered electron yield increases strongly.

Different scales of the simulations.

Resolution with BSE is poorer than with SE, but chemical contrast may be better.

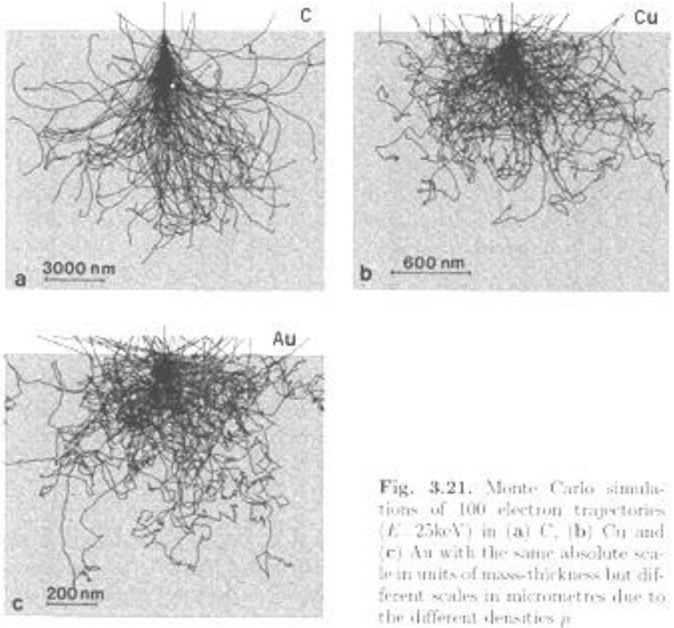
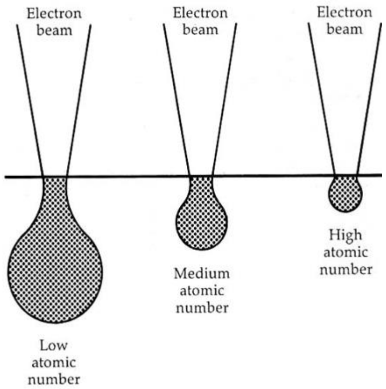
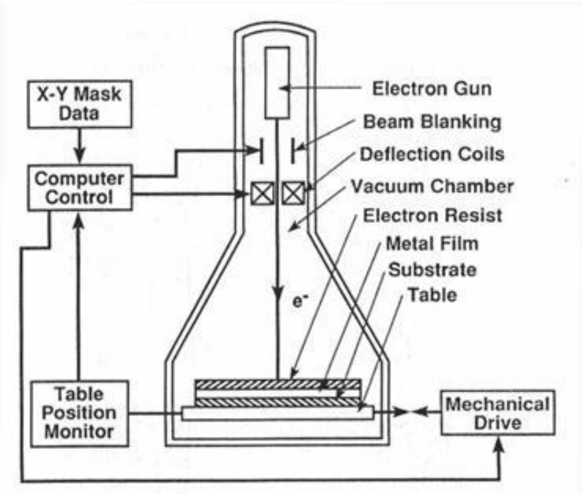
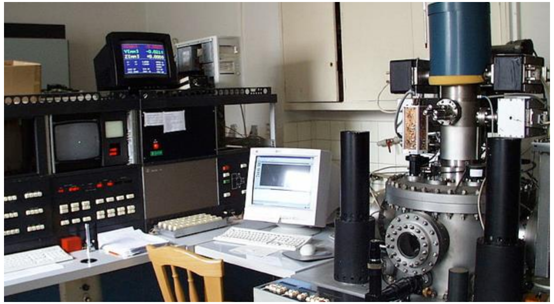


Fig. 3.21. Monte Carlo simulations of 100 electron trajectories ($E = 25$keV) in (**a**) C, (**b**) Cu and (**c**) Au with the same absolute scale in units of mass-thickness but different scales in micrometres due to the different densities ρ



Electron Beam Lithography (EBL)





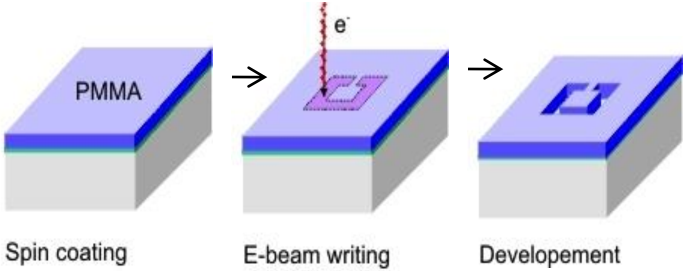
E-Beam lithography = Electron microscope + Pattern generator + Resist and Substrate

The column also contain the lenses to move the electron beam.

Energy: 30 ~100 keV
Beam spot size: ~1-10 nm
Current: ~1-100 nA
BSS and I stability are critical

Resist processing and local energy radiation by an e-beam
High resolution and pattern fidelity (~5 nm)
Computer controlled *serial* process
It does not require pattern masters (masks)
So far not suitable for large scale production.

A sensitive material (ex. PMMA) is locally modified
by energy radiation from an electron beam.



EBL: electron optics / lenses

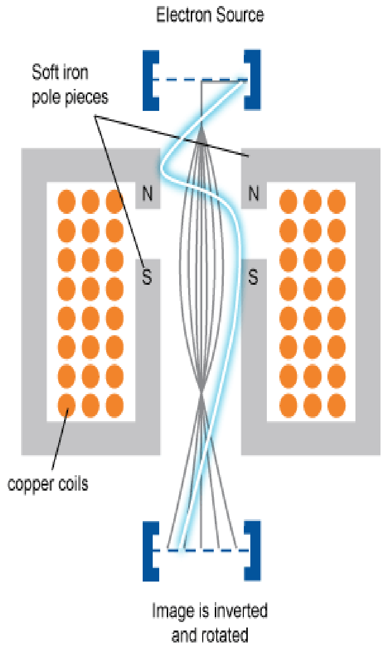
$$\vec{F} = \underset{\text{Electric force}}{q\vec{E}} + \underset{\text{Magnetic force}}{q\vec{v}\ x\ \vec{B}}$$

F = Lorentz force
q = charge
E = electric field

v = velocity
B = magnetic field

- Electrostatic vs electro-magnetic
- Electrostatic
  - Fast but large aberrations
  - Ideal for the beam blanker
- Electro-magnetic
  - Aberration correction possible
  - Electrons spiral through the lens
  - Inductance of the magnetic coils limits their frequency response

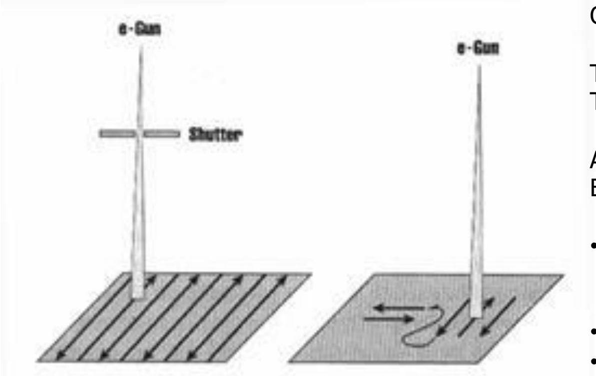
Magnetic lens



Australian Microscopy & Microanalysis Research Facility

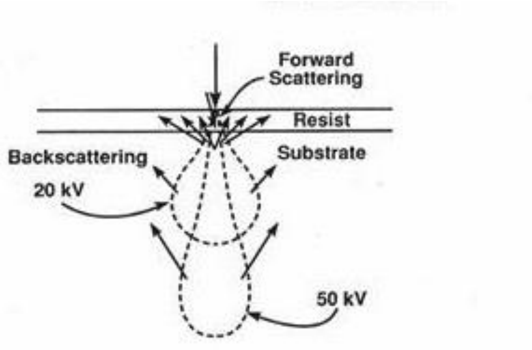
E-Beam pattern generator

Scanning modes



Raster scanning and beam blanking

Vector scanning

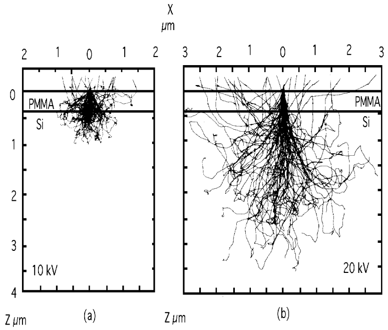


Important parameters:
Dose (how much energy), Exposure time, Resolution, Step size, Overlapping, Field size

The maximum deflection of the beam is ~100um
The machines operate at 10~50 MHz.

A software is required to convert a CAD file into a writing file for the E-Beam exposure system.

- Same physical behavior as electron microscopy. BUT, the material is not observed, it is modified. Electron scattering in PMMA/Si for Primary beam of 10 and 20 kV
- Secondary electrons are the main contributors to resist exposure
- In the 20kV example, lots of electrons are lost, but anyway there is a higher resolution, since the backscattered electrons are 'lost' further in the silicon.
- In order to increase the resolution, the solution is to use a very thin Si layer (a membrane) such that the electrons cannot be backscattered.

