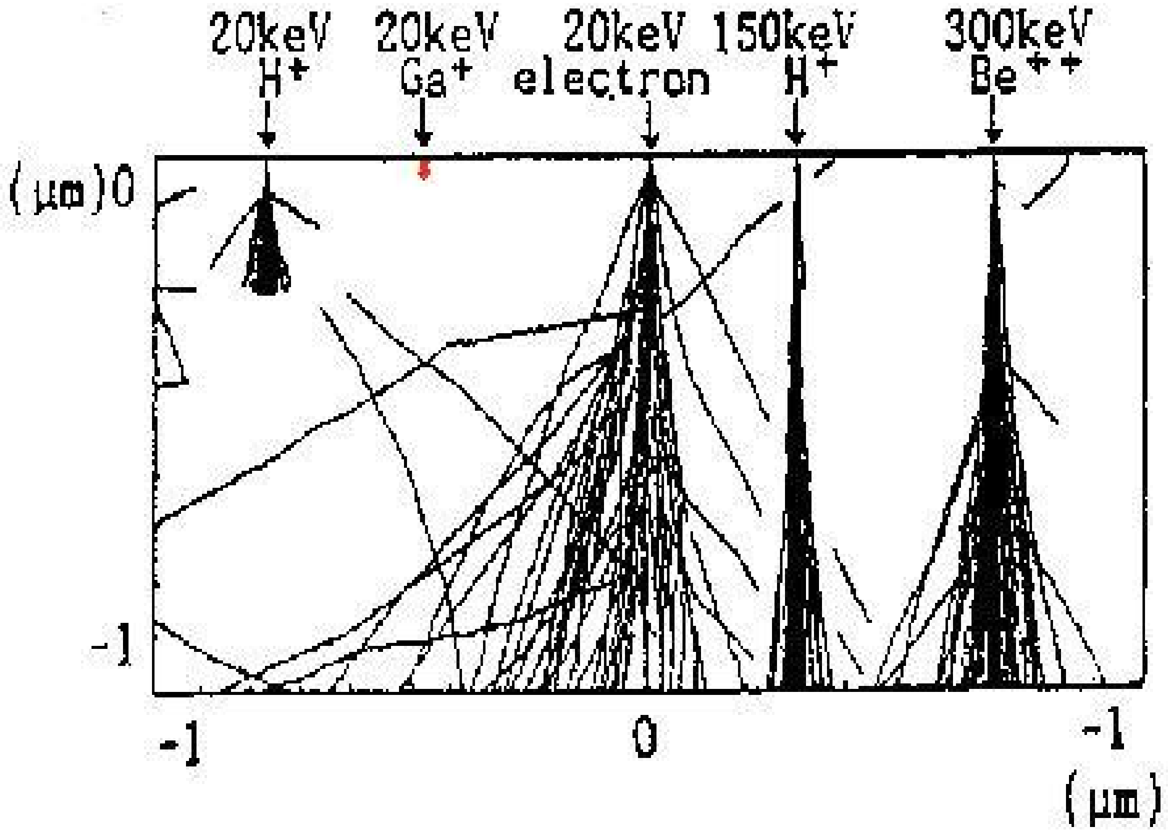
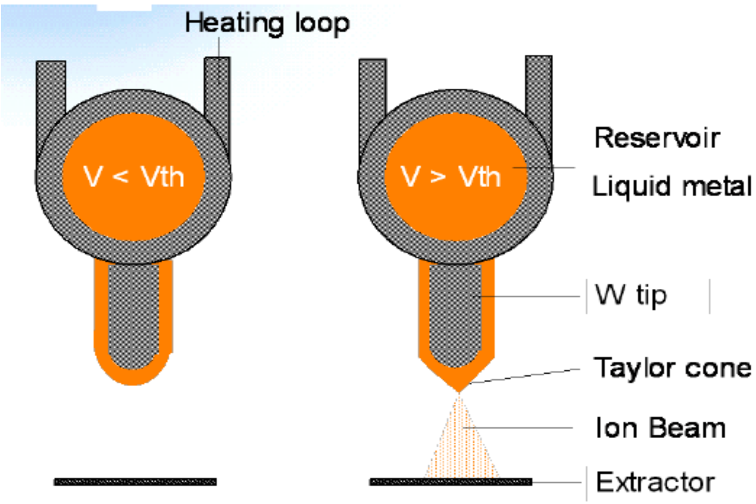
Ion beam lithography

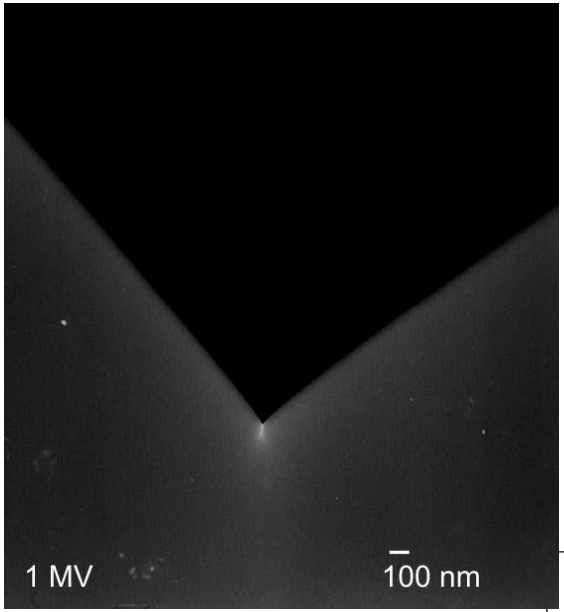
- Progress in ion technology spot size <10nm
- Direct writing : resist, milling, implantation
- Ions rapidely absorbed by matter –almost no proximity effect
- low dose -
- 3D structures possibles

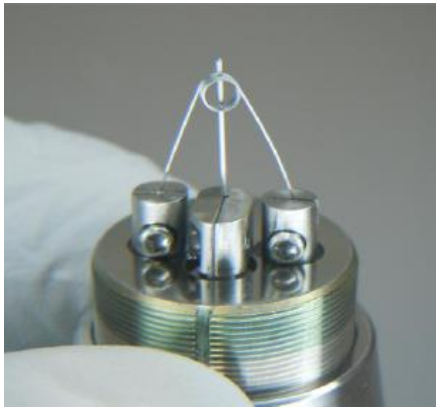
Ions trajectories



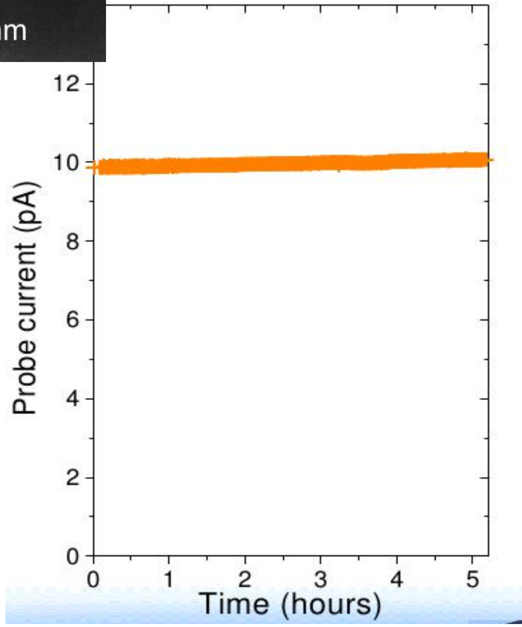
Liquid Metal Ion Source (LMIS)



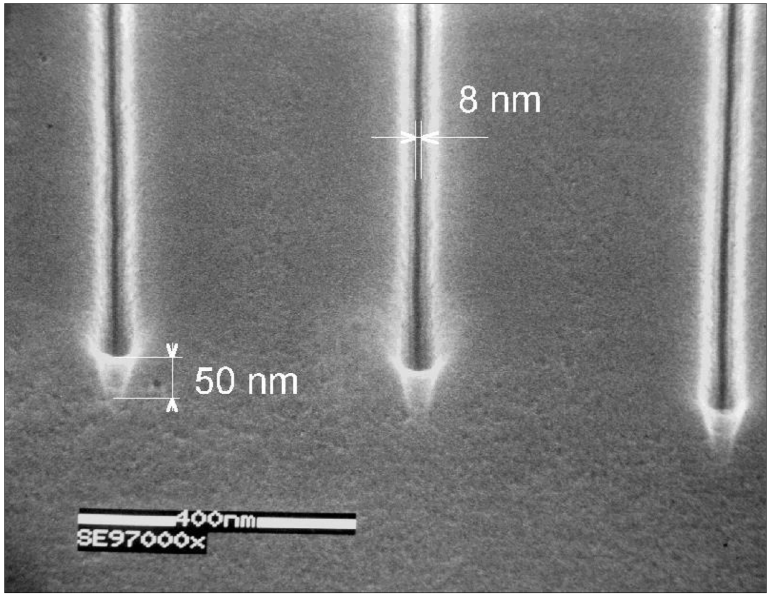


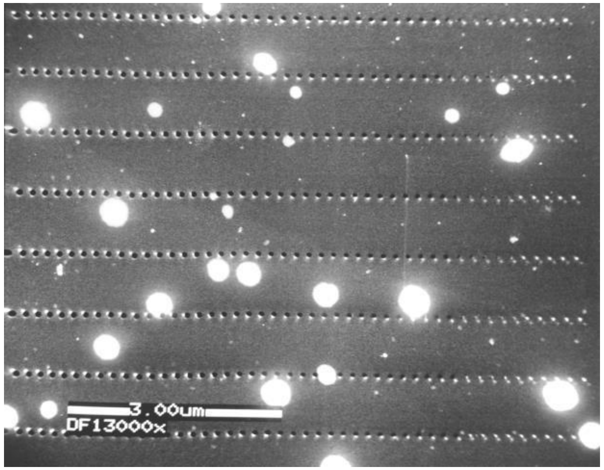


Energy dispersion : 4eV
Spot size limited by chromatic aberratrions : 3nm
Brgihtness $10^6 A/cm^2.sr$
Good current stability



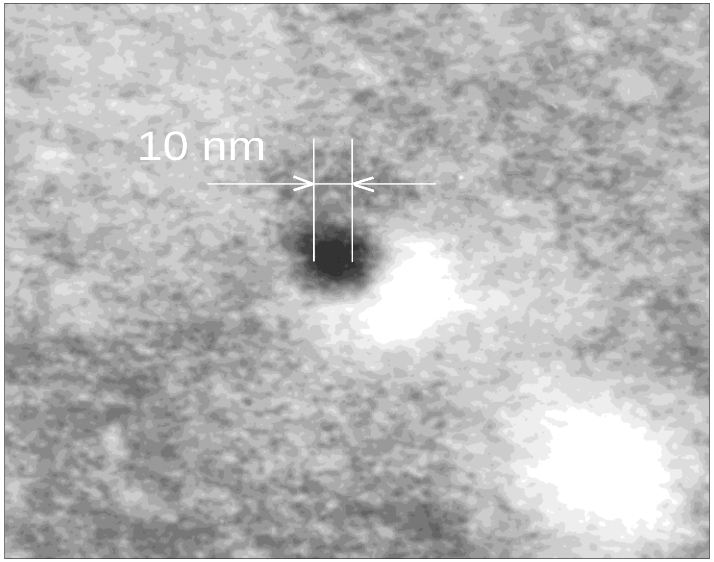
examples





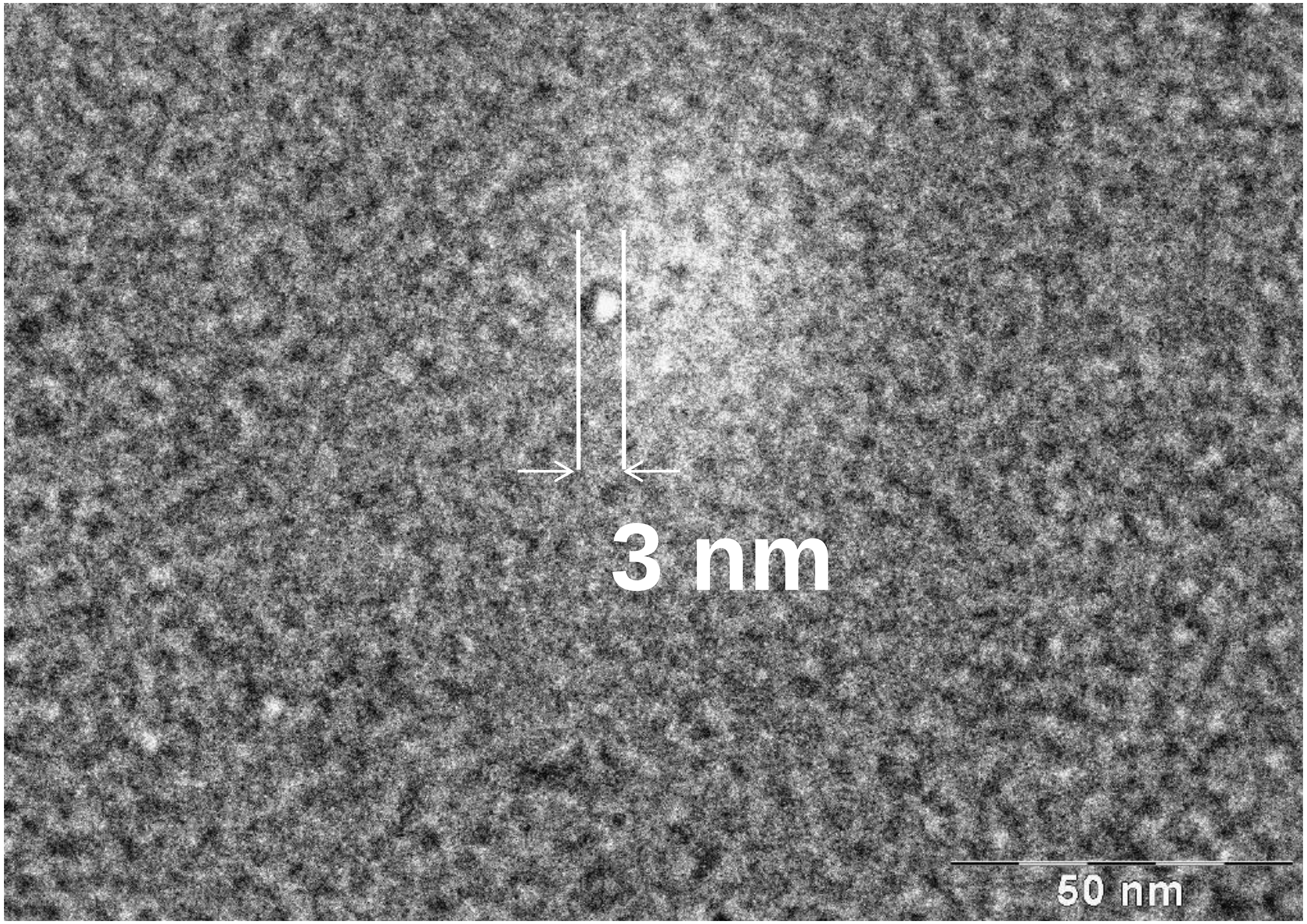
30kV ions Gallium

Hole in a Si_3N_4 membrane



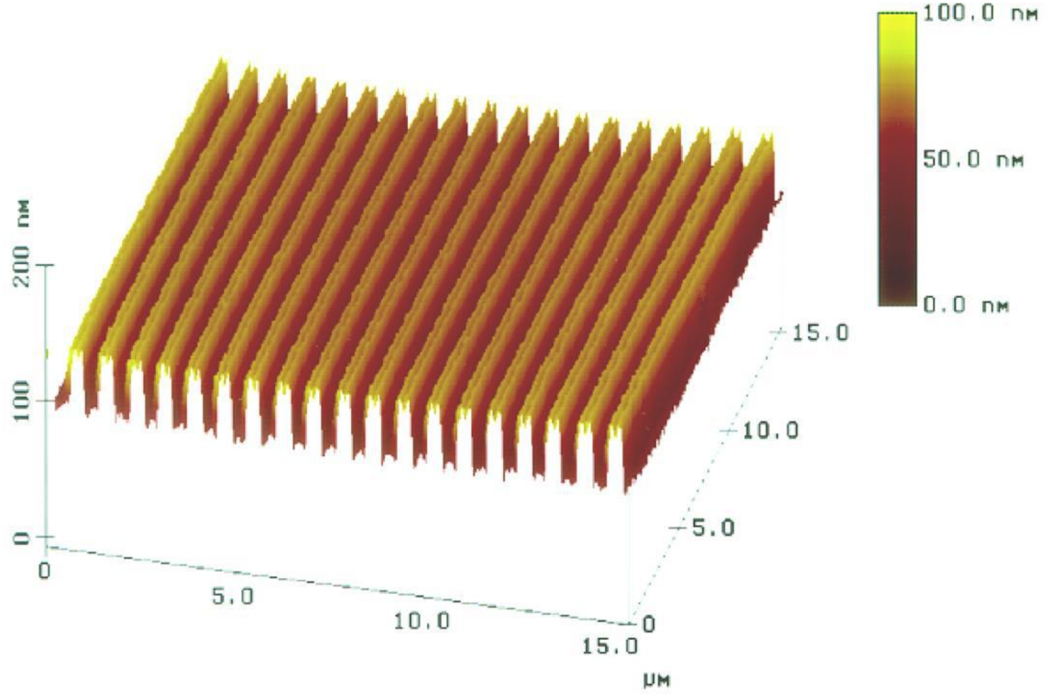
LPN Marcoussis

3nm hole pierced in a 20nm thick SiC membrane



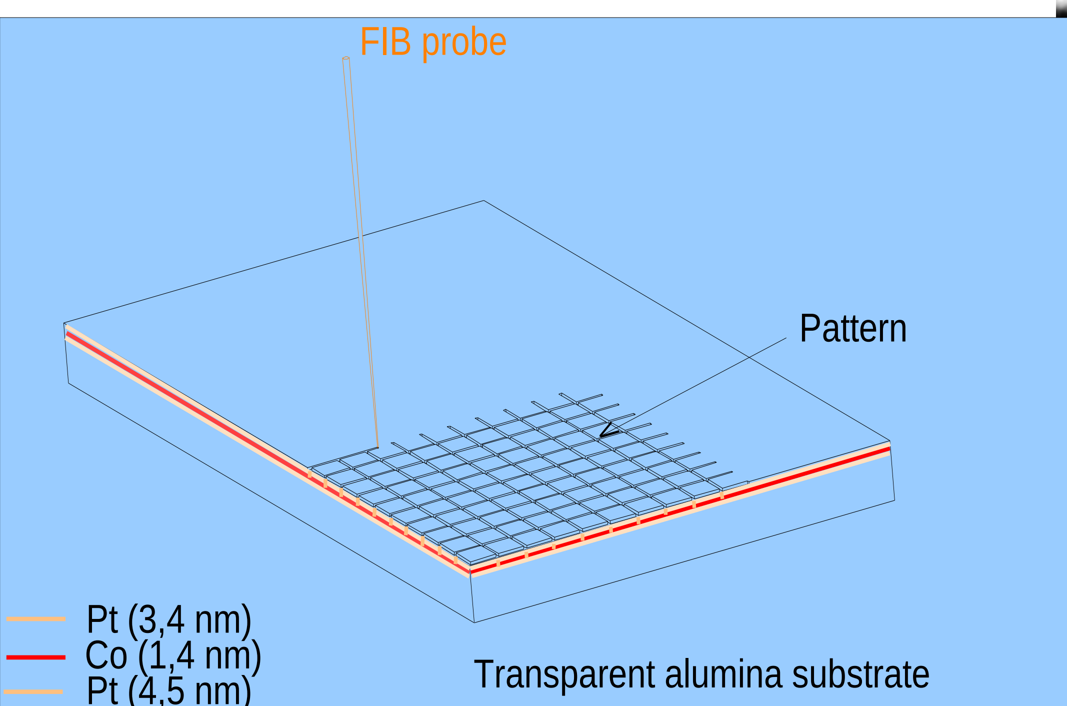
LPN Marcoussis

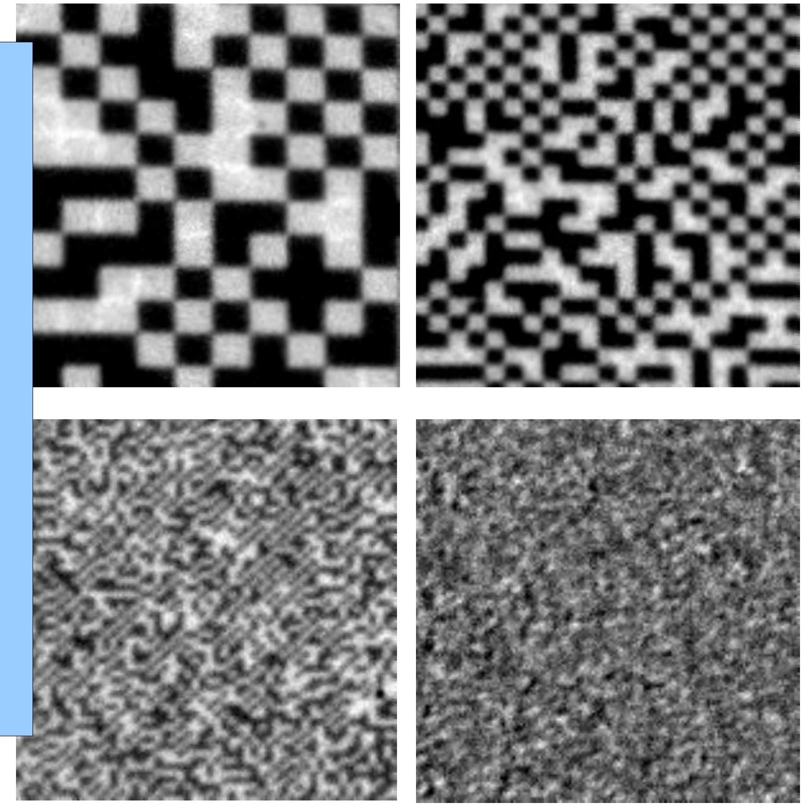
Inorganic resist AlF3



LPN Marcoussis

Magnetic field patterning

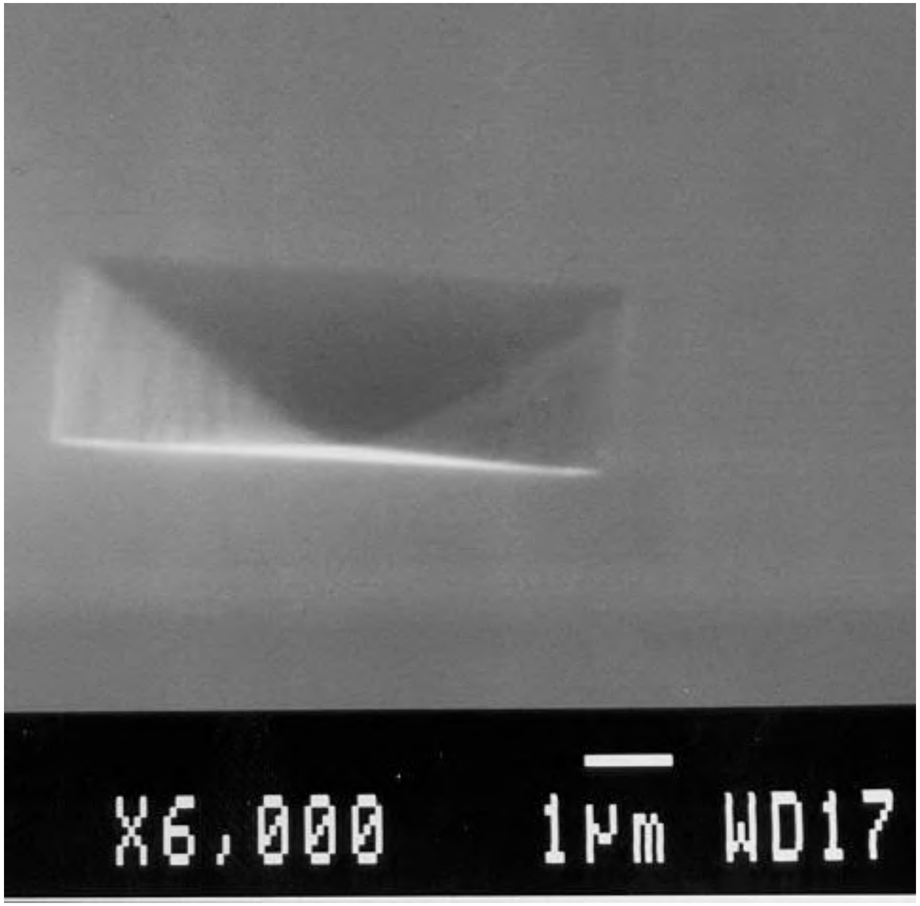




Kerr image of the patterned PtCoPt film
(Ga^+ ions, 30 keV, 5 10^{15} ions/cm^2).

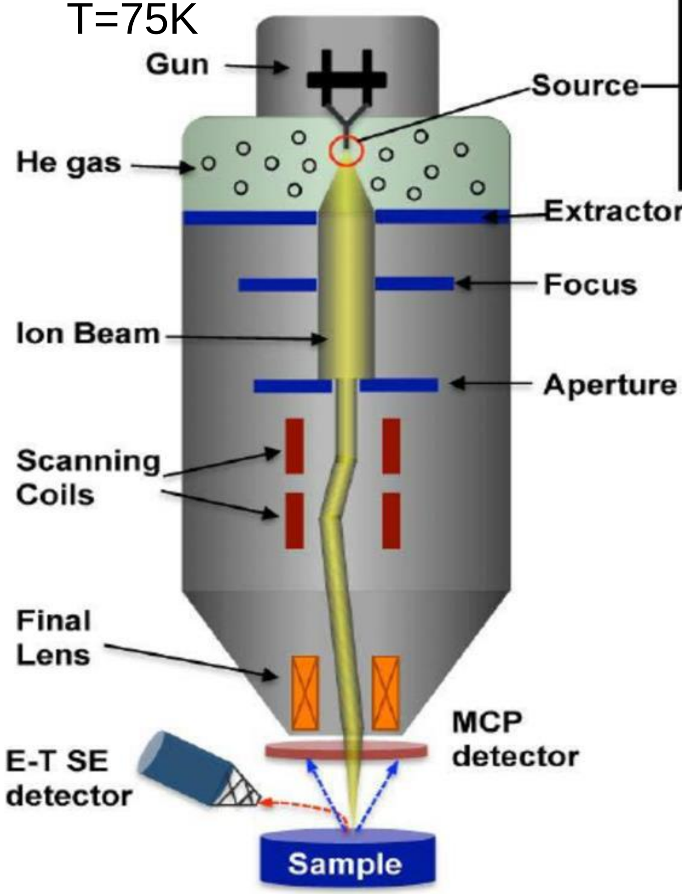
- define stable domains: 1500 nm, 750 nm, 300 nm, 50 nm