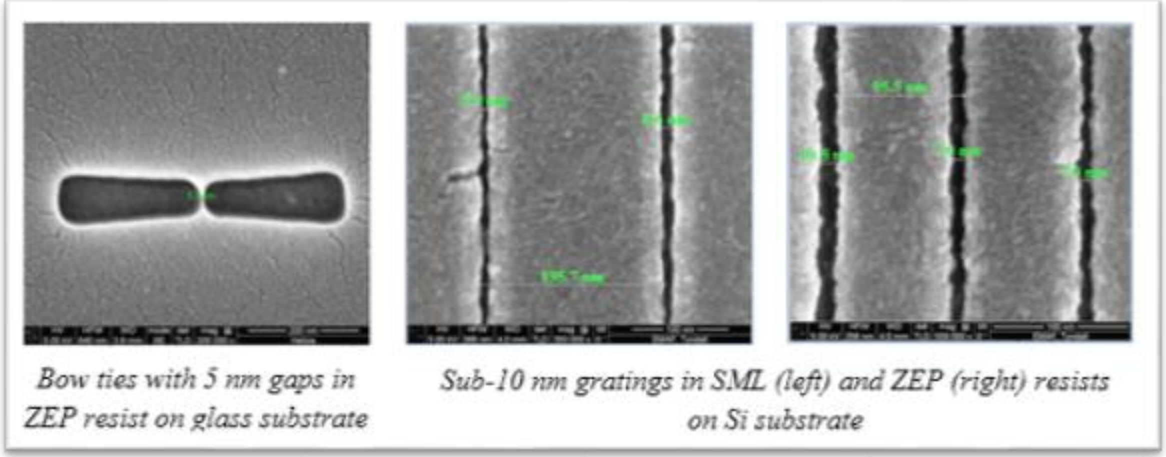


EBL pattern examples / applications

http://www.vistec-semi.com/applications/

https://raith.com/

https://www.zeiss.com/semiconductor-manufacturing-technology/products/photomask-solutions/mask-repair.html

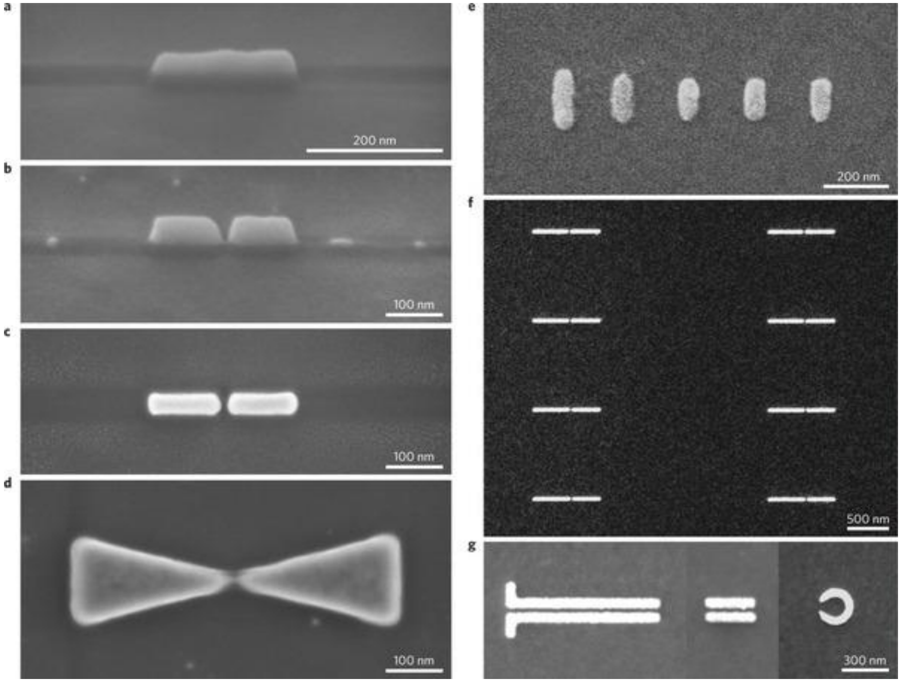


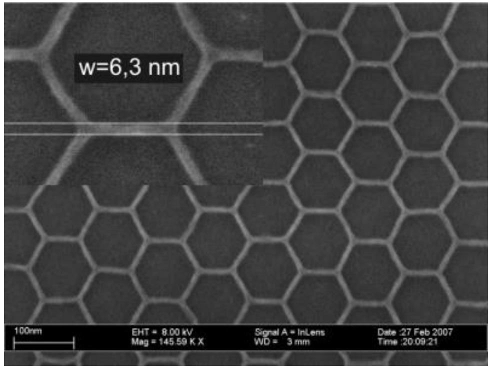
Bow ties with 5 nm gaps in ZEP resist on glass substrate

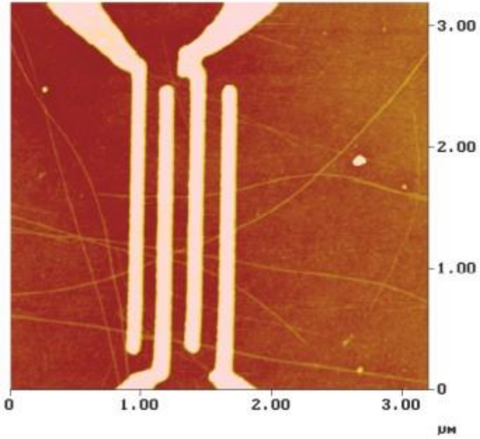
Sub-10 nm gratings in SML (left) and ZEP (right) resists on Si substrate

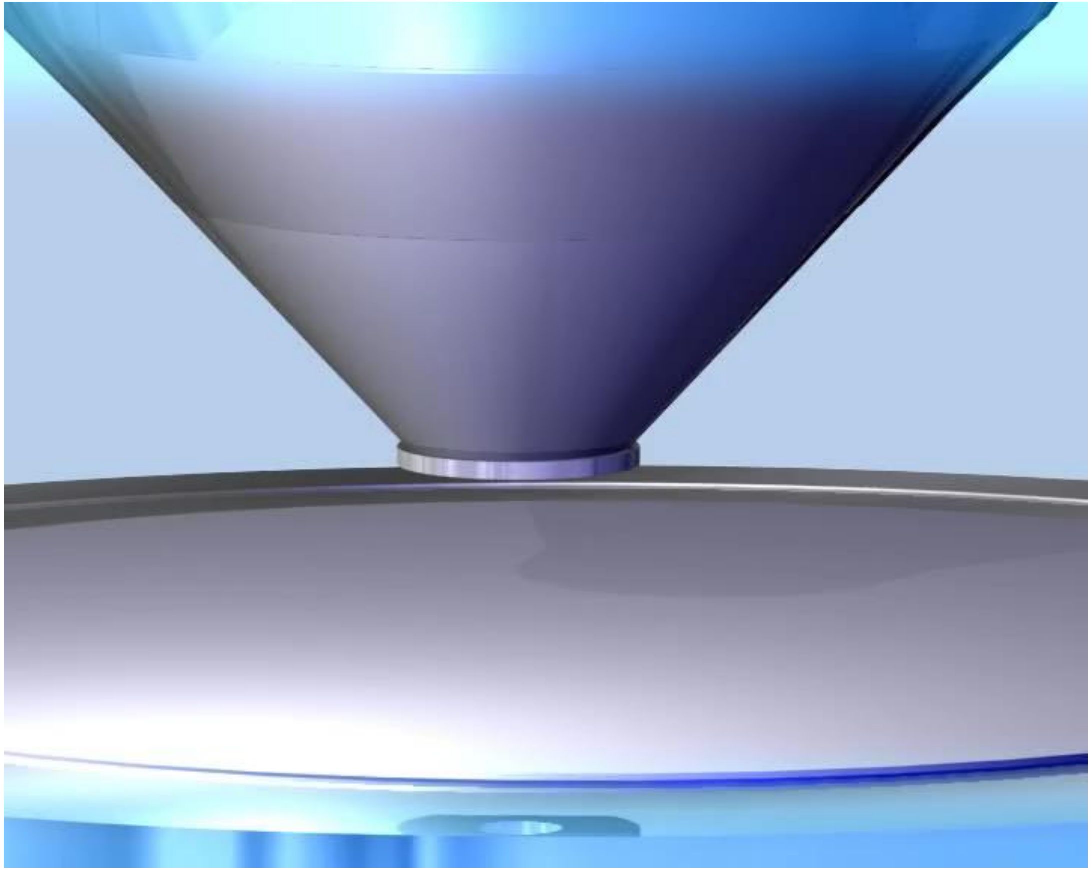
http://www.mcag.ie/top-down-nanofabrication/

EBL samples

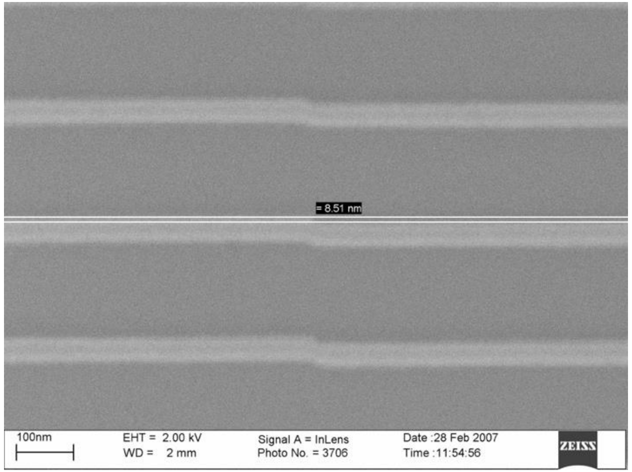

a
200 nm
b
100 nm
c
100 nm
d
100 nm
e
200 nm
f
500 nm
g
300 nm


w=6,3 nm
100nm
EHT = 8.00 kV
Mag = 145.59 K X
Signal A = InLens
WD = 3 mm
Date :27 Feb 2007
Time :20:09:21


3.00
2.00
1.00
0
0
1.00
2.00
3.00
μm



Stage control … stitching



Boundary between two fields

One of the most complicated and expensive components of an EBL machine is the stage controller.
The electron optics deflects the beam up to 100 µm. For larger structures, the stage has to move. Field size: Larger size written without moving the stage.

Beam deflection is a fast process (MHz)
Stage movement is slow (Hz)
Small blocks give higher resolution but long writing time.

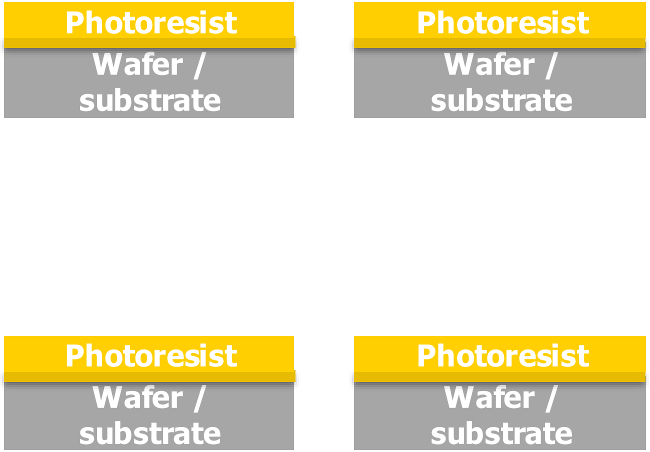
It is a big challenge to align the different fields in a EBL.

Stitching: Misalignment between two adjacent fields.