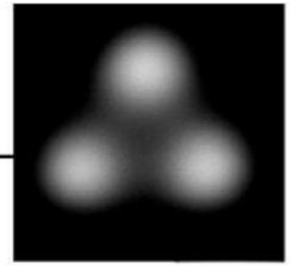
3D shape



Helium microscope

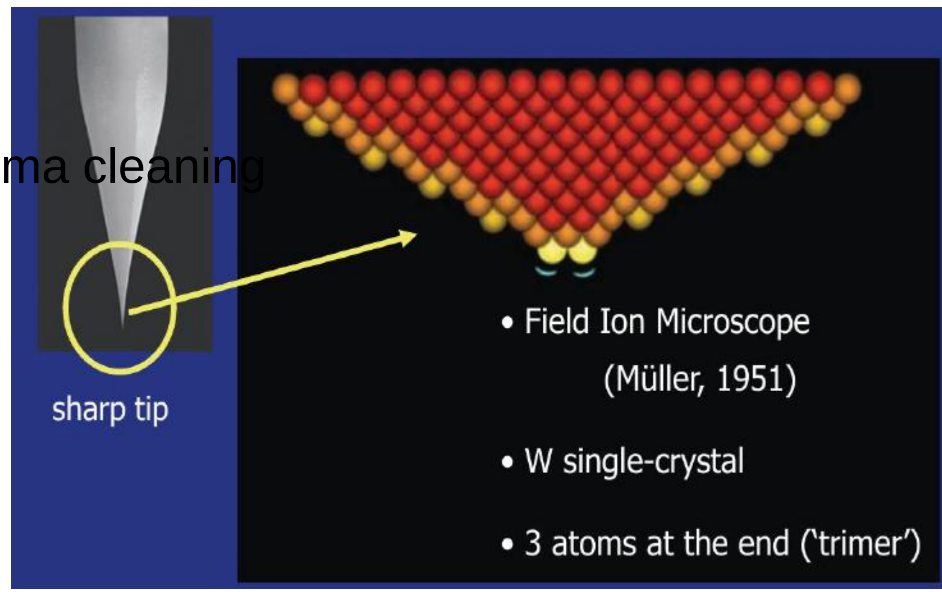
T=75K



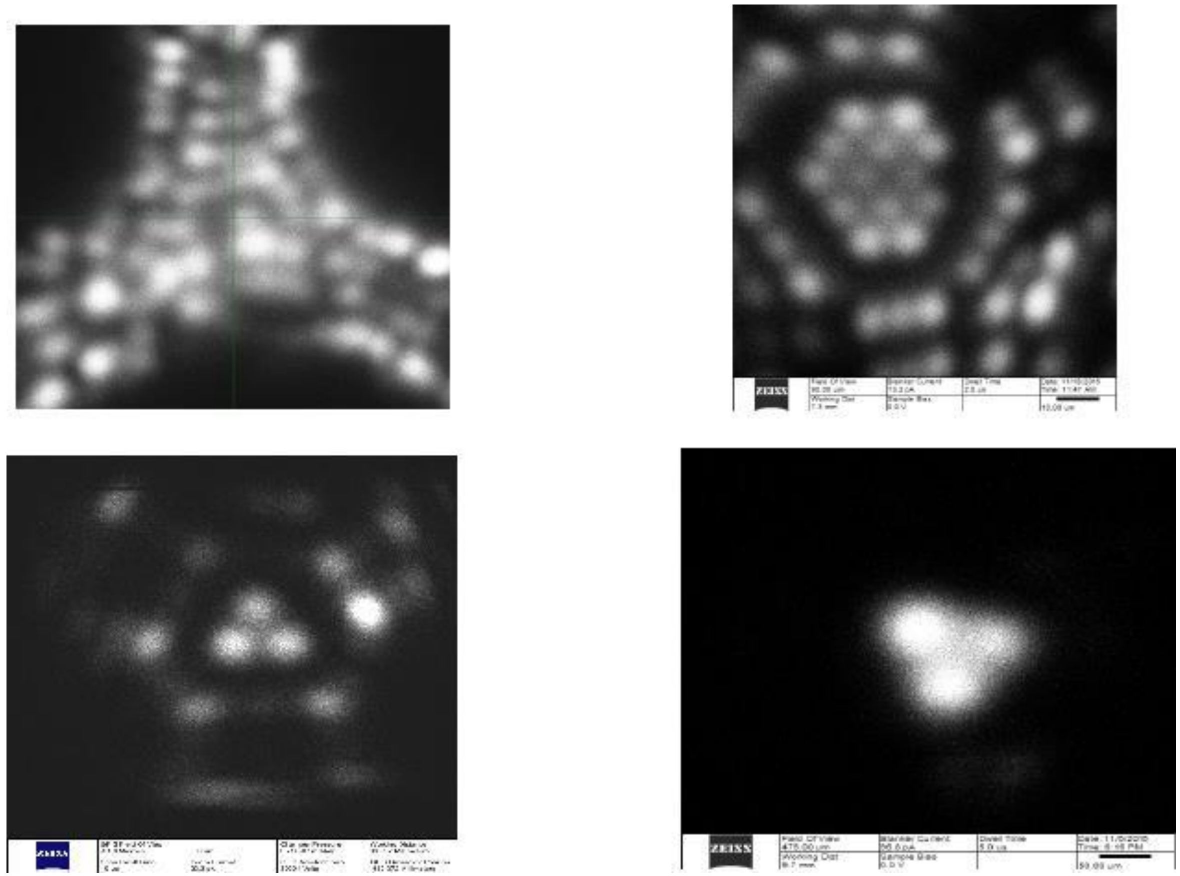


A trimer of W atoms emits the He ions: spot on the sample ~0.3-0,5nm

Plasma cleaning



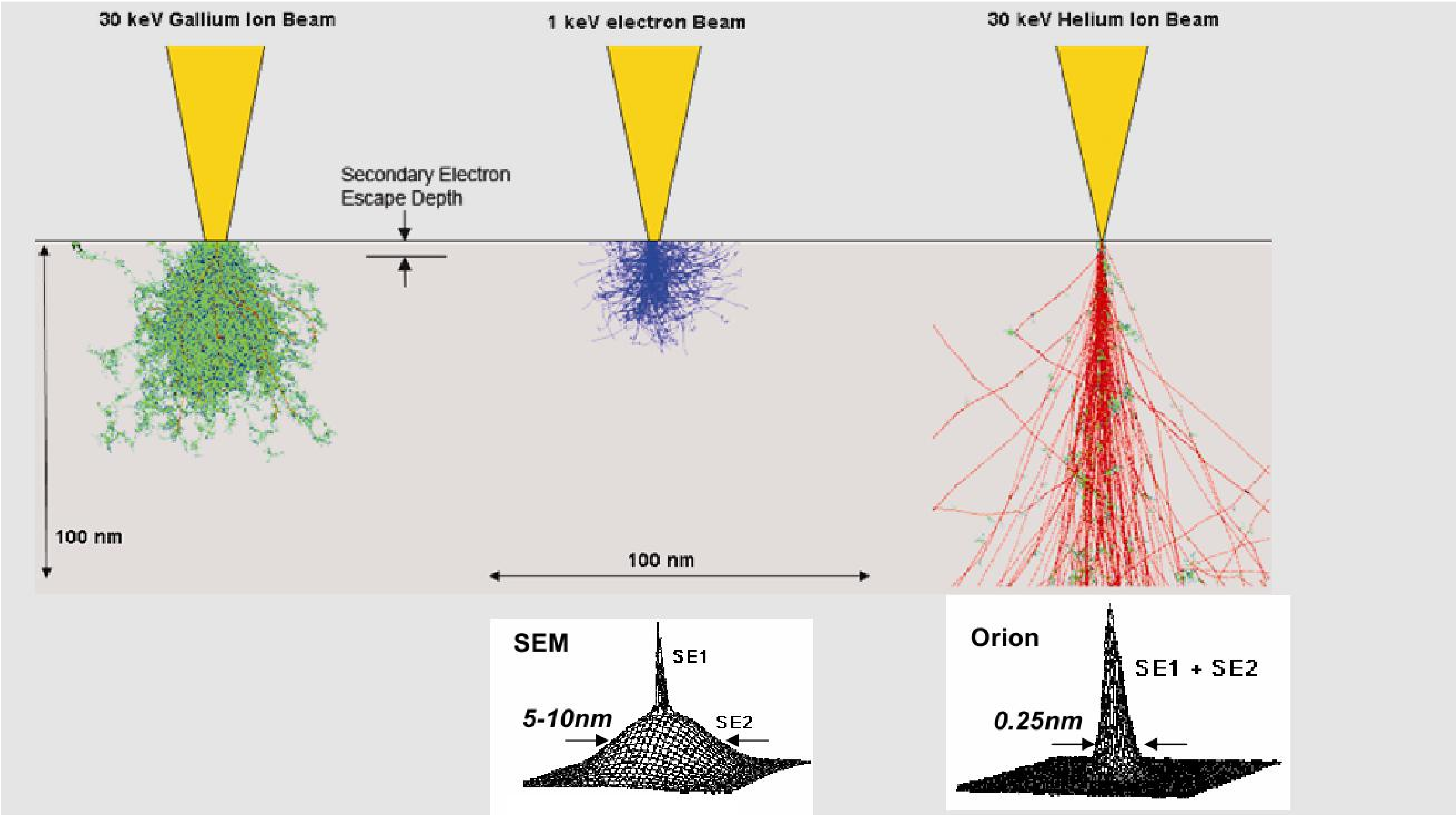
An atomic size source



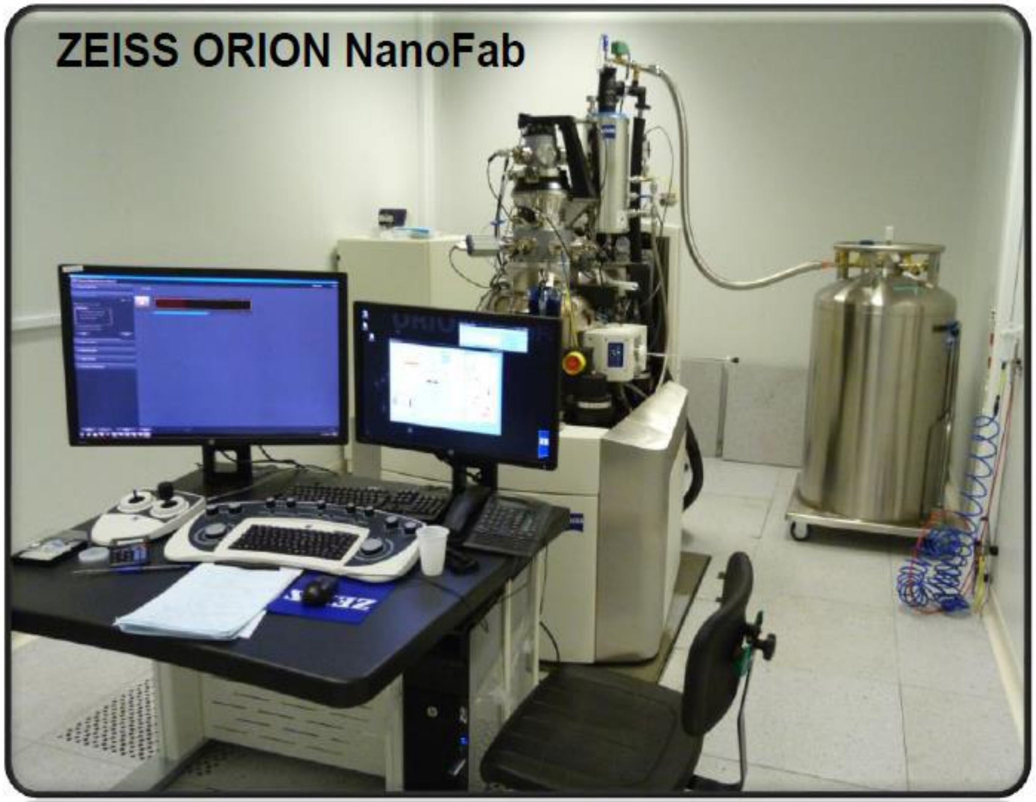
Source is one atome → spot size can be as low as 0.35nm on sample

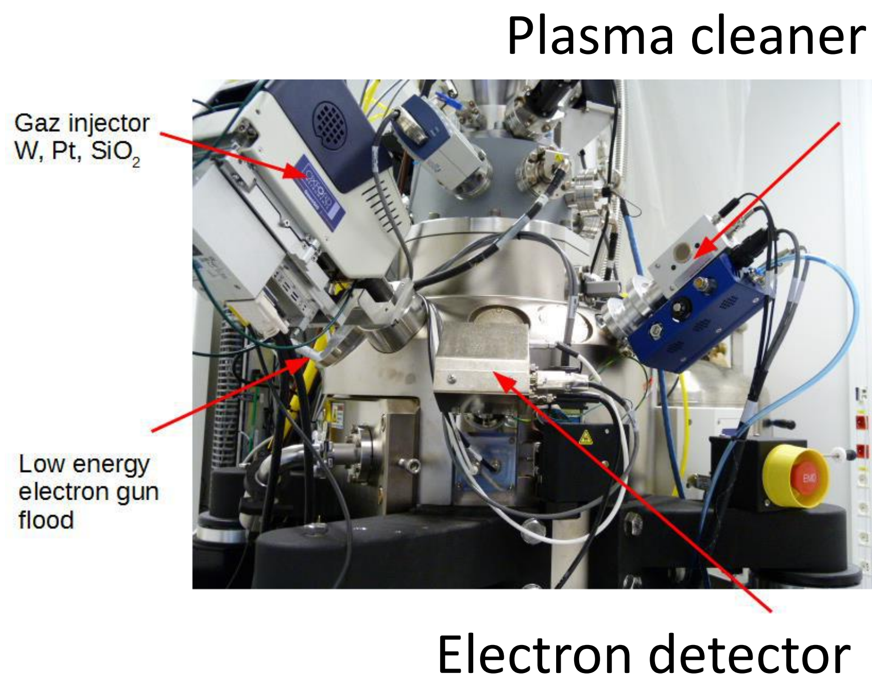
Small spatial extension of the diffused He ions

SEM images are produced by SE1 and SE2 electron
Here it is mostly SE1 small sppatial extension and sensitivity to surface



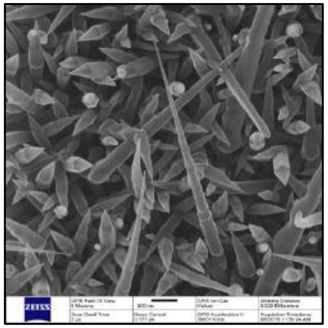
Overall equipment





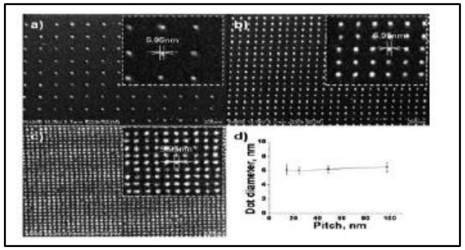
A versatile tool

Microscope : high resolution, sensitive to surface, very high deep of focus, flood to neutralize ions allows imaging insulator and biological stuff



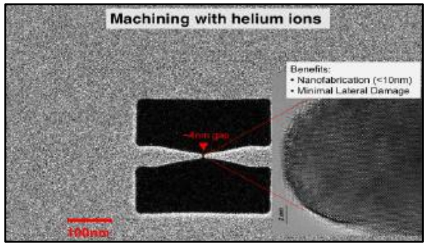
microscopy

Lithography : high sensitivity, high resolution, no proximity effect.



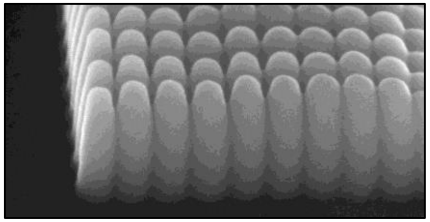
lithography

Direct milling : low damage (low sputter yield) high precision, no interdiffusion (Ga ions) . Possibility to use Neon for higher yield but less stability and resolution