High standard: <10 nm

Exposure methods and resolution

- **Optical (UV, DUV, EUV)**
- **Charged particle (EBL)**
- **X-ray**
- **Scanning probe**



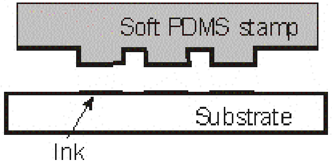
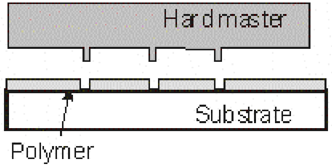
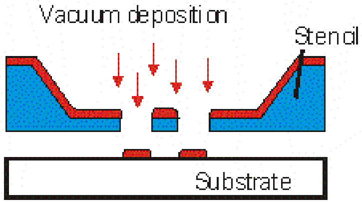
Photoresist
Wafer / substrate

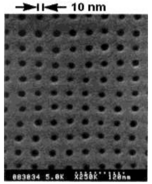
Photoresist
Wafer / substrate

Photoresist
Wafer / substrate

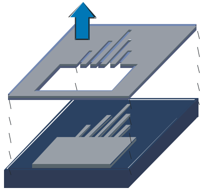
Photoresist
Wafer / substrate

Emerging Nanopatterning Methods (Replication)

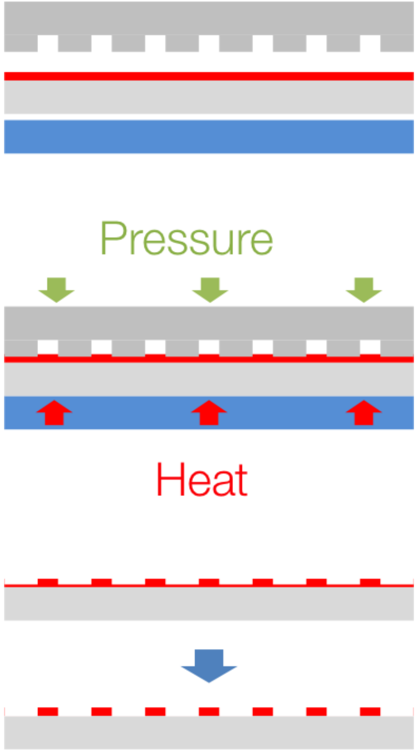
Soft-lithography	**Nanoimprint lithography**	**Nanostencil lithography**
Ink delivery molecules, wet *soft-contact*	Thermo-mechanical, nano-imprinting, *hard contact*	Local deposition stencil, vacuum *no contact*
		



10 nm
Candidate for
Integrated Circuit



Nano-Imprint Lithography



Imprint stack preparation

Stamp (or mold), Resist, Substrate, Chuck

Imprinting

Pressure / temperature / time profile

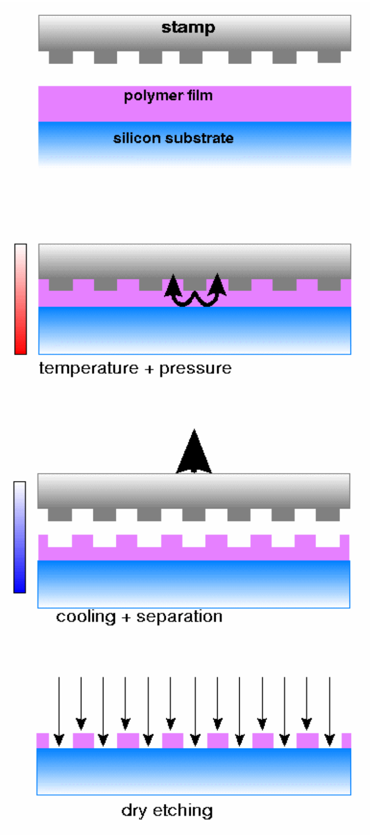
Separation

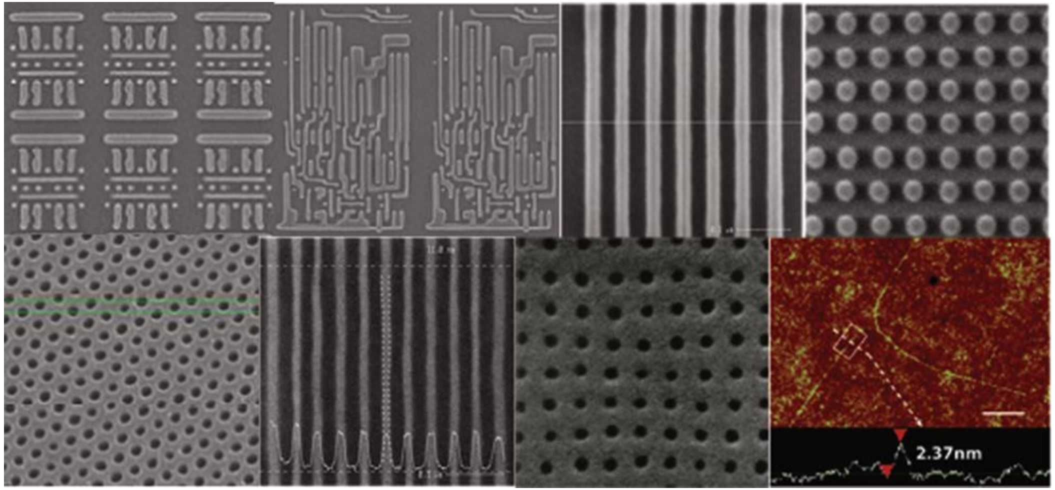
Temp control

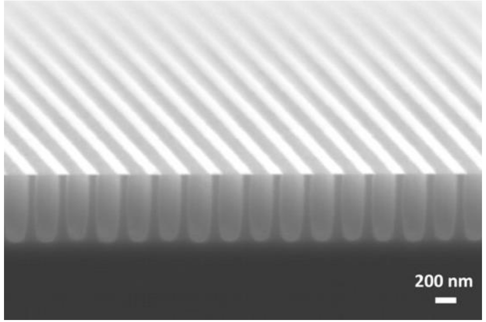
Residual layer etch

Remove thin resist layer by O2 plasma

Nano-Imprint Lithography

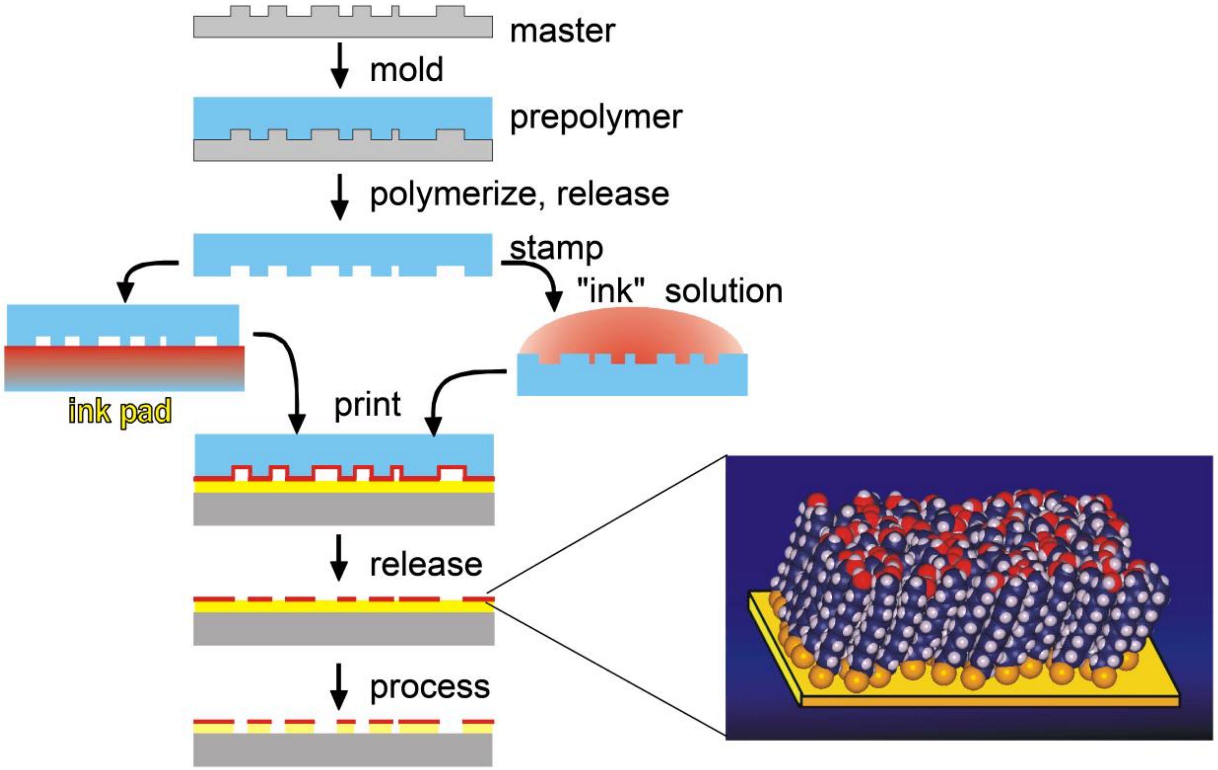






S. Chou et al. ***Science 5 April 1996: Vol. 272 no. 5258 pp. 85-87***

Microcontact Printing (μCP)



http://zurich.ibm.com

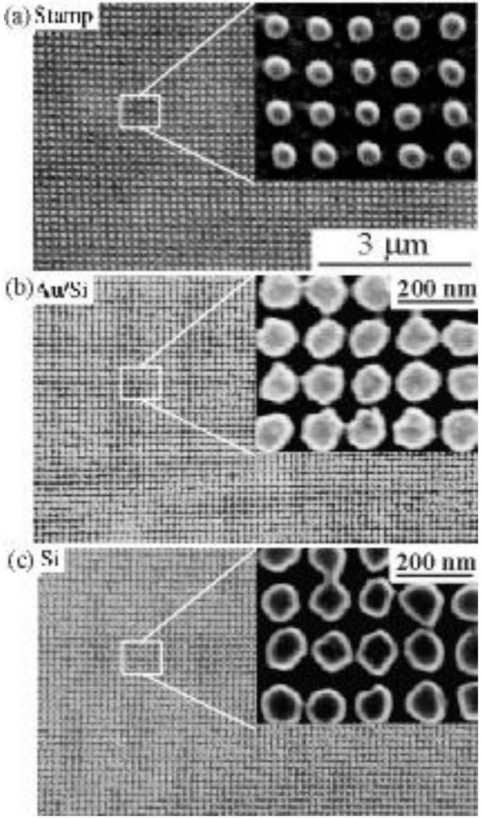
Microcontact Printing

High-resolution µCP:

a) Scanning electron micrograph of a stamp with 60 nm dots.

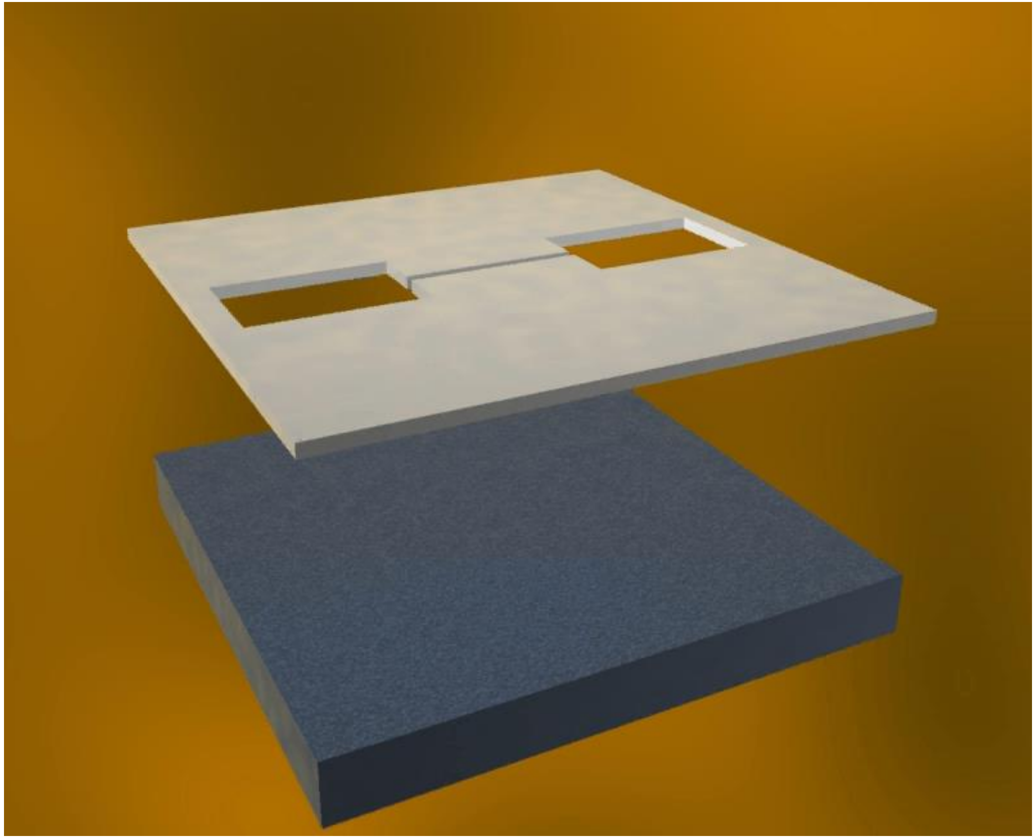
b) The corresponding gold dots fabricated by printing and etching were slightly broadened due to ink diffusion and substrate roughness.

c) The gold pattern served as a mask to etch the bare regions 250 nm deep into the underlying silicon by reactive ion etching.



http://zurich.ibm.com

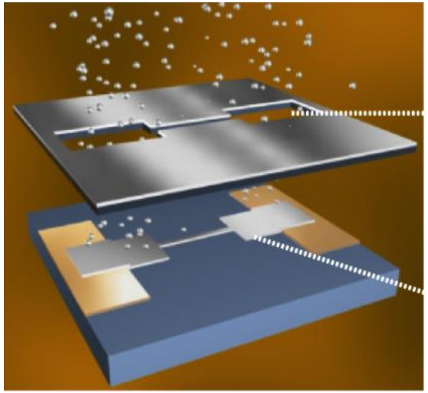
Stencil lithography

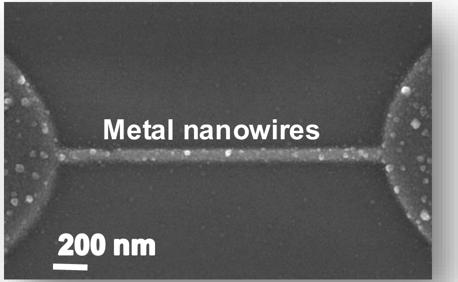


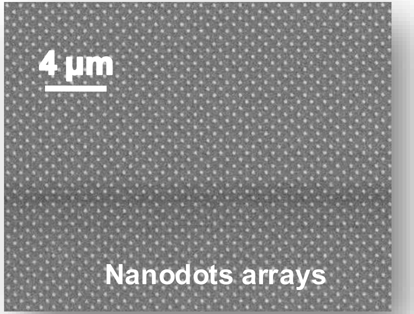
Stencil lithography

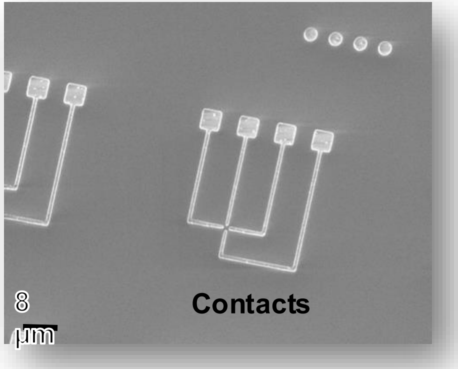
- Shadow mask technique
- Resistless
- One-step process
- Direct patterning
- High resolution (<100 nm)
- Full wafer