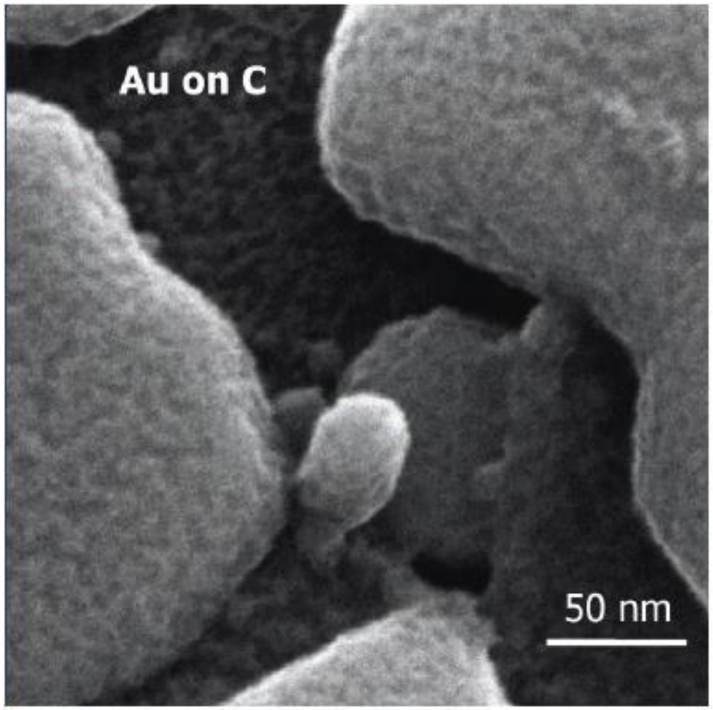
milling

Beam induced deposition : W , Pt ,SiO_2 no contamination

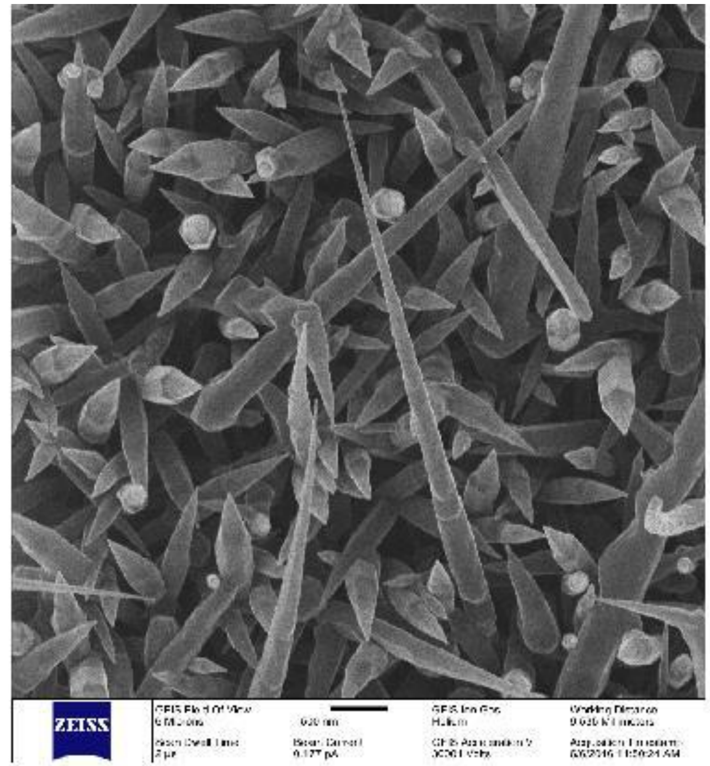


deposition

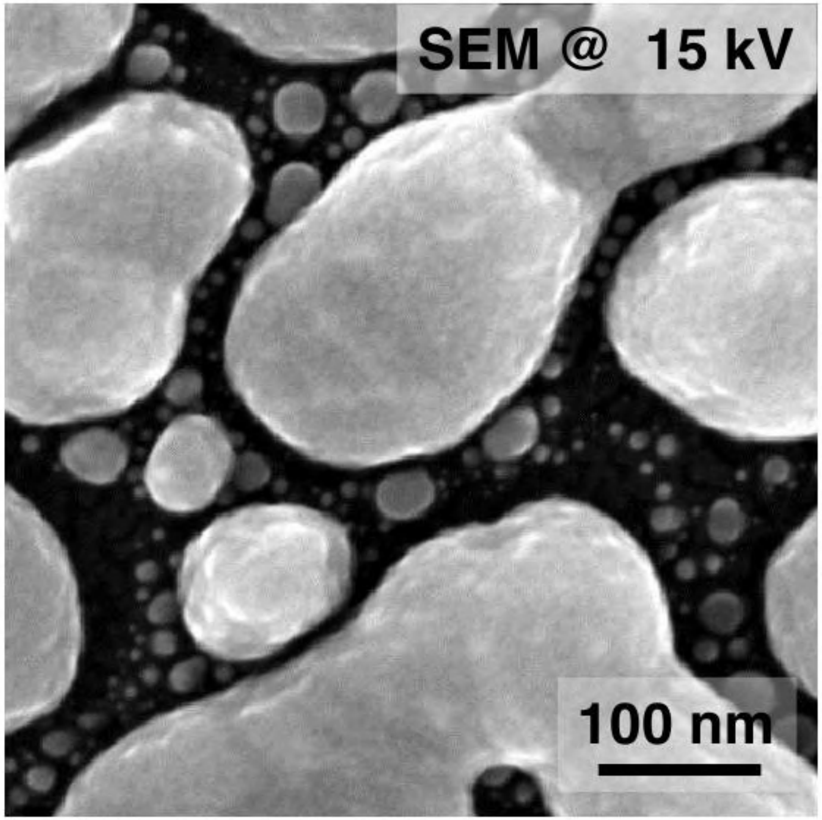
A microscope

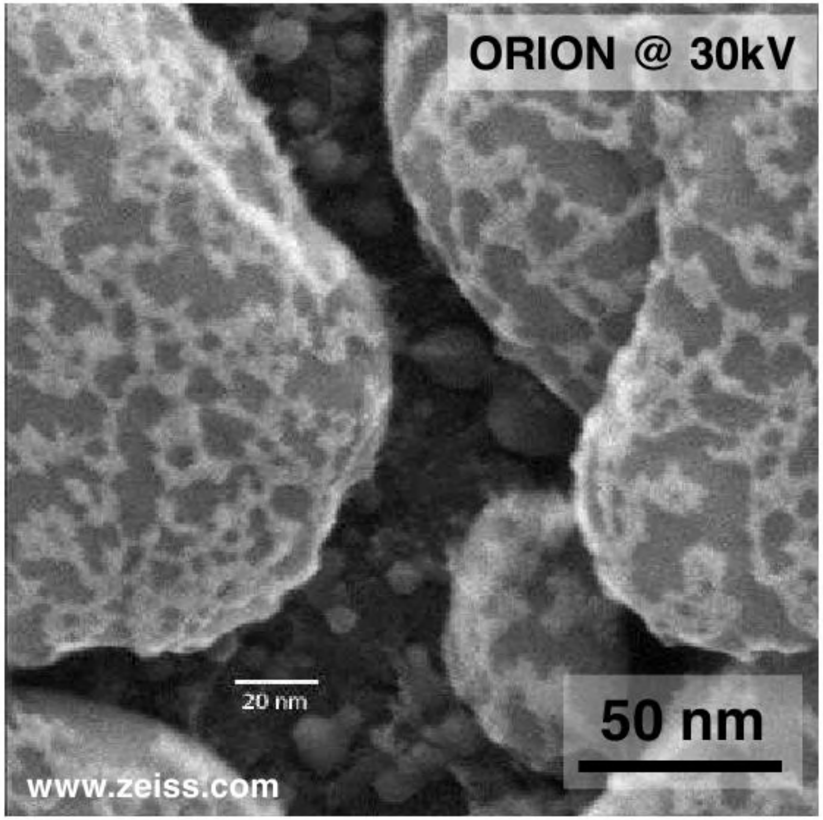


High resolution and sensitivity to the surface



High depth of focus


SEM @ 15 kV
100 nm


ORION @ 30kV
20 nm
50 nm
www.zeiss.com

High resolution lithography with HSQ

Small spot size high resolution

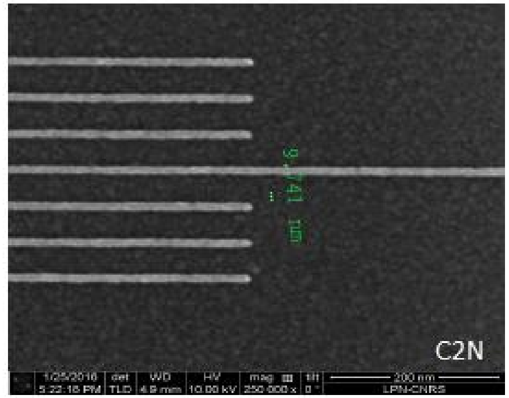
High yield high sensitivity

Very small proximity effects

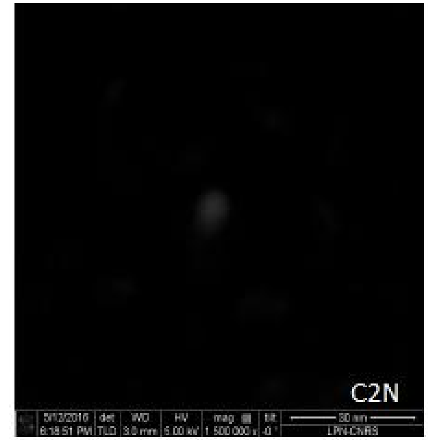
High DoF high aspect ratio

Small thickness resist

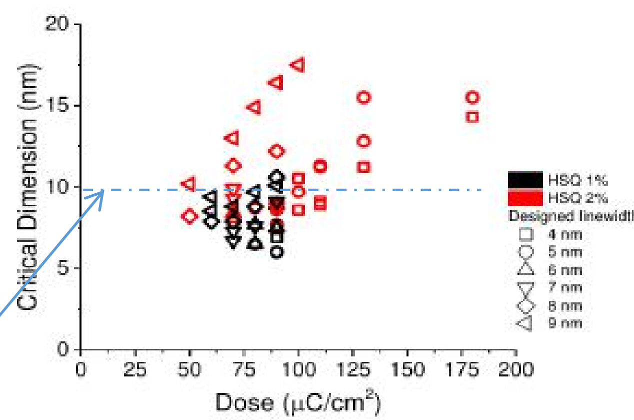
Negative resist for etching



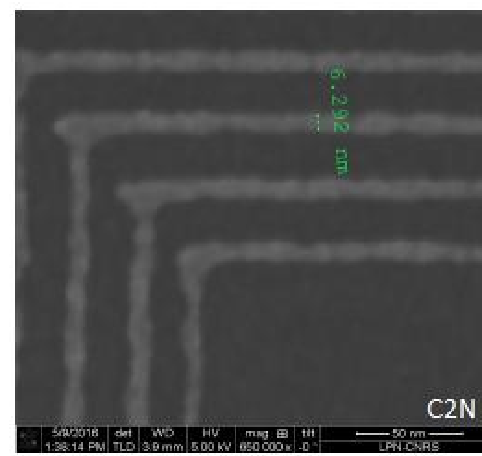
Ligne 9.7nm HSQ 20nm



Plot 5nm HSQ 20nm



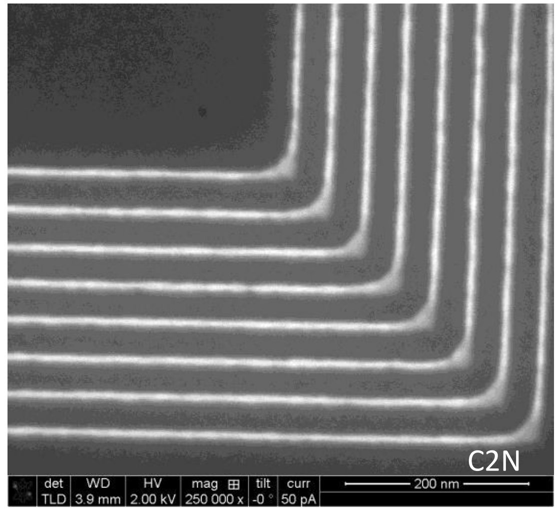
Sub 10nm achieved

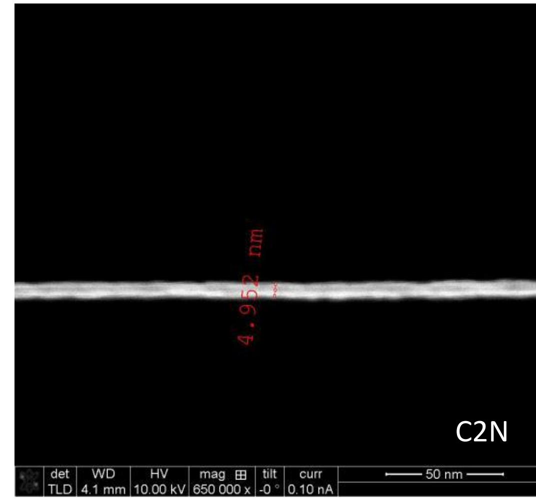


nanolithography

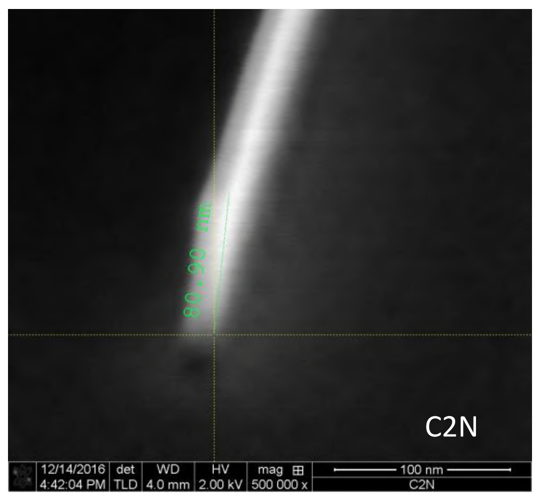
Development on a new resist based on Aluminum oxide.

Better resist profile and roughness than HSQ

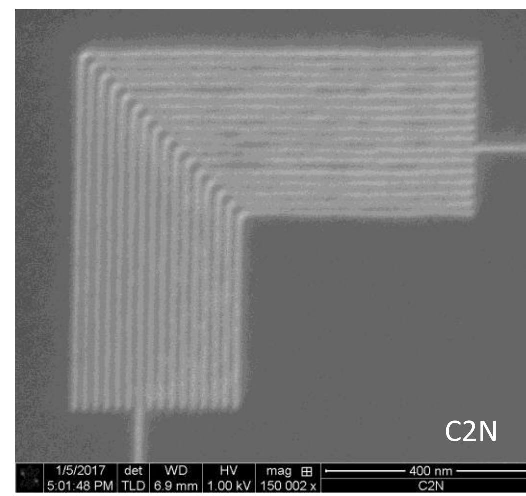




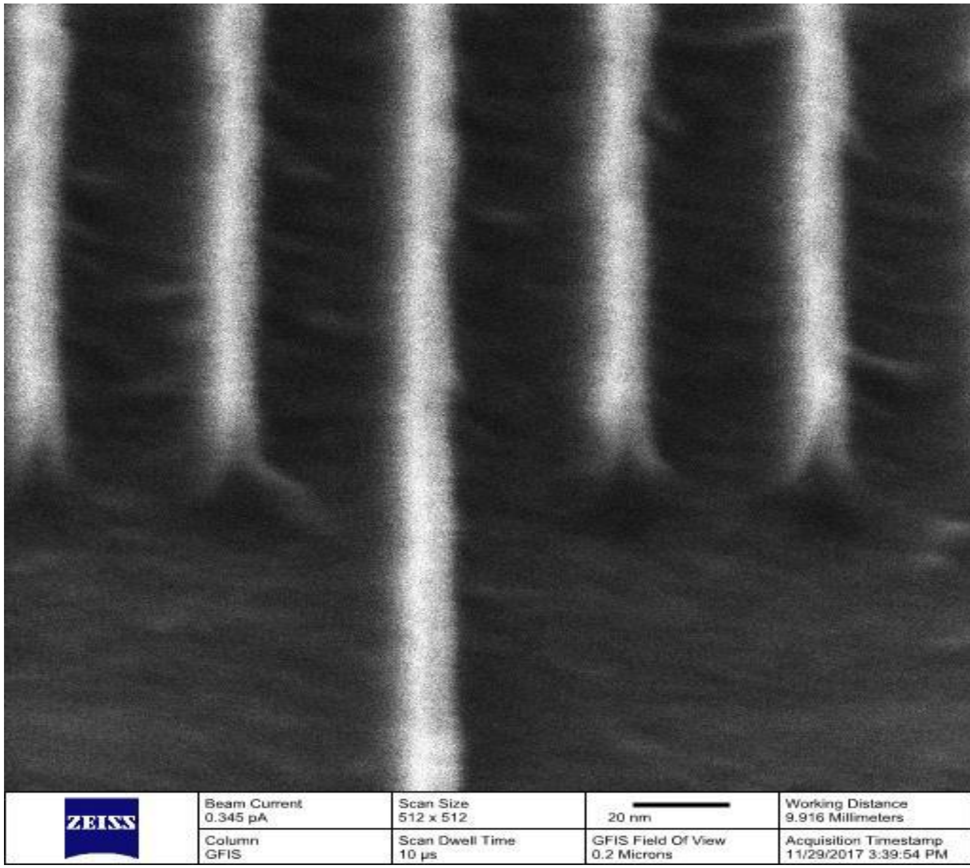
Width below 10nm can be easily achieved with an aspect ration higher than 4.

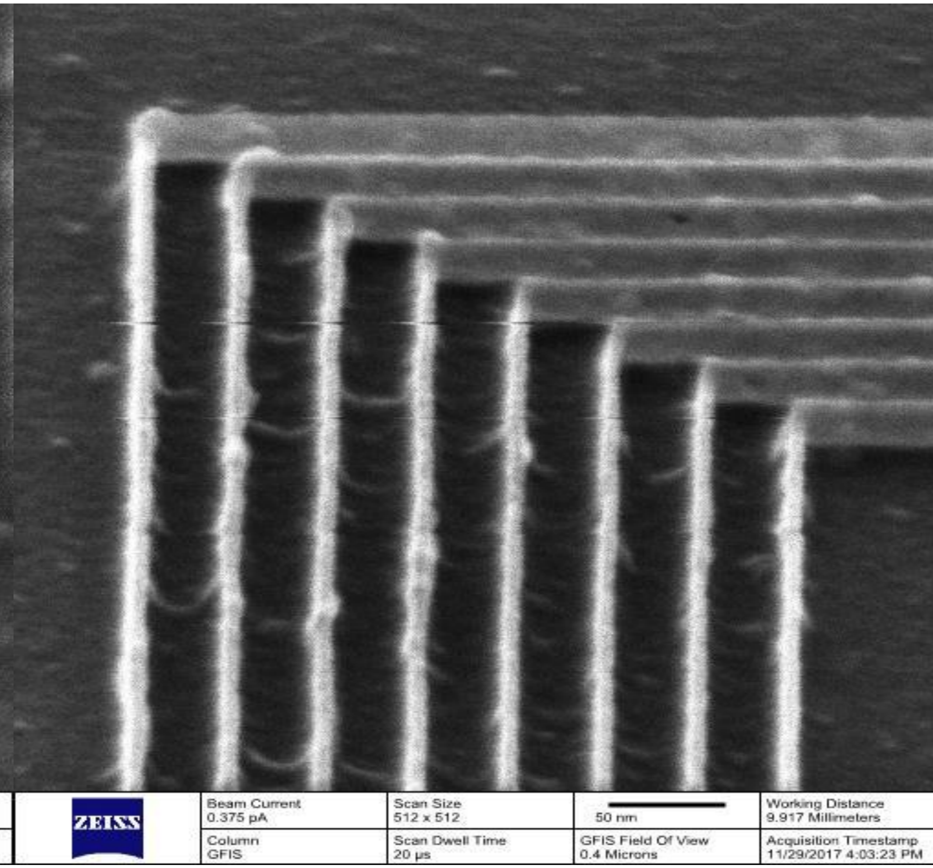


Dense lines



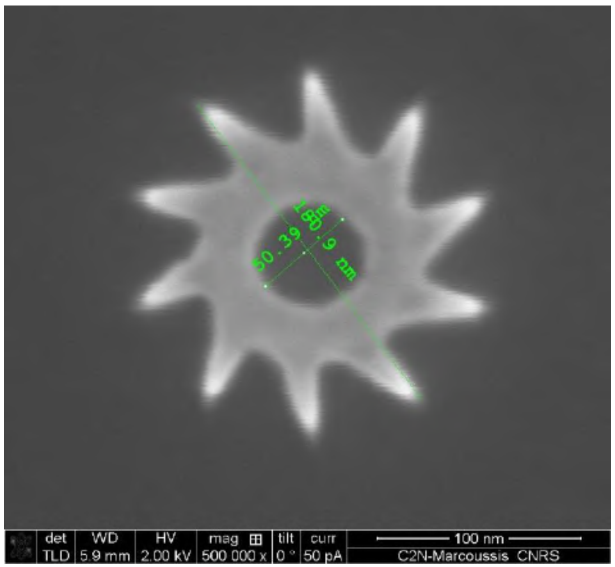
RIE etching of Silicon with the AlOx resist

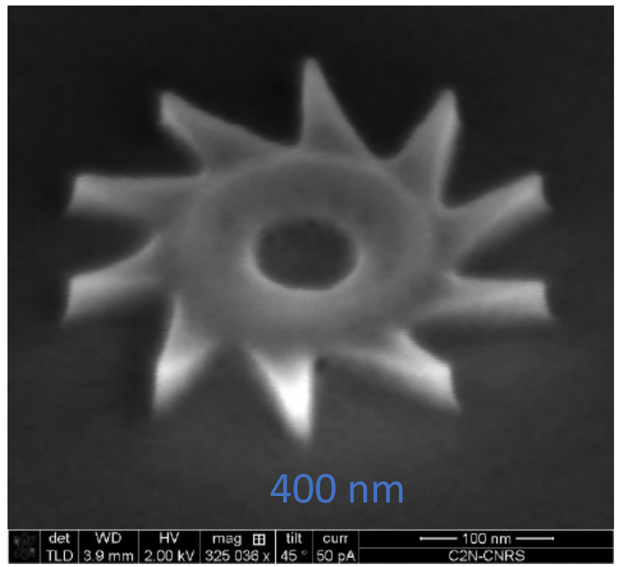


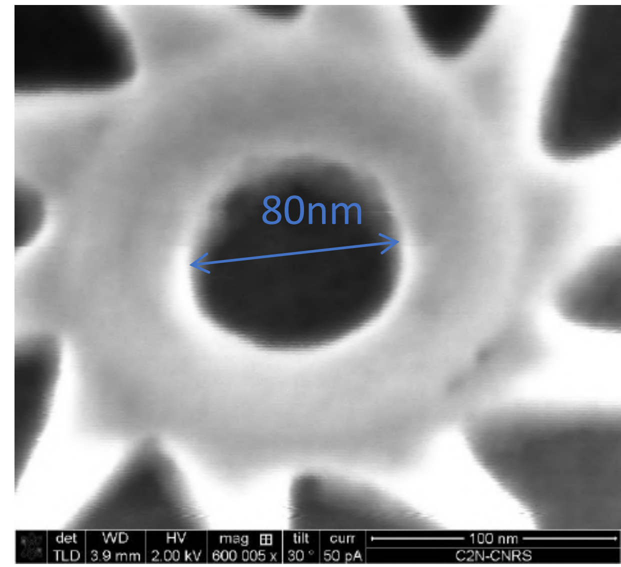


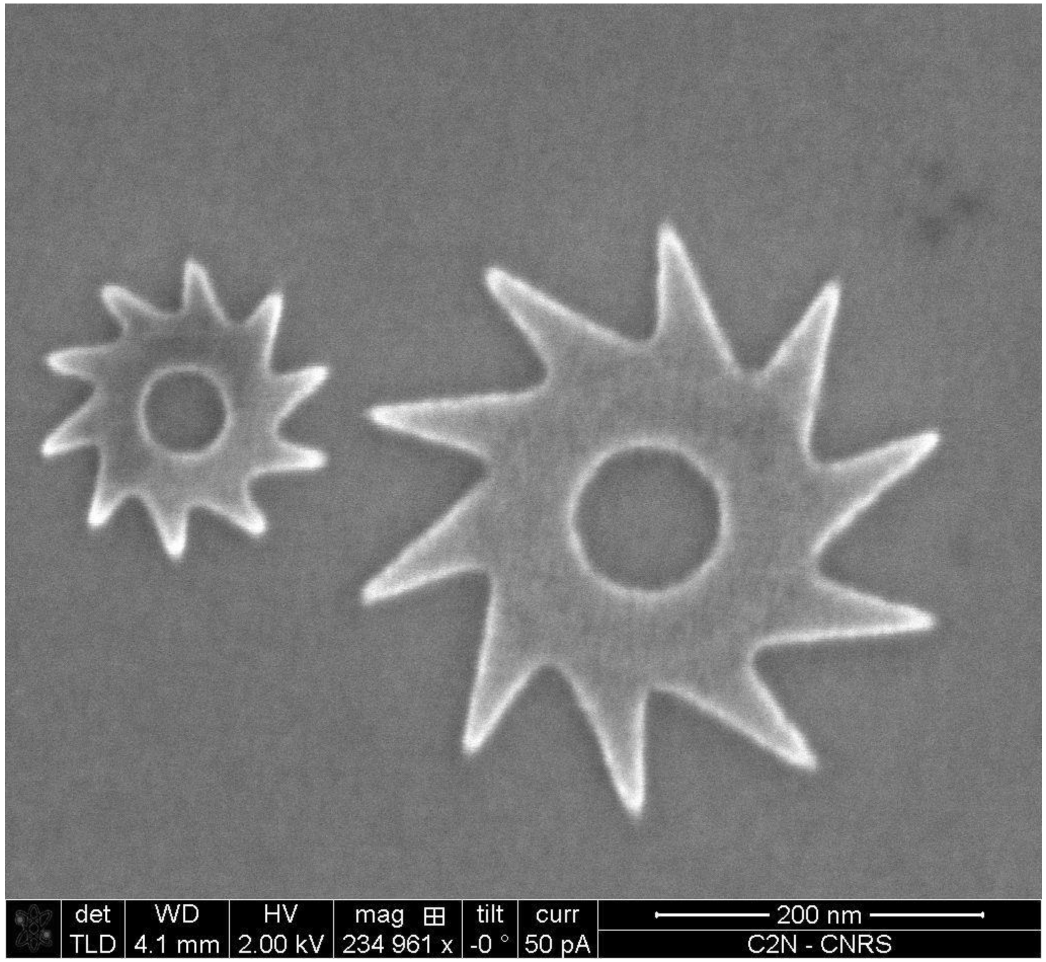
Good selectivity with fluorine based etching.
We obtain 5nm width and 40nm height Silicone nanowires.

AlOx resist

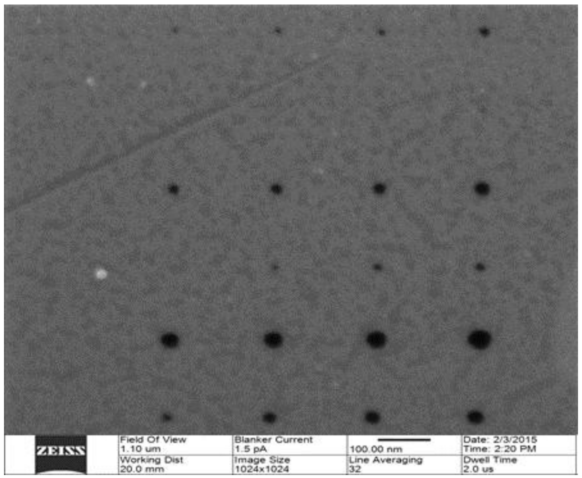

det WD HV mag tilt curr
100 nm
TLD 5.9 mm 2.00 kV 500 000 x 0 ° 50 pA
C2N-Marcoussis CNRS


400 nm
det WD HV mag tilt curr
100 nm
TLD 3.9 mm 2.00 kV 325 036 x 45 ° 50 pA
C2N-CNRS

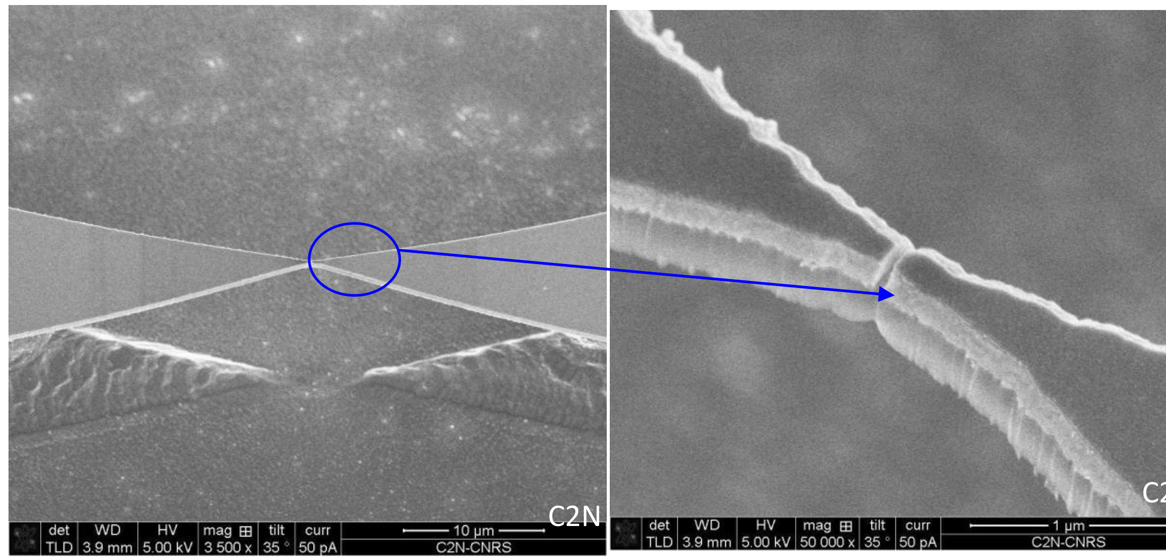

80nm
det WD HV mag tilt curr
100 nm
TLD 3.9 mm 2.00 kV 600 005 x 30 ° 50 pA
C2N-CNRS


det
TLD
WD
4.1 mm
HV
2.00 kV
mag
234 961 x
tilt
-0 °
curr
50 pA
200 nm
C2N - CNRS

High precision milling

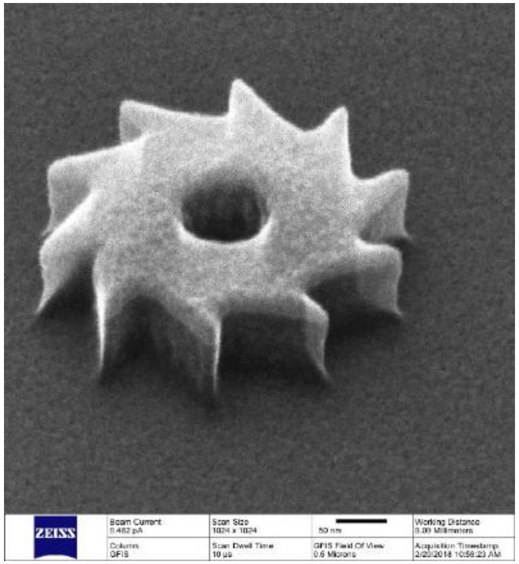


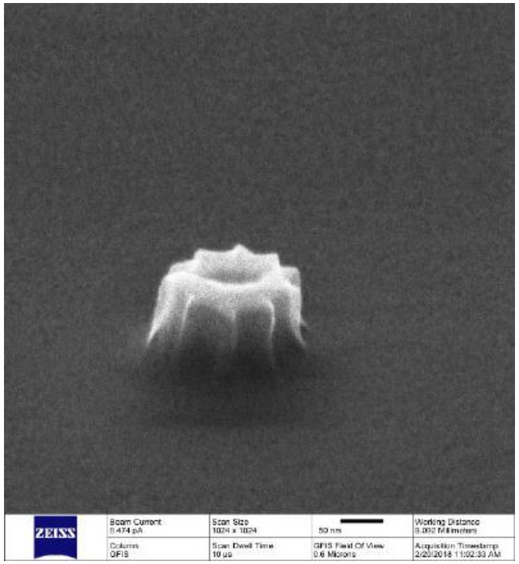
Hole in suspended graphene : dia<5nm

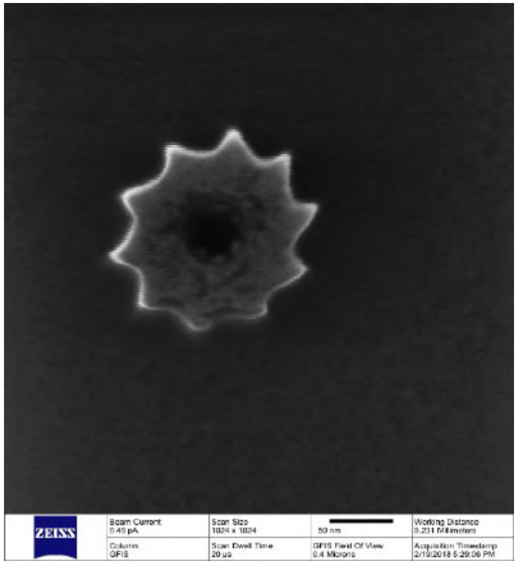


Nanogap etched on a gold bridge for molecule grafting (collab C2N, ICMMO)