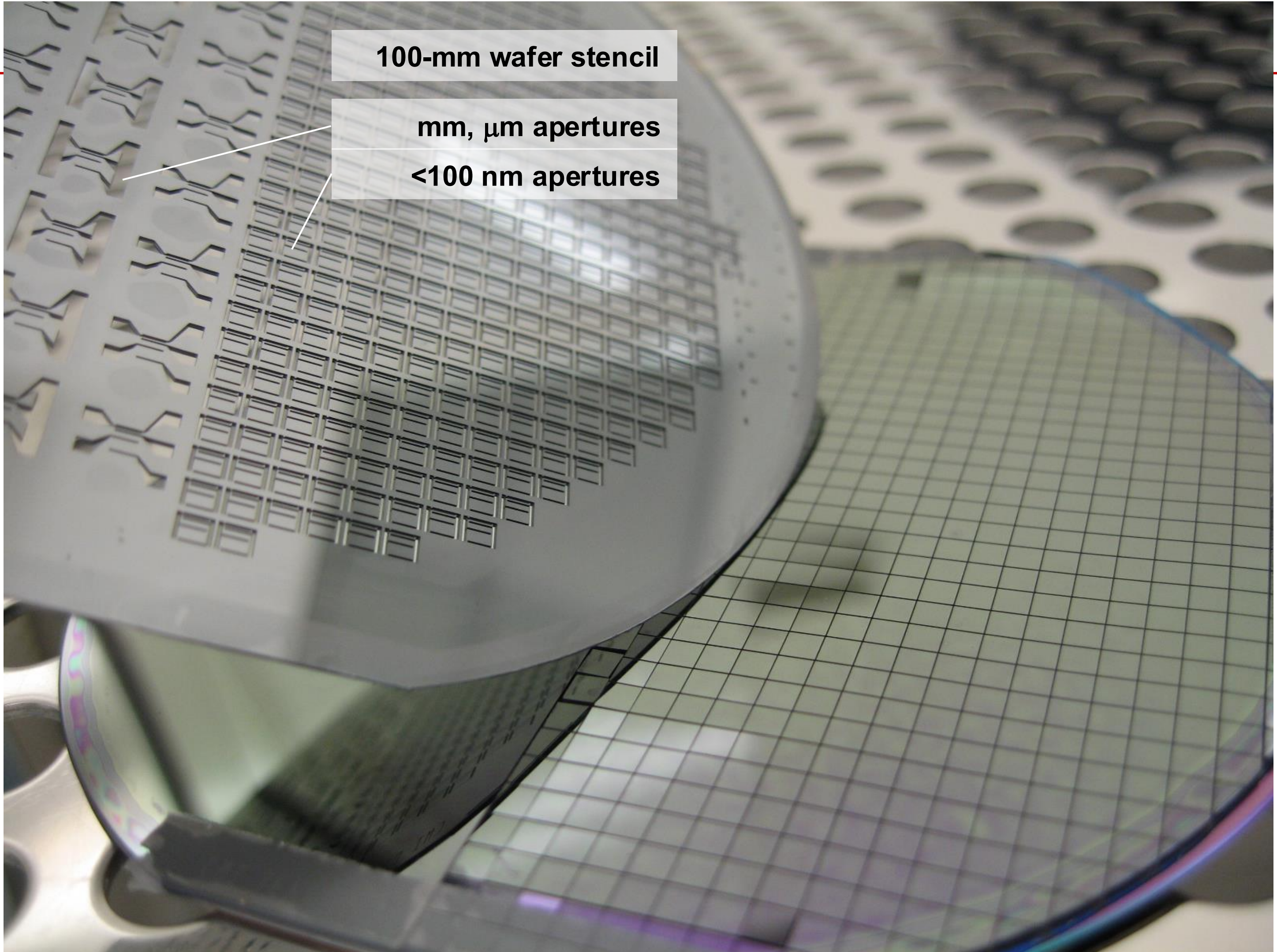
10 mm chip stencil



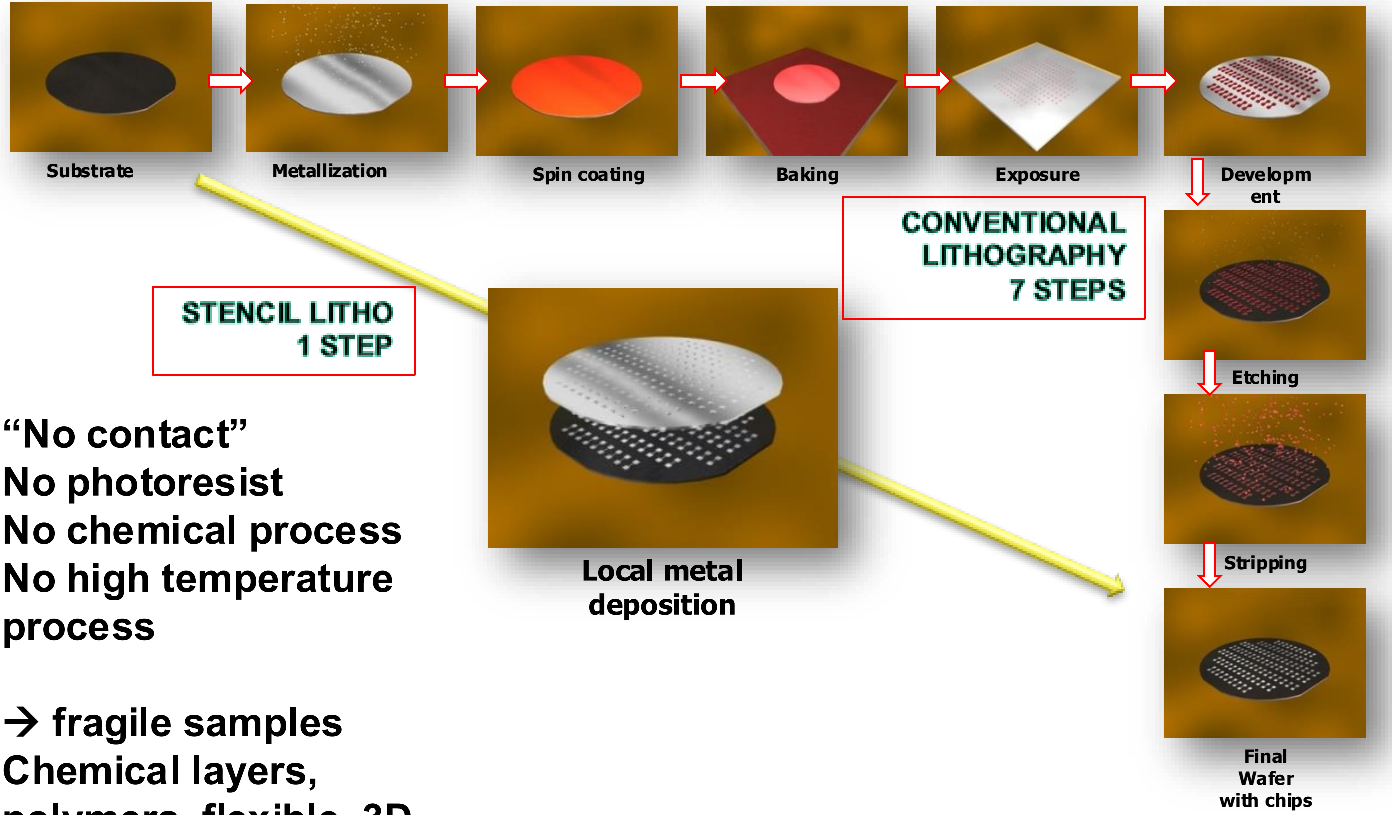







100-mm wafer stencil
mm, μm apertures
<100 nm apertures

Single step process / local deposition



STENCIL LITHO
1 STEP

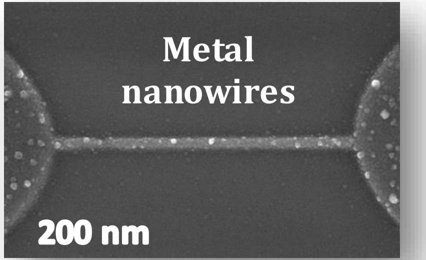
CONVENTIONAL
LITHOGRAPHY
7 STEPS

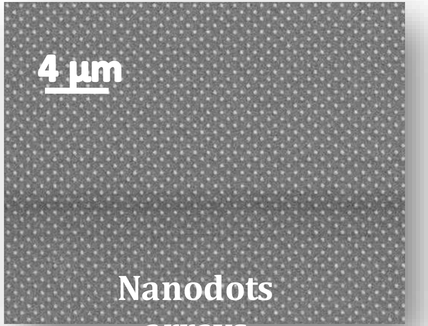
“No contact”
No photoresist
No chemical process
No high temperature process

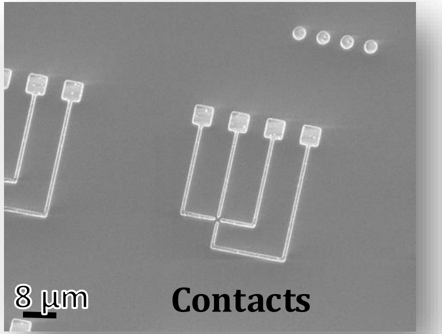
→ fragile samples
Chemical layers, polymers, flexible, 3D surfaces

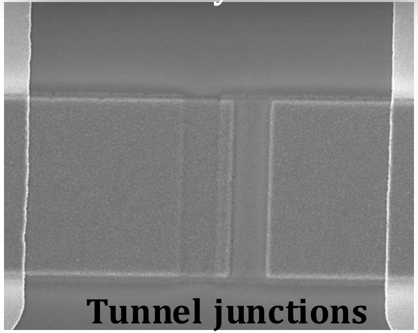
Nanostencil examples (I)

- Deposition of different metals
  - Aluminium, Gold, Chromium, Titanium, Platinum


Metal nanowires


Nanodots arrays


Contacts

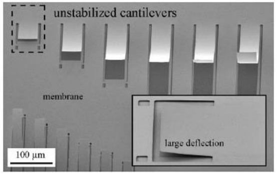

Tunnel junctions

In-class question

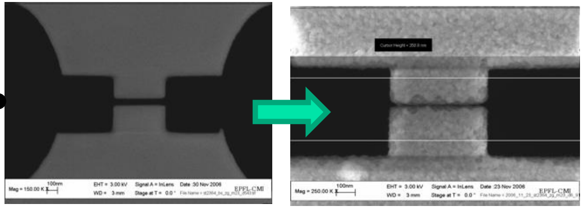
- Q: Where are the challenges in stencil lithography and its limitations?

Major challenges

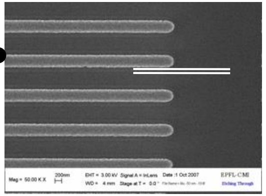
- Membrane stability



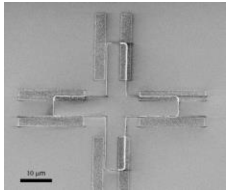
- Clogging



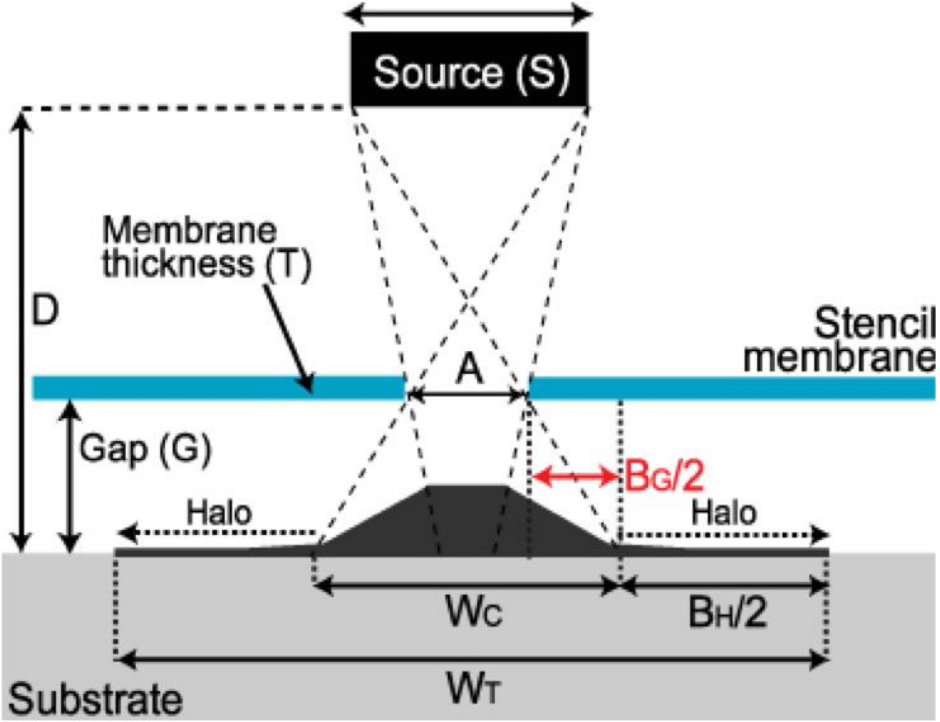
- Blurring



- Alignment

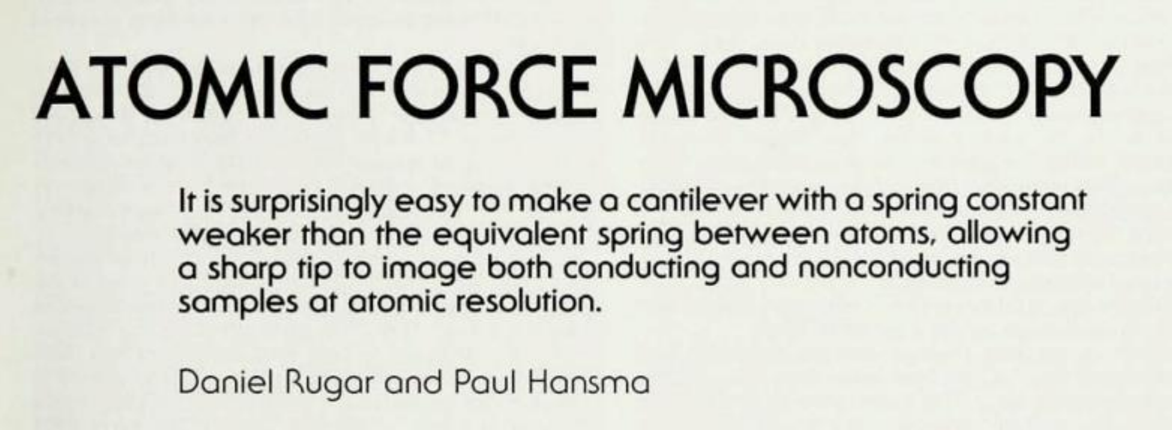


Stencil litho details



Litho - recap

- From CAD to device
- From micro to nano
- From writing to projection/replication
- Resolution limit: Diffraction – scattering – probe interaction
- Role of resist?
- Lift-off
- → stencil
- T-SPL
- self-assembly, CAPA

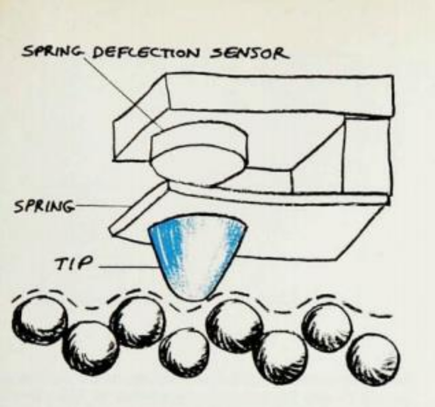


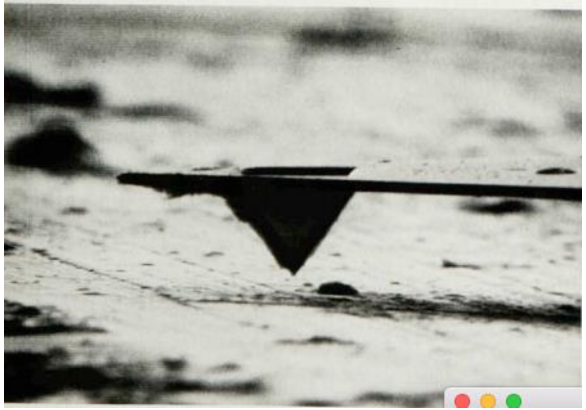
ATOMIC FORCE MICROSCOPY

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





Cantilever as force transducer

- Cantilever = force transducer
- Important parameters
- Spring constant k
- Resonance frequency f
- E: Young's modulus (material constant) $E_{si} = 1.7\text{E}11\ \text{N/m}^2$
- I: cross sectional moment of inertia (square cross section $I = w\,t^3/12$)