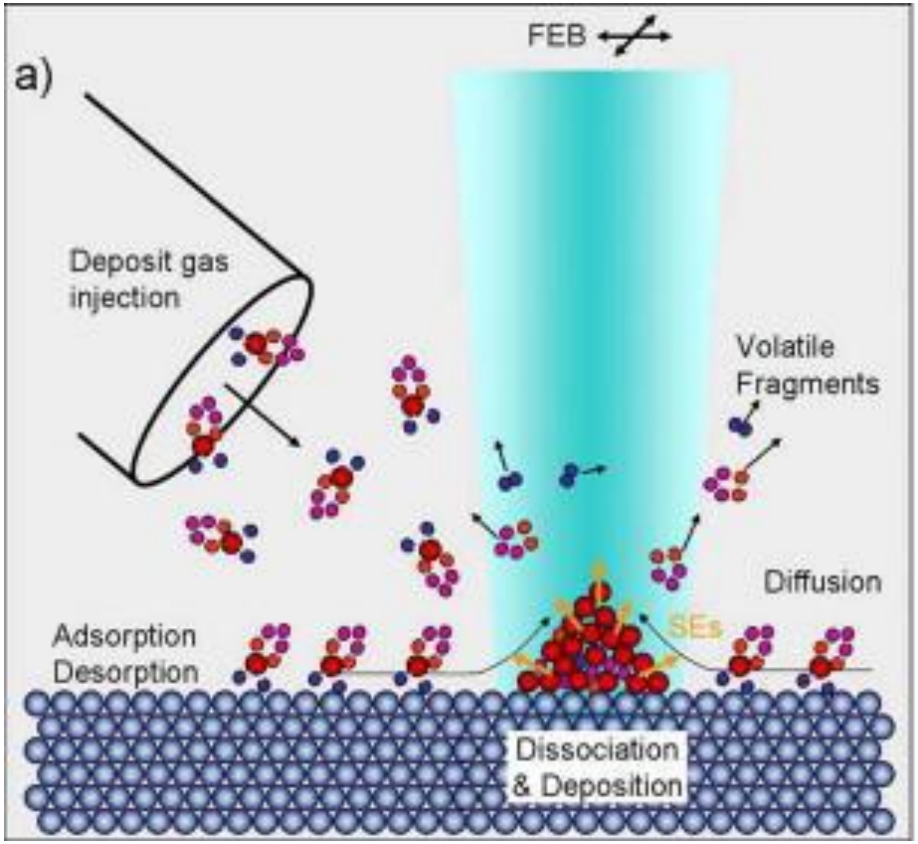
etching







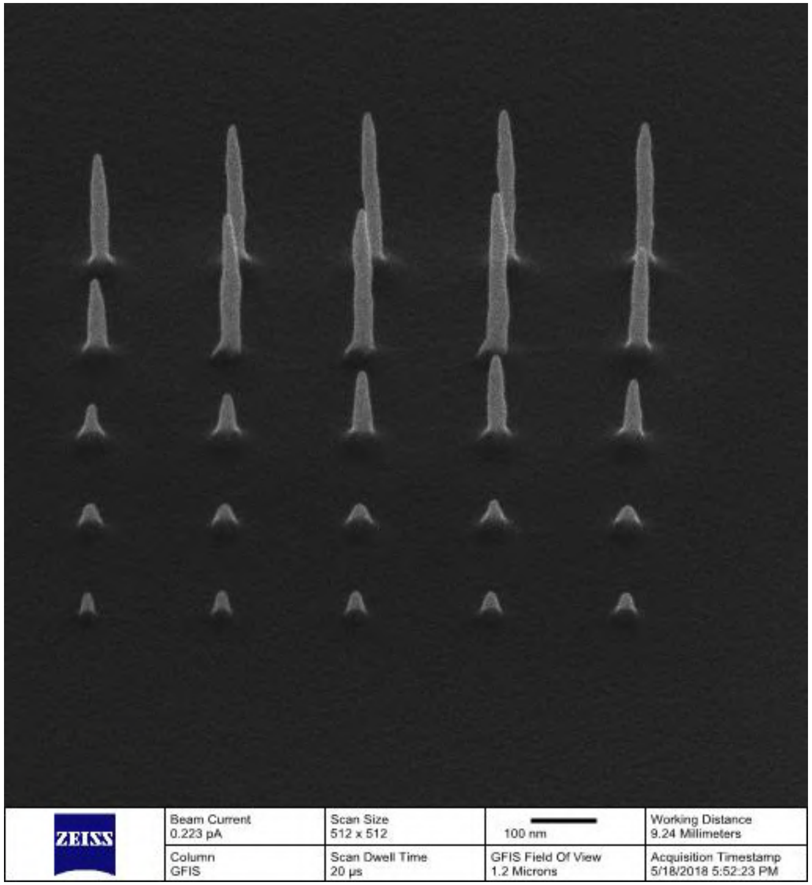
Beam induced deposition

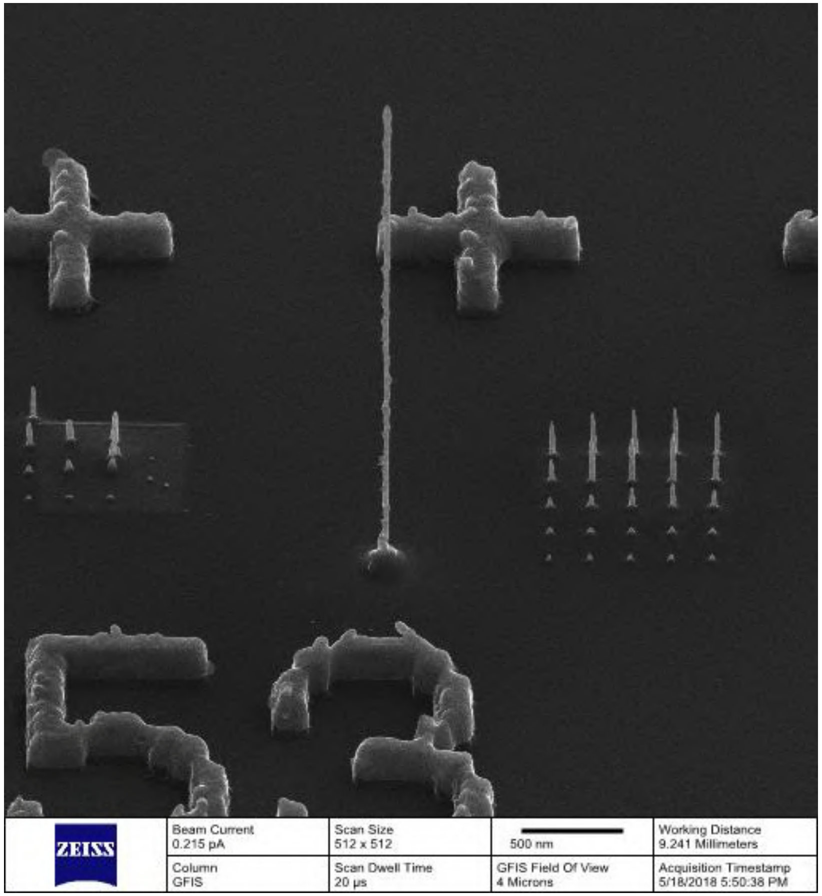


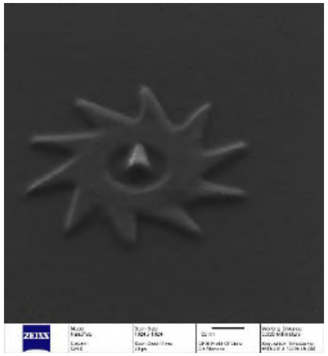
Precursors mostly metal carbonyls: Me(CO)x
$W(CO)_6$, $Fe(CO)_5$
For platinium :$C_5H_4CH_3Pt(CH_3)_3$
For cooper : $Cu(C_5HF_6O_2)_2$

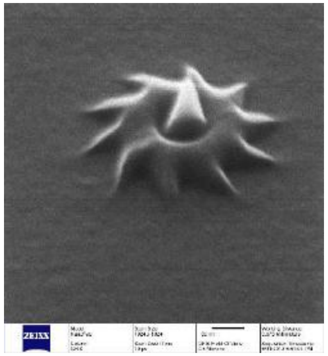
usually C contimination

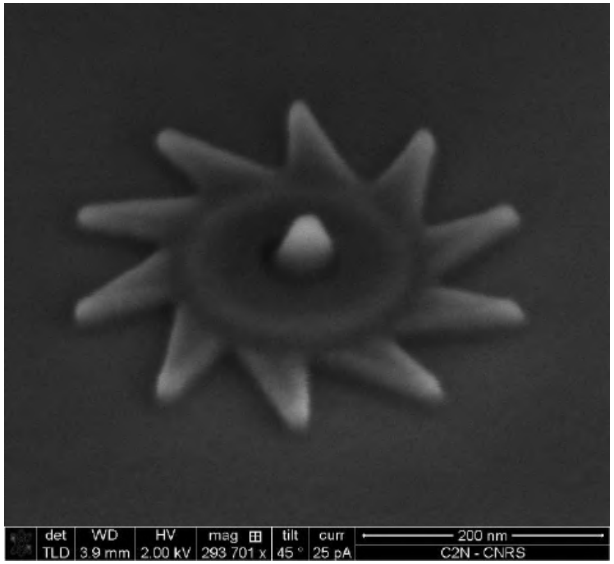
Growing W wire (in fact $W_{0.7}C_{0.3}$)










det
TLD
WD
3.9 mm
HV
2.00 kV
mag
293 701 x
tilt
45 °
curr
25 pA
200 nm
C2N - CNRS

Commercial equipment

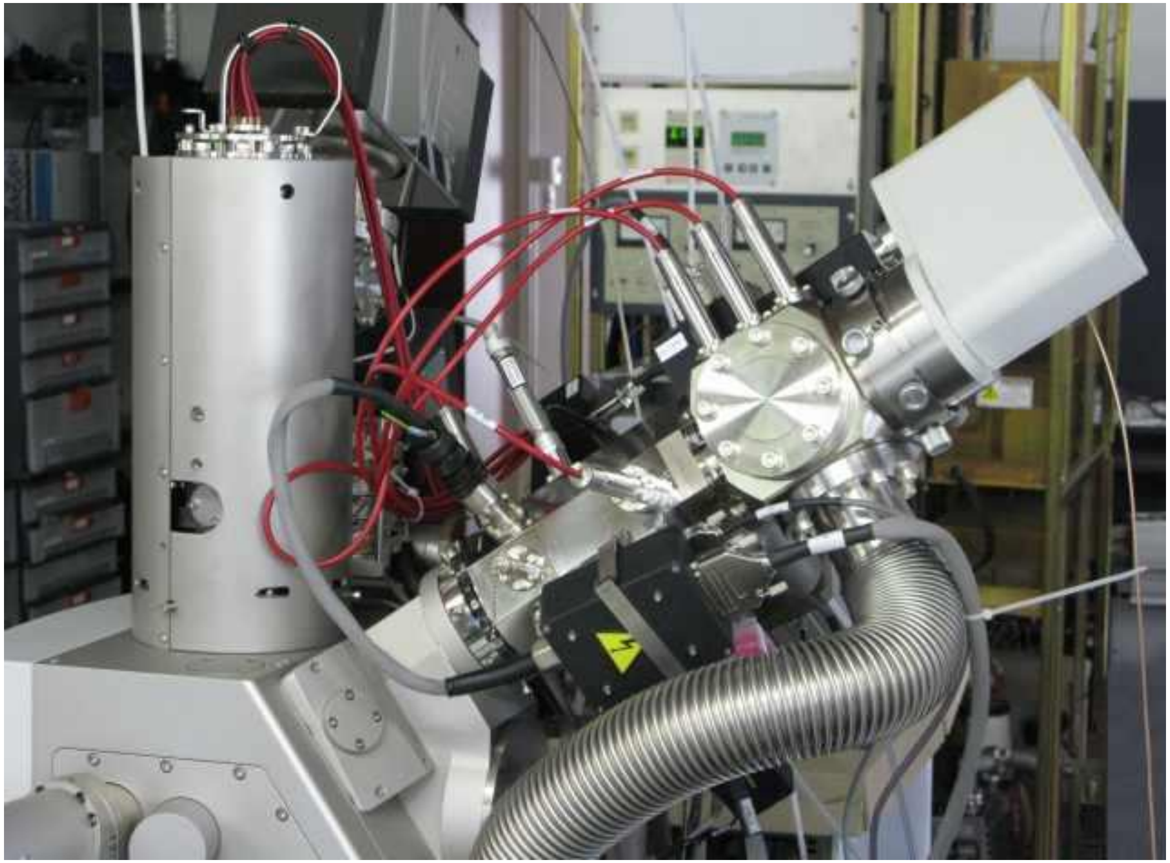
Source Gallium
30kV

750k€

Source Hélium or Néon
30kV

1.2M€

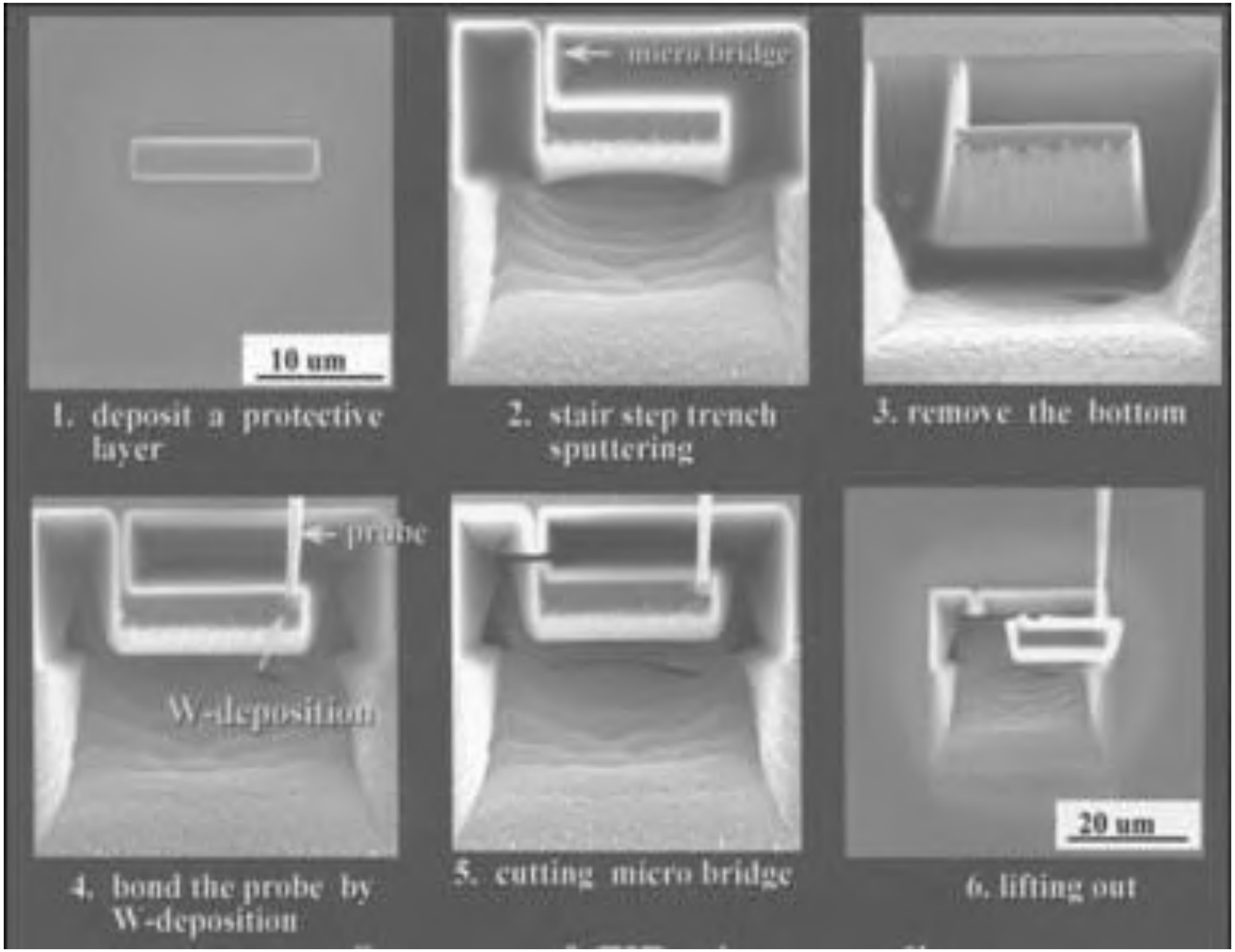
The dual beams



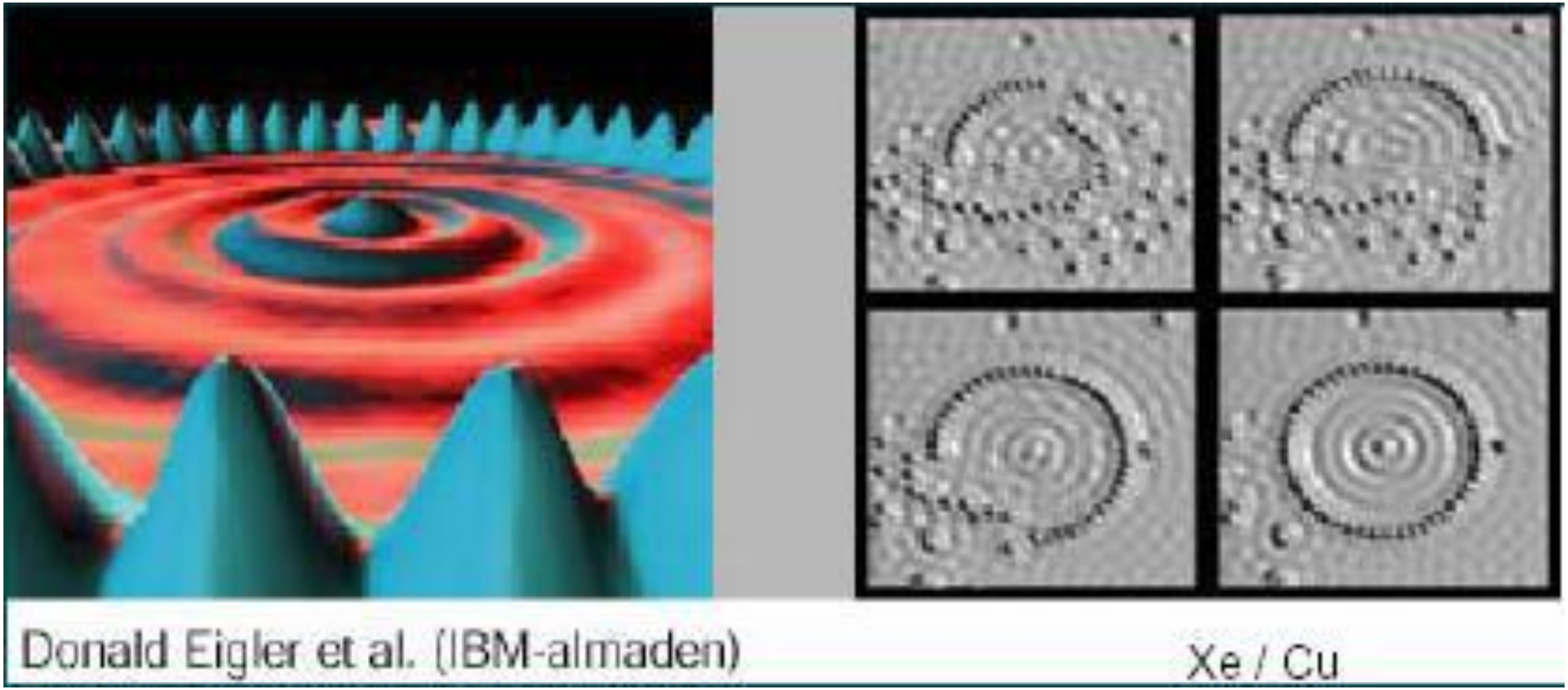
Electron column: insitu real time Observation

Ion column : milling, cutting and beam induced deposition.