Expression general

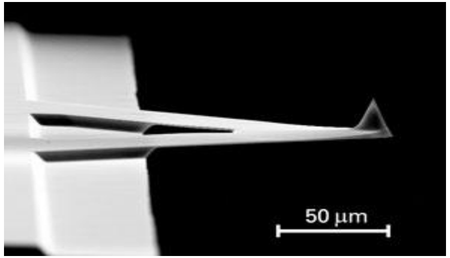
$$k = 3\,E\,I\,/\,L^3$$

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m_{eff}}}$$

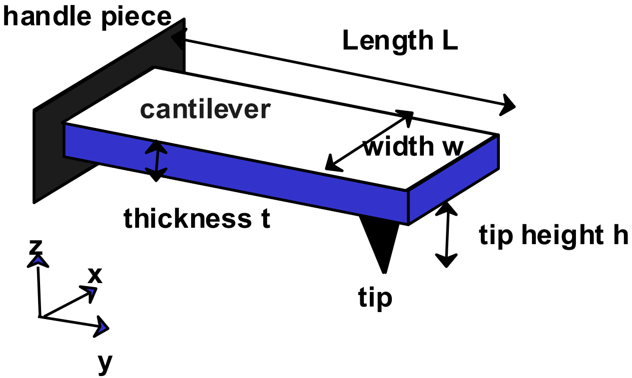
Rectangular shape

$$k = \frac{Ewt^3}{4l^3}$$

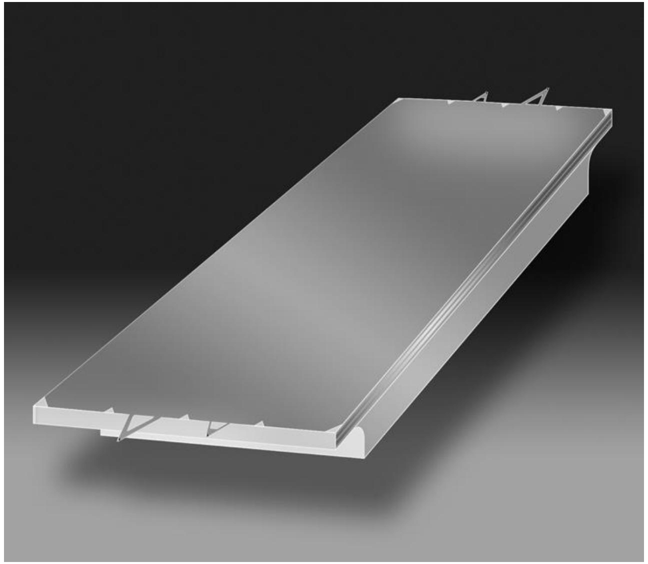
Typical values for AFM
k: 0.001-100 N/m
f: > 10 kHz

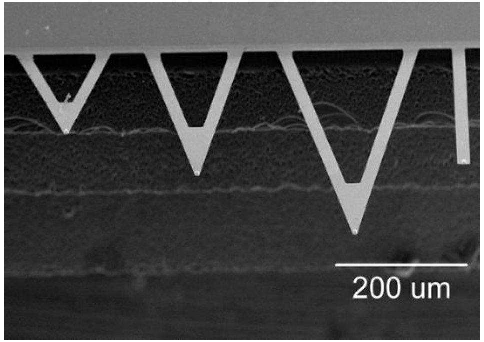


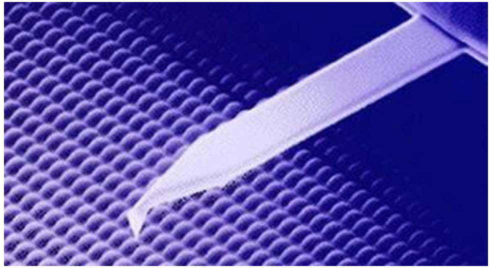
Microfabricated AFM cantilever



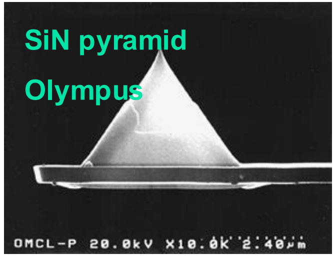
Cantilever, tips, probes

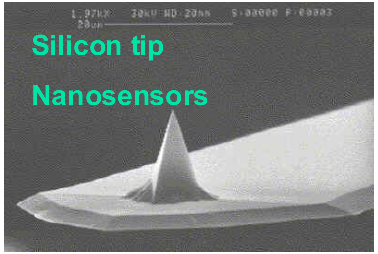






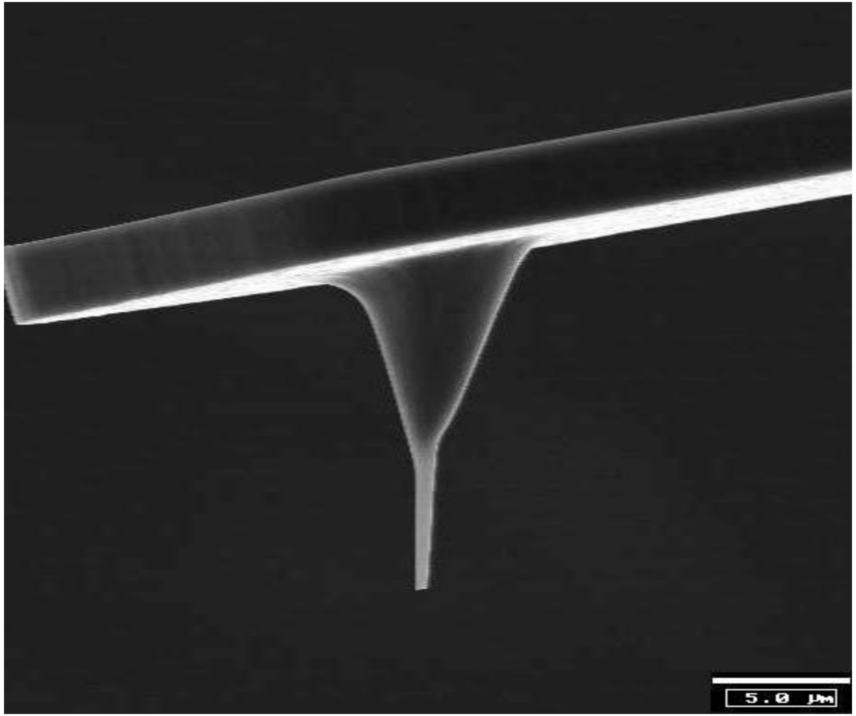
Olympus

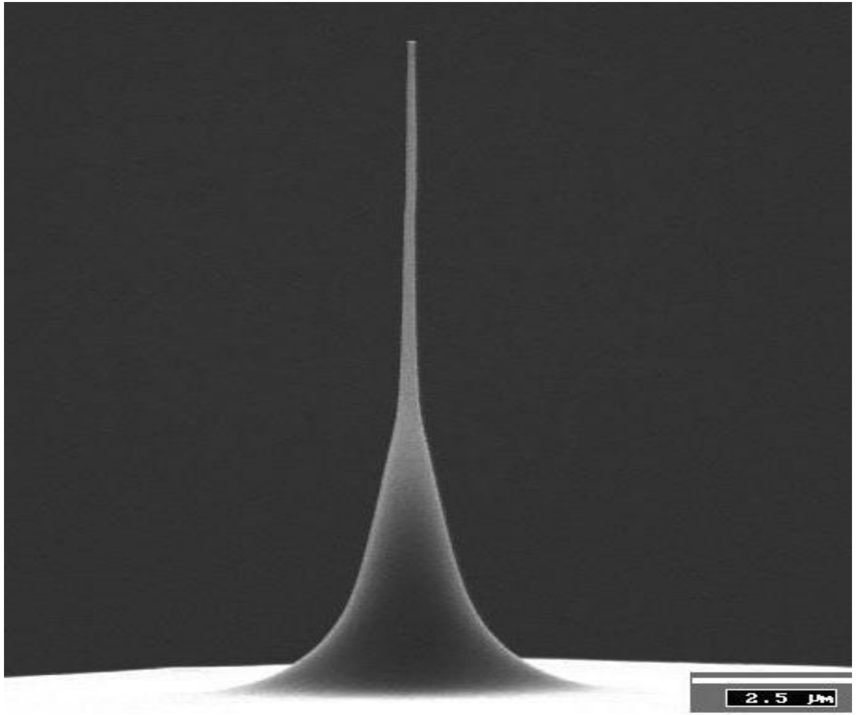




NanoWorld AG

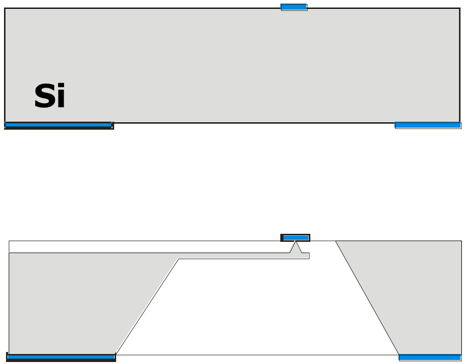
Microfabricated silicon tips for AFM





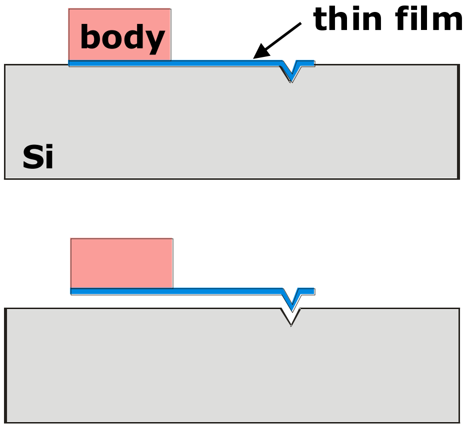
Microfabrication of Nanoprobes

Bulk micromachining



Single crystal material (Si)
High Q
Semiconducting
Oxidation sharpening (tip)
→Tips formed at end of process

Surface micromachining



Thin film (metal, dielectric, polymer)
Oxidation sharpening (mold)
Sacrificial layer
Release process of cantilever is important
→Tips (mold) formed at the beginning of process

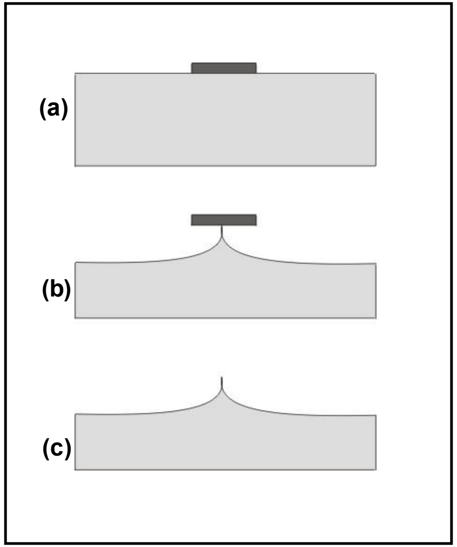
Microfabrication of Nanoprobes

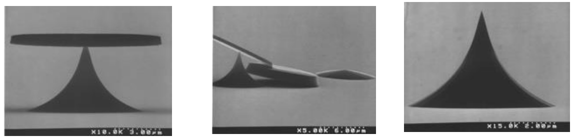
Inspired from Nature

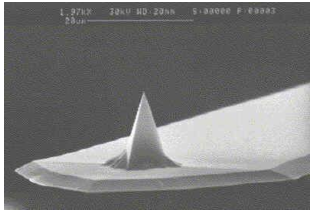
Les Pyramides d'Eusègne
Valais, Switzerland

Erosion

- Material
  - Silicon
- Etch mask (a)
  - nitride, dioxide, resist
- Wet etching (b)
  - potassium hydroxide (KOH), anisotropic
  - HNO3:HF, isotropic
- Dry etching (c)
  - plasma
  - fluorine, chlorine based



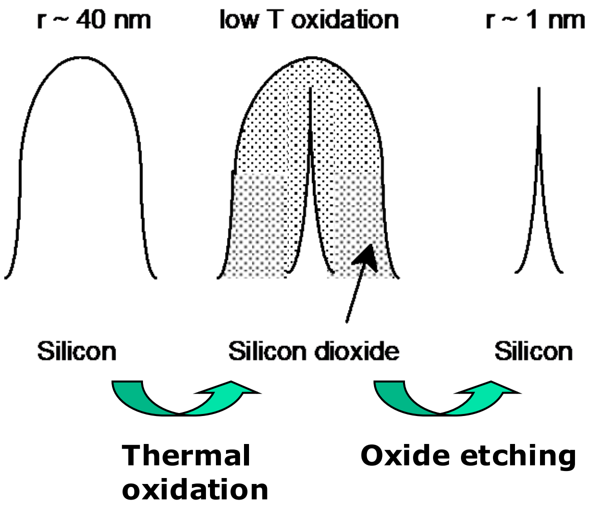




Tip Sharpening by Oxidation

- Self-terminating process
- Example: Silicon tip
- ‘low’ temperature oxidation sharpening T<950 °C
- Anomalous oxide growth of SiO2 at regions with high curvature radii

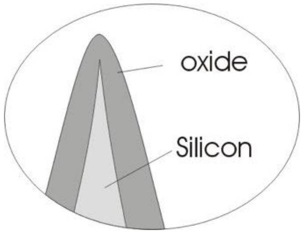
  → exploit this effect to “sharpen” the silicon



There are two ways of forming a SiO_2 layer on the surface of Si. Only oxidation allows sharpening effects:

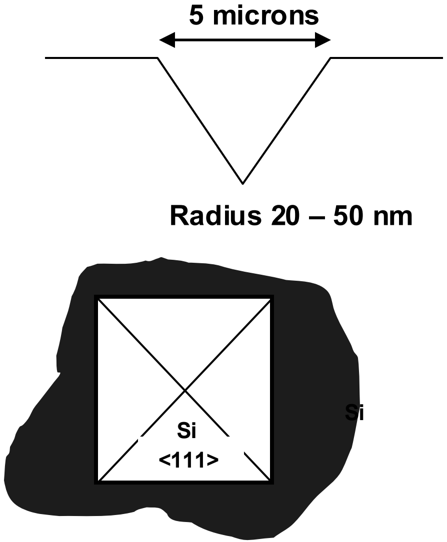
Oxidation:
The oxidation growths a SiO_2 layer as the O_2 reacts with the Si substrate. The SiO_2 layer is roughly 1/3inside the Si layer and 2/3 above it. It is performed at 1100° C.

CVD or sputtering:
The deposition by CVD or sputtering creates a layer 100% on top of the Si substrate. The process is made at 600° C.



Molded Tips for AFM

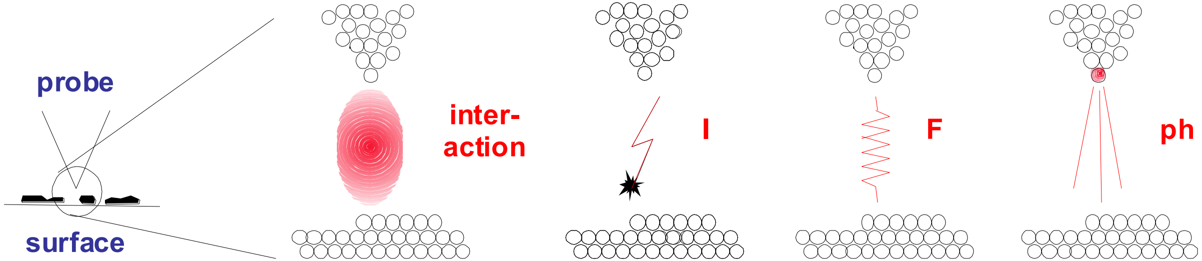
- Molds by anisotropic Si etching (e.g. KOH, TMAH)
- Oxidation of the groove
- Deposition of the tip material (e.g. metals, polymers) into the SiO_2 covered groove



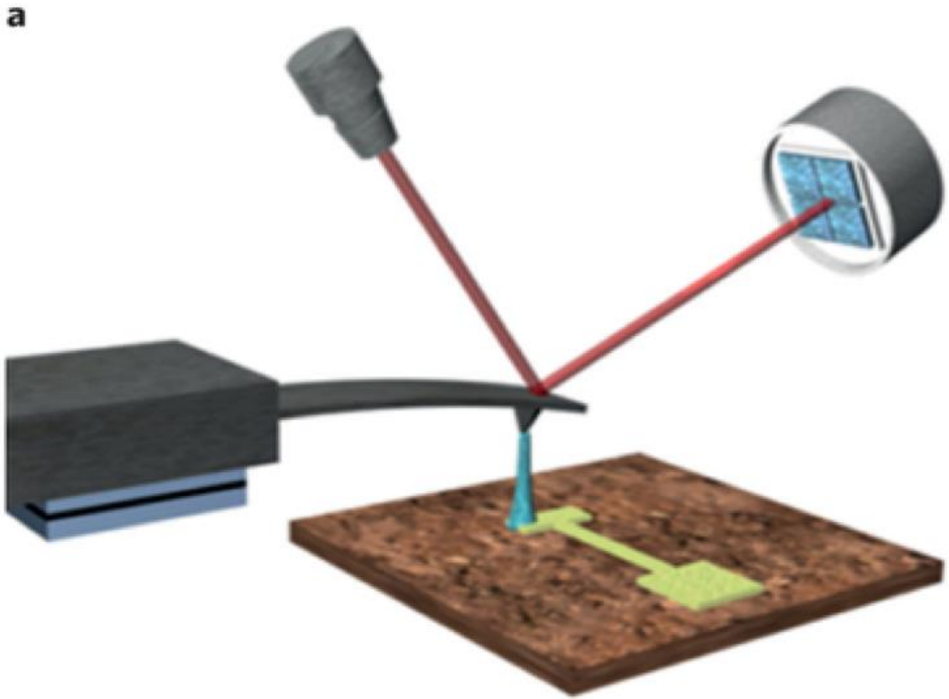
Scanning Probe Lithography

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*

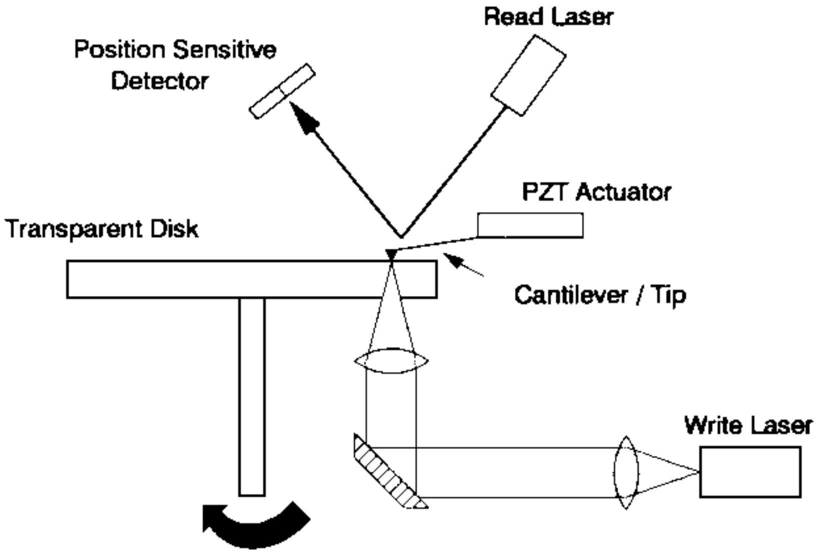


Scanning Probe Lithography variations



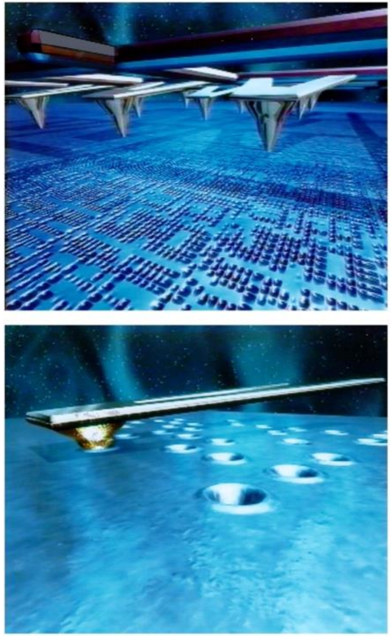
Thermomechanical Writing with an AFM

- A focused laser beam propagates through a transparent PMMA sample and heats an optically absorbing AFM tip
- The heated tip softens the substrate and the local tip pressure creates an indentation
- The sample is placed on a precision air-bearing spindle to allow for sample rotation.
- H.J. Mamin and D. Rugar, Appl. Phys. Lett. 61 (8), 1003 (1992).