TEM preparation



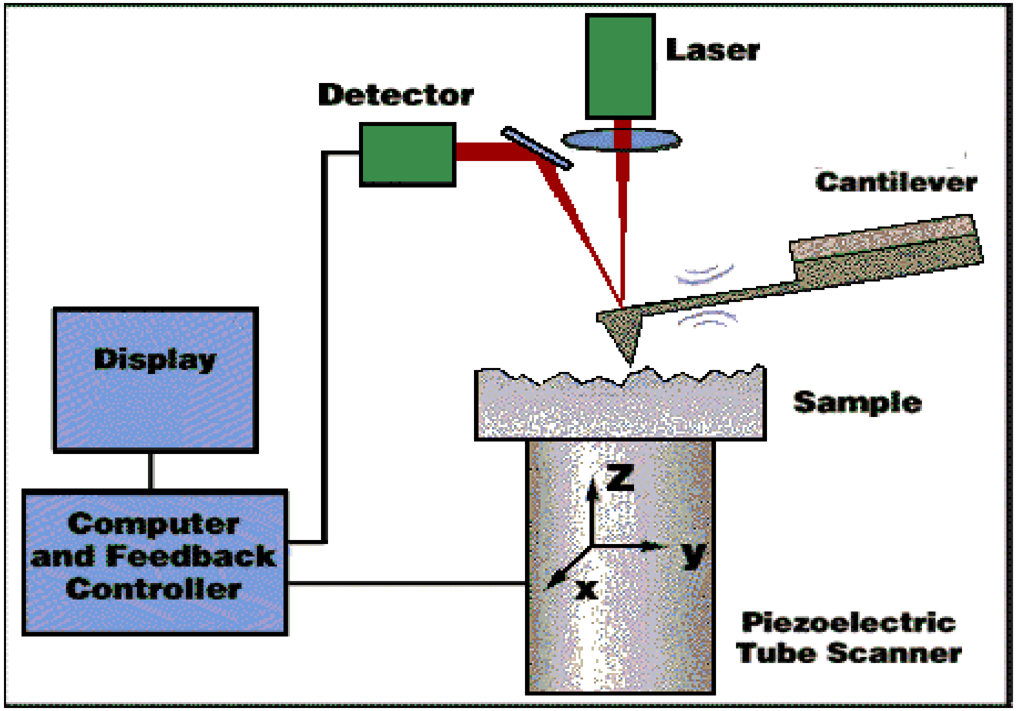
Near field lithography



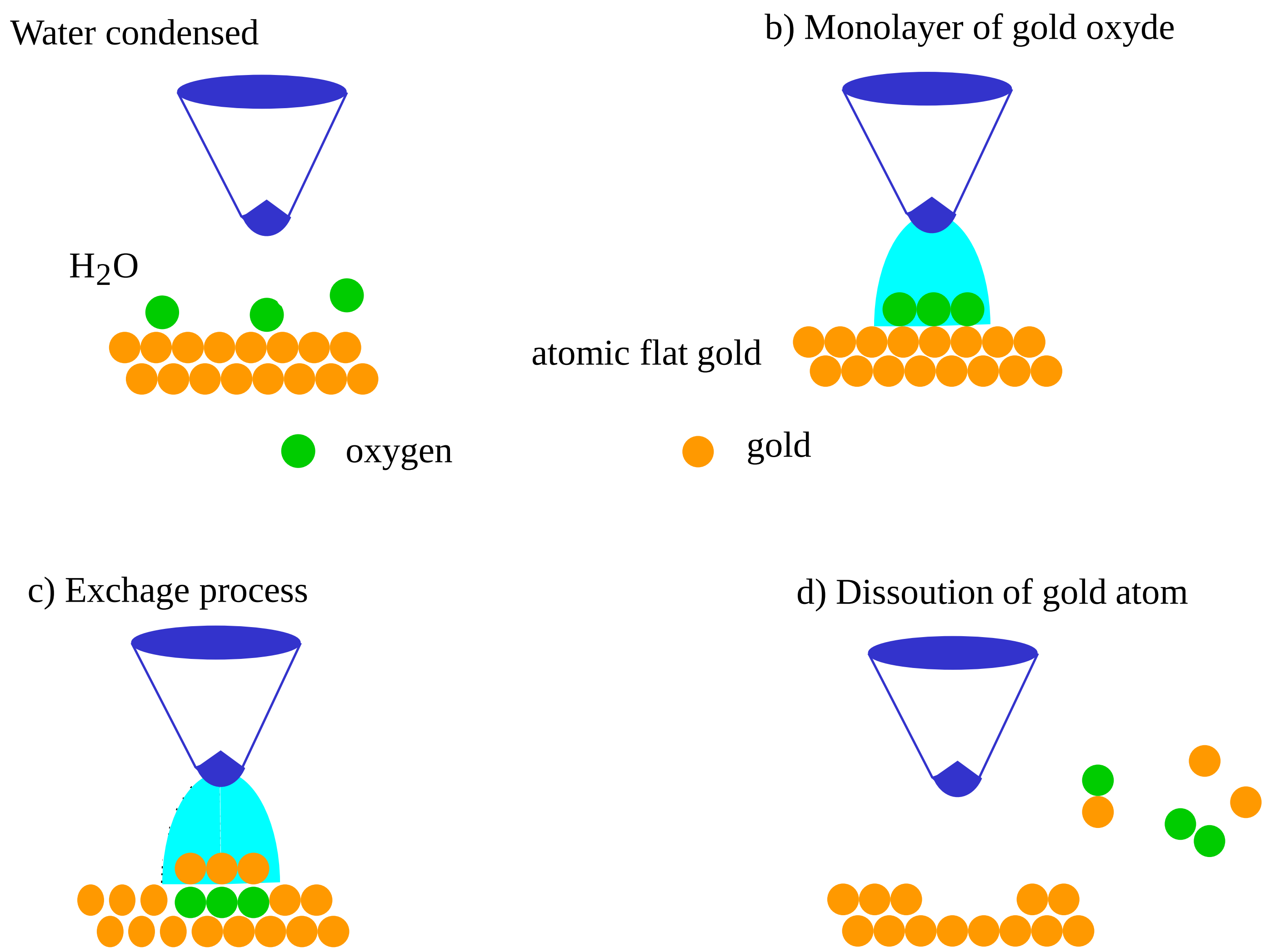
Near field methodology

Electric pulse
Mechanical pressure → threshold

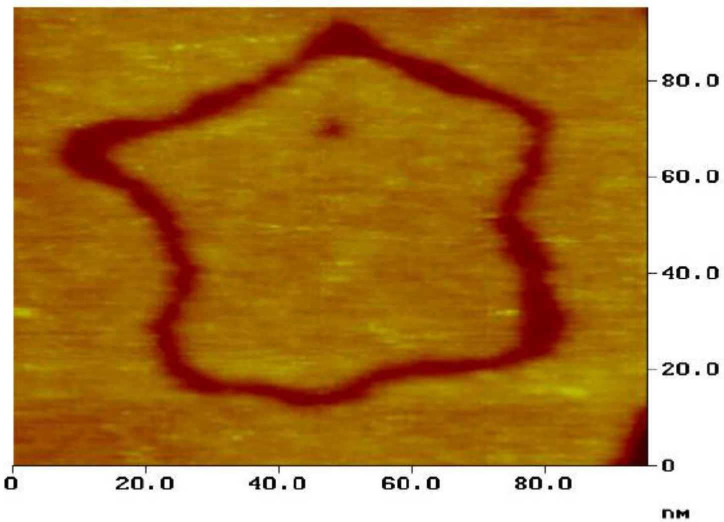
Under threshold → Alignment, observation