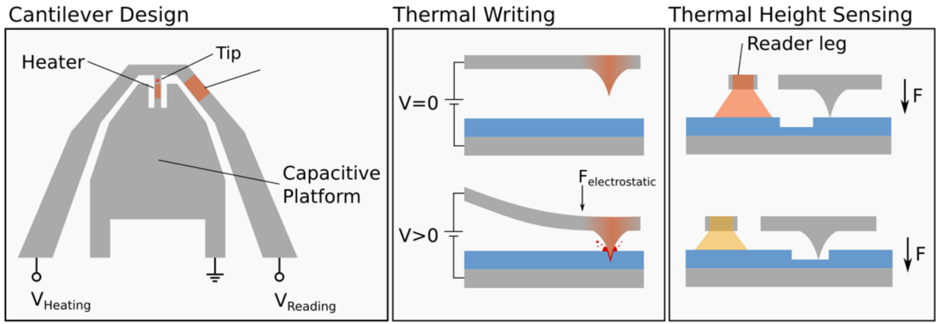
IBM Almaden Research

Millipede in Operation



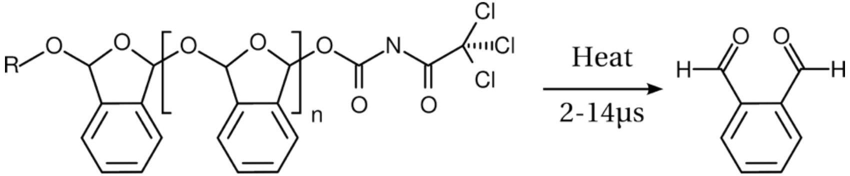
IBM Research

Patterning principle / Resist



- **Electrostatic actuation**
- **Hot tip: Joule Heating**
- **Topography readout**

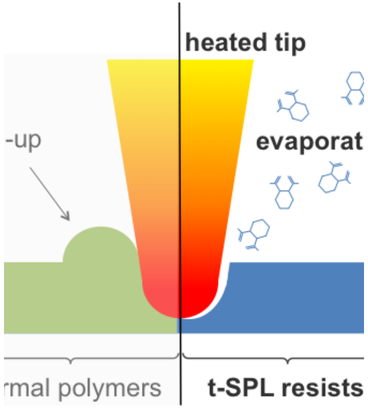
Polyphthalaldehyde

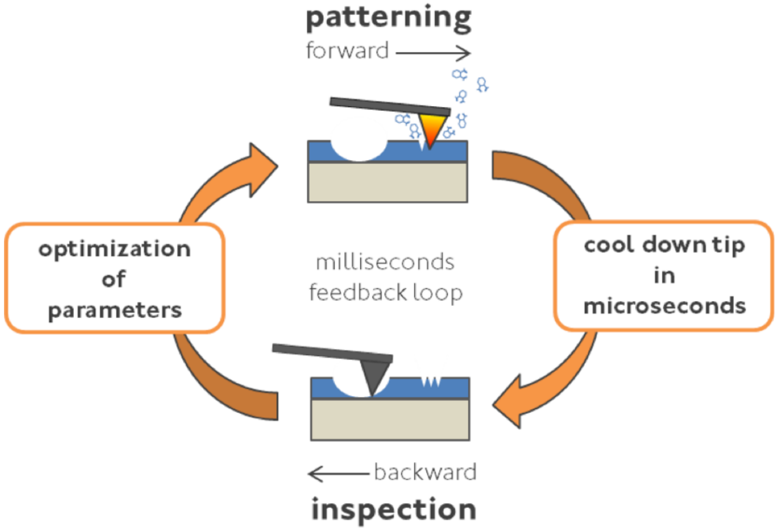


- **Self-amplified depolymerization resist**
- **Metastable at room temperature**
- **Degrades when exposed to Heat or Acid**

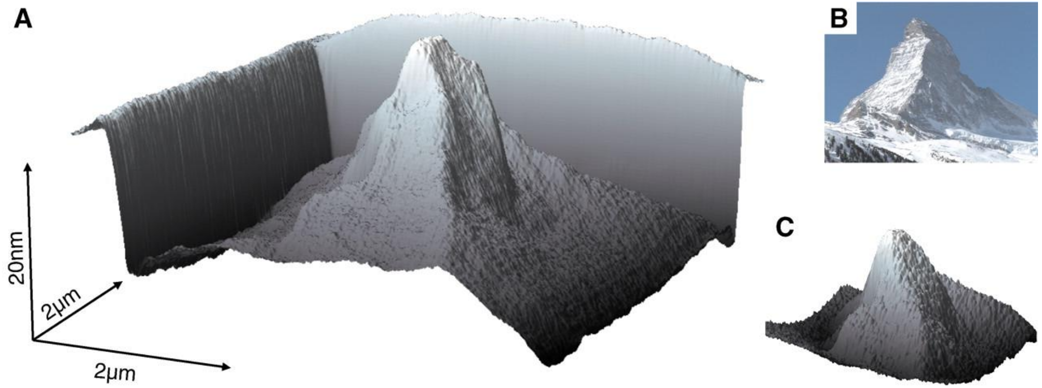
Thermal Scanning Probe Lithography

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





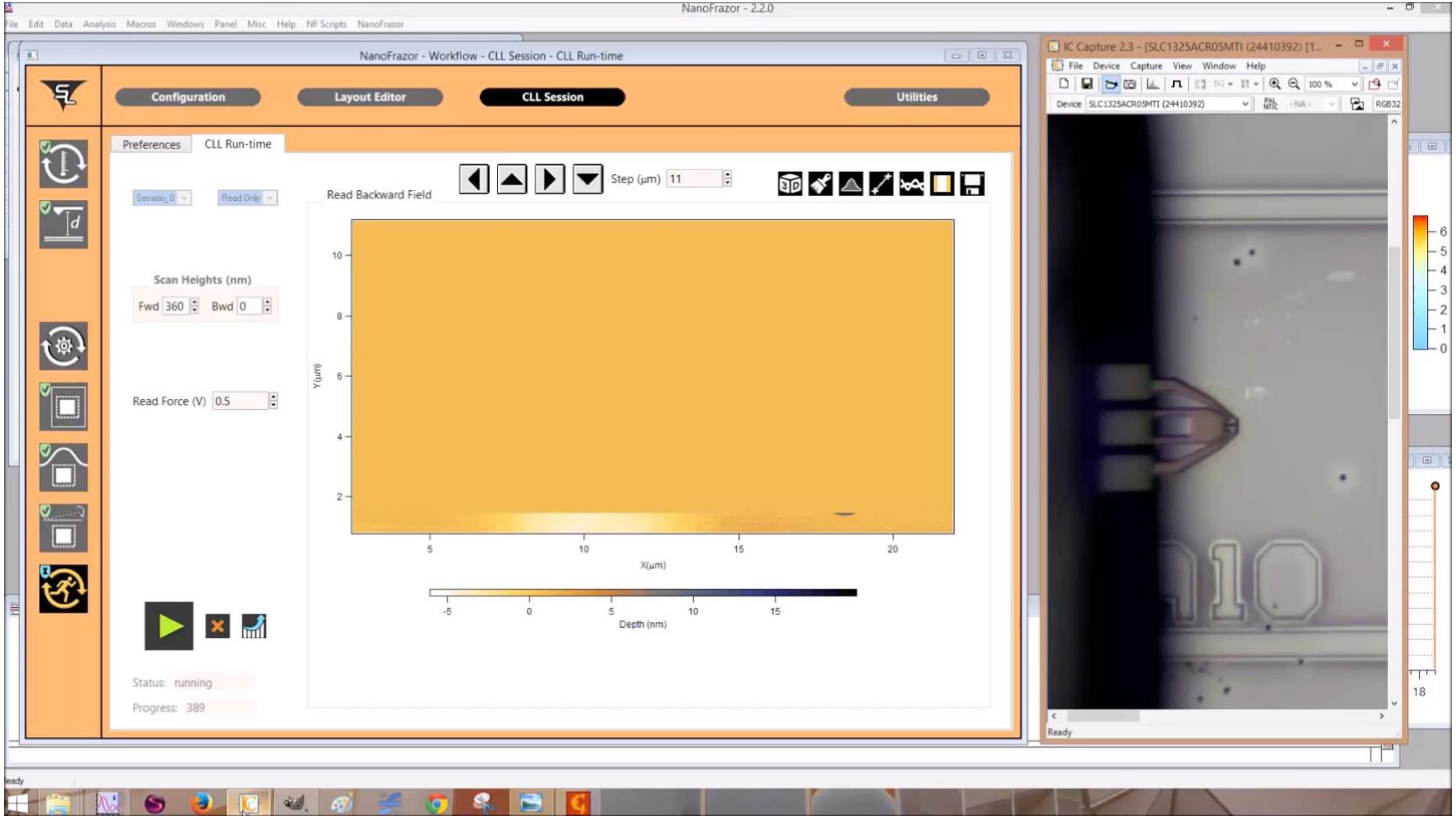
3D patterning



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

May 2023

Modern t-SPL system (closed loop)



Step (µm) 11

Scan Heights (nm)
Fwd 360 Bwd 0

Read Force (V) 0.5

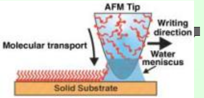
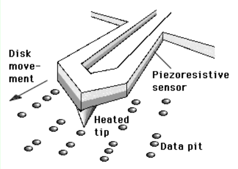
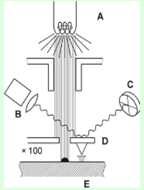
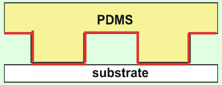
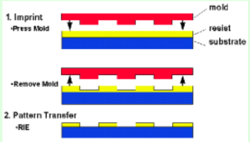
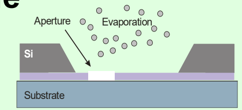
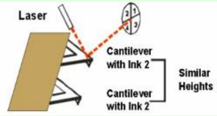
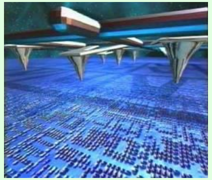
Status: running
Progress: 389

Heidelberg Instruments, Swisslitho, IBM

» **Screenshot video of NanoFrazor software (real time)**

Student nanoselfies created in 10 min

Emerging Nanopatterning

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