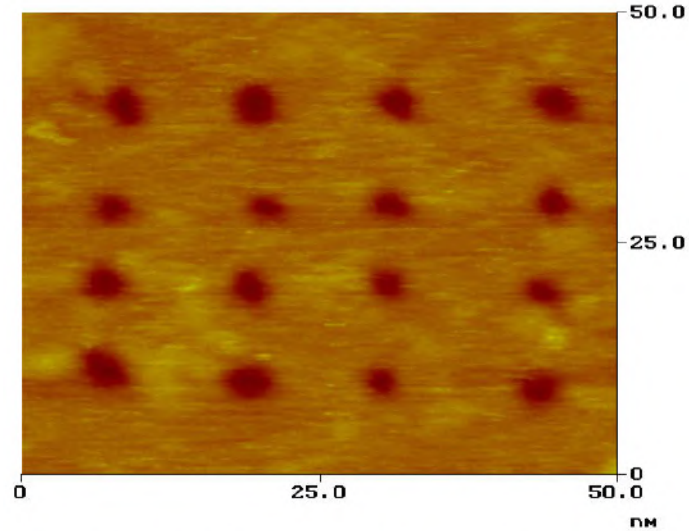


More pratical : local anodization



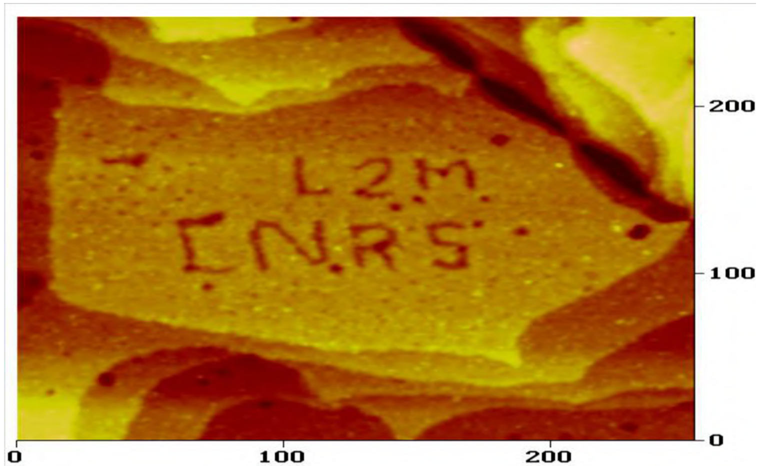
exemples

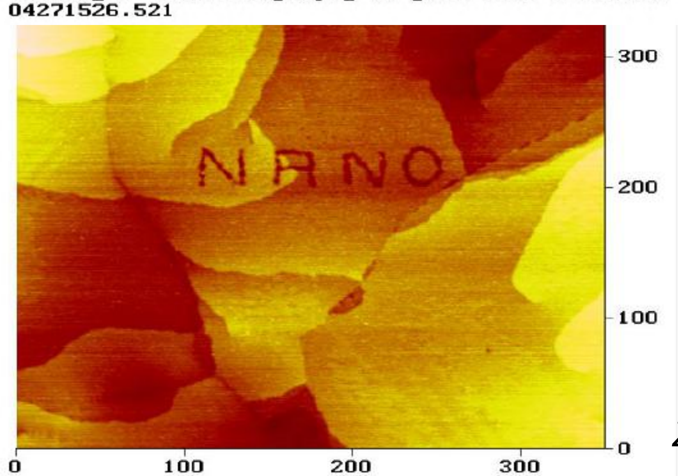




Carte de France (32,000 atomes d'or enleves) L2M
04081014.501

Monolayer nanolithography on gold film L2M/CNRS
04271526.521

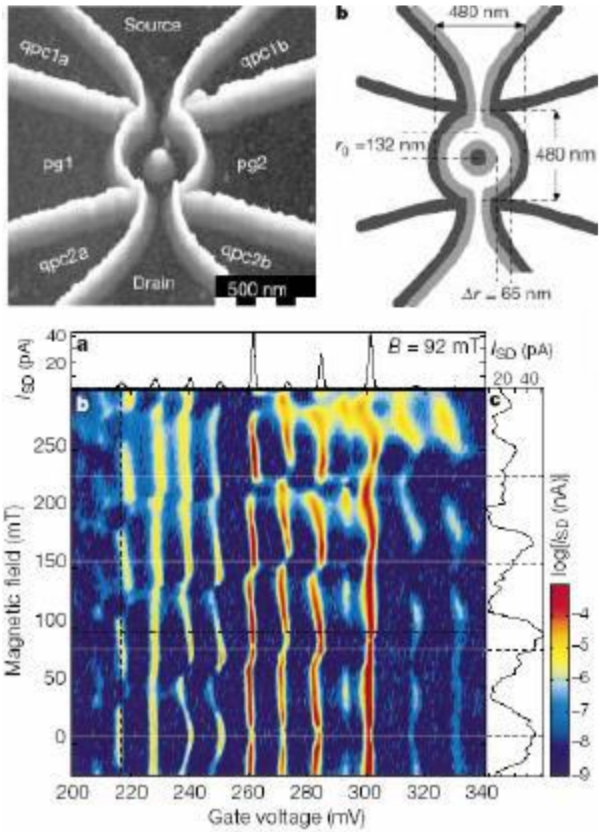




Z.Z. Wang LPN

Other examples

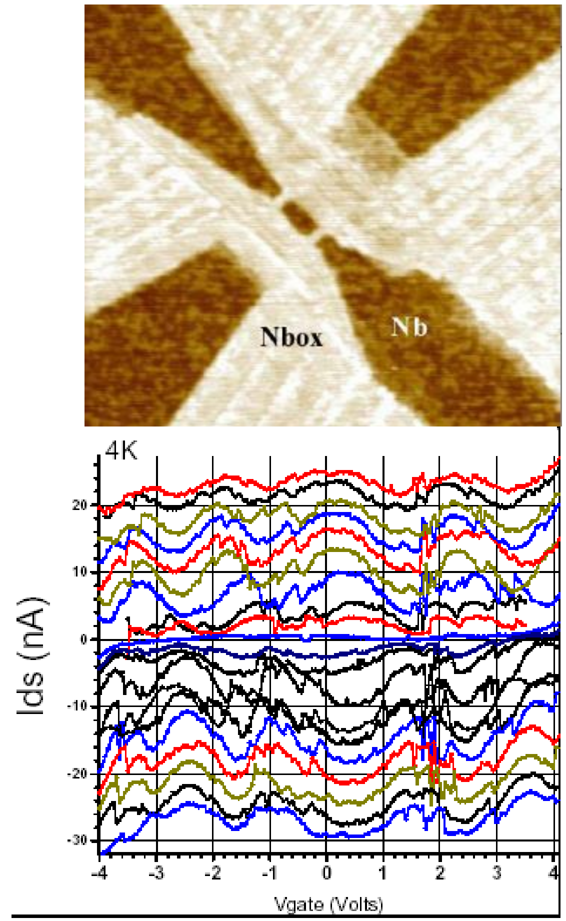
Anodisa²on of GaAs



Aharonov-Bohm ring

ETH Zürich

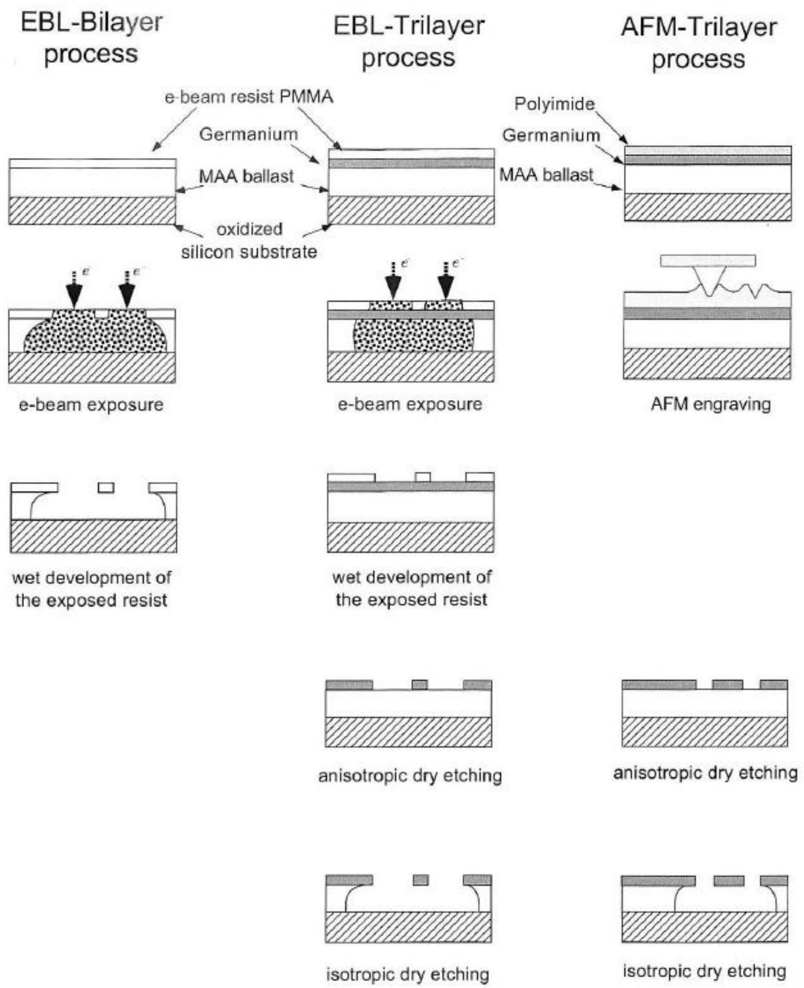
Anodisation du Nb

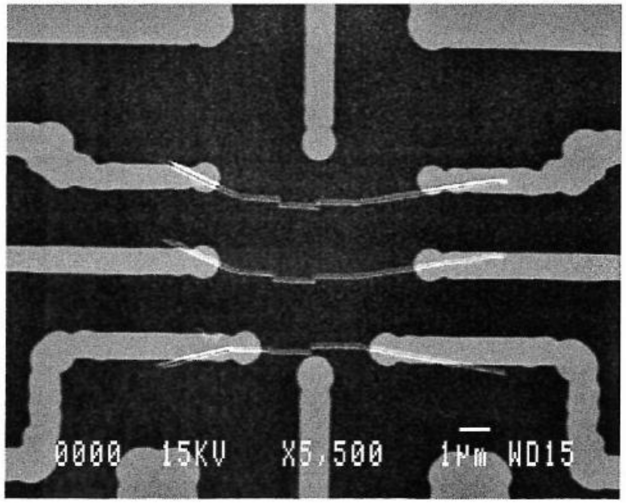


SQUID

CRTBT

Engraving resist with an AFM tip





Single electron transistor made by AFM litho – PhD thesis V. Bouchiat

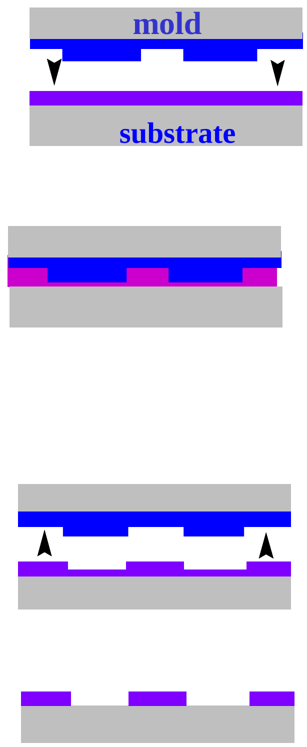
Nano-imprint

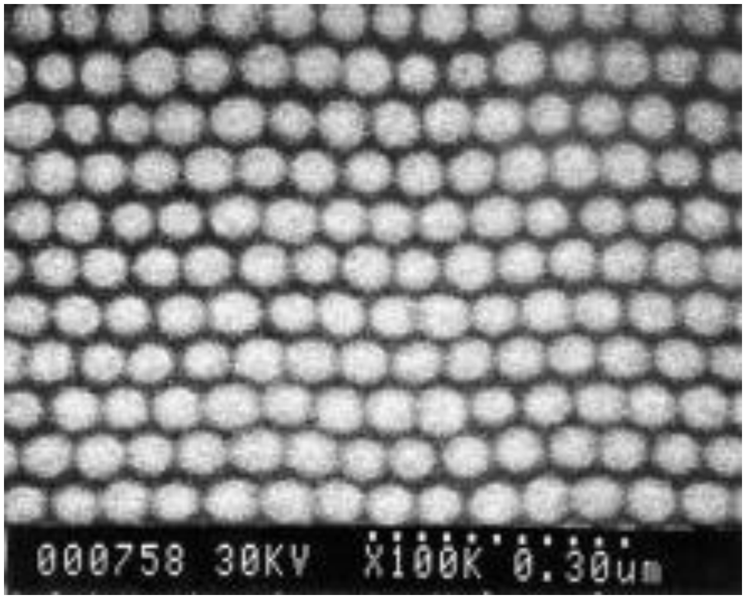
1.temp +pressure 50Bars

2. cooling

3. dimolding
(ca be tricky)

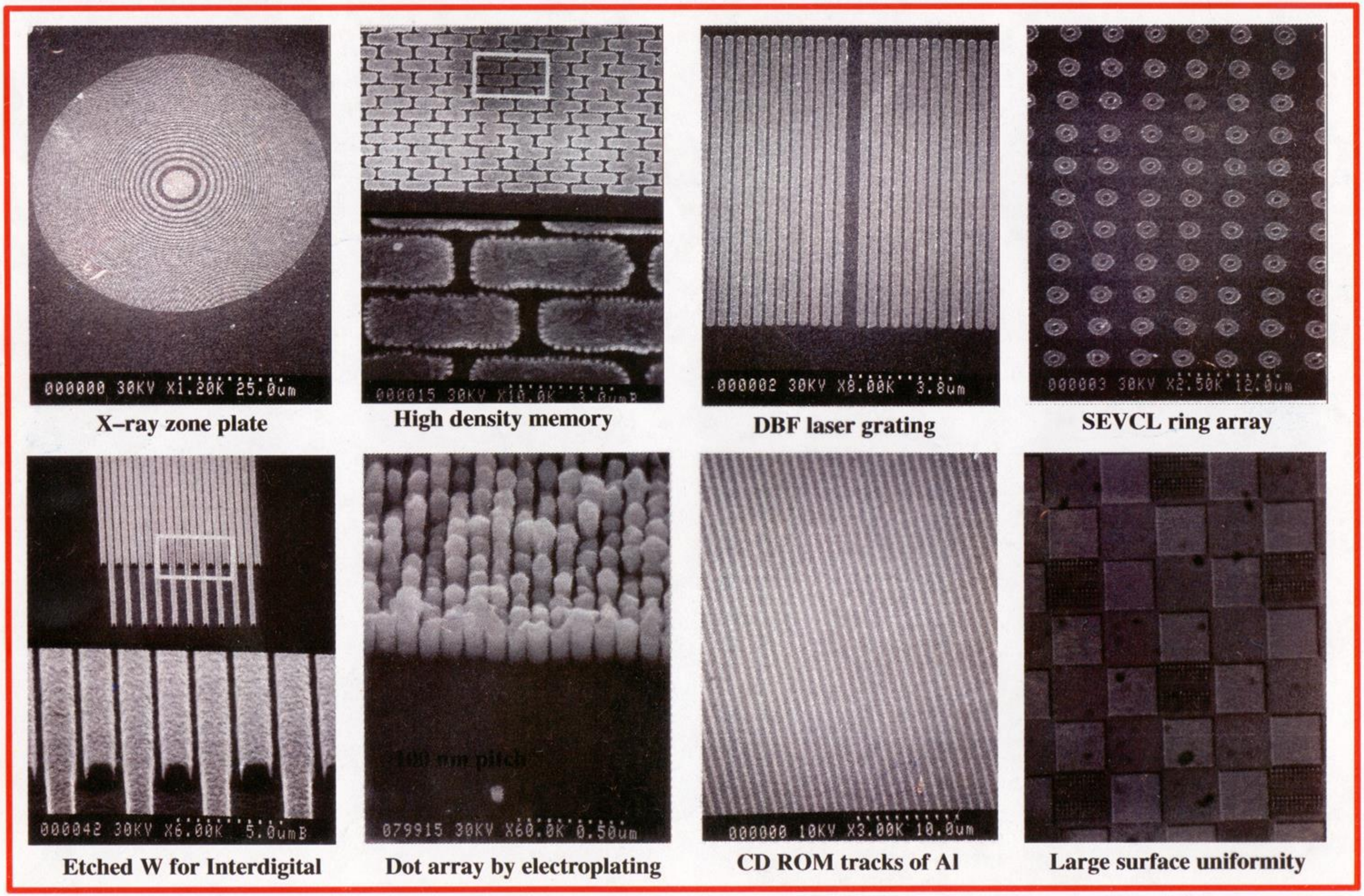
4. Residus etchnig





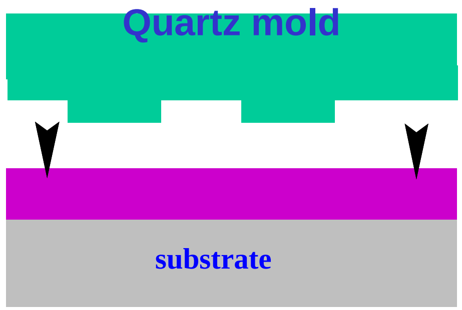
Slow process, mask 1/1 scale i.e. ebeam lithography
10nm resolution demonstrated , very cheap

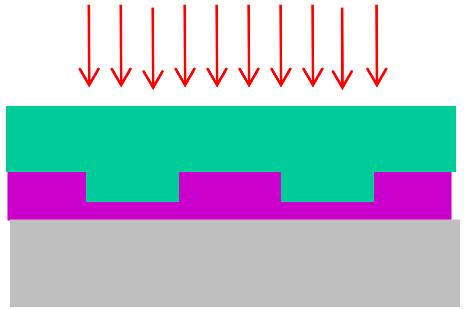
examples



X–ray zone plate
High density memory
DBF laser grating
SEVCL ring array
Etched W for Interdigital
Dot array by electroplating
CD ROM tracks of Al
Large surface uniformity

UV assisted imprint





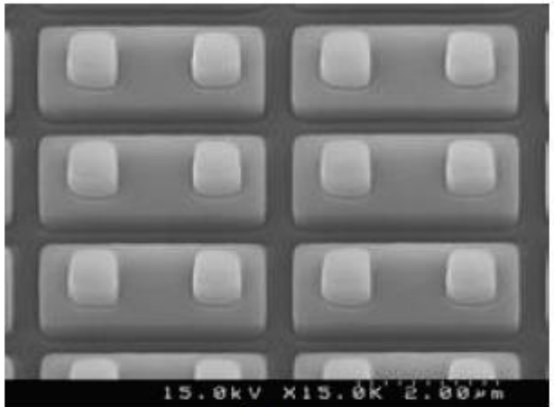
Resist hardening underUV

Faster

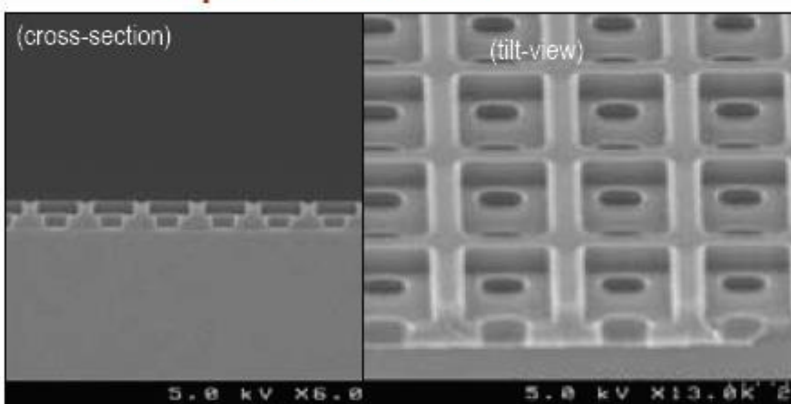
resolution

3 Dimensional printing

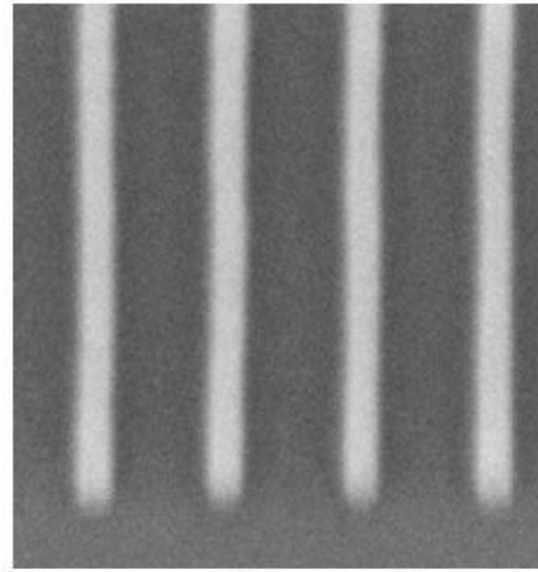
Via chain structure (Via / Metal2)



Imprint into dielectric



Low LER



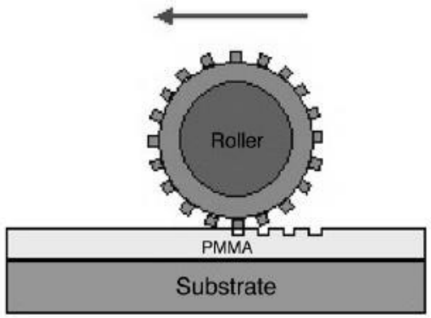
20nm Replication

Courtesy of MII

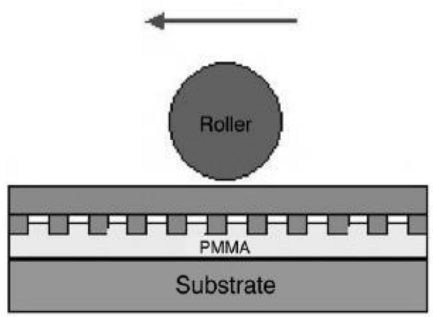
Commercial equipment

Roller lithography

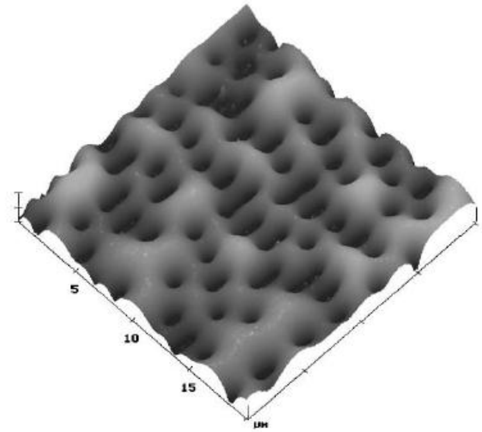
Easy and rapid but simple pattern – solar cells?

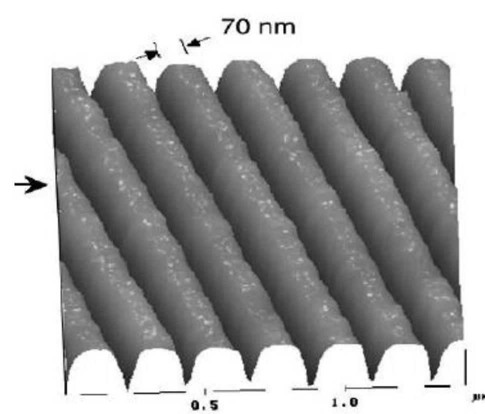


(a)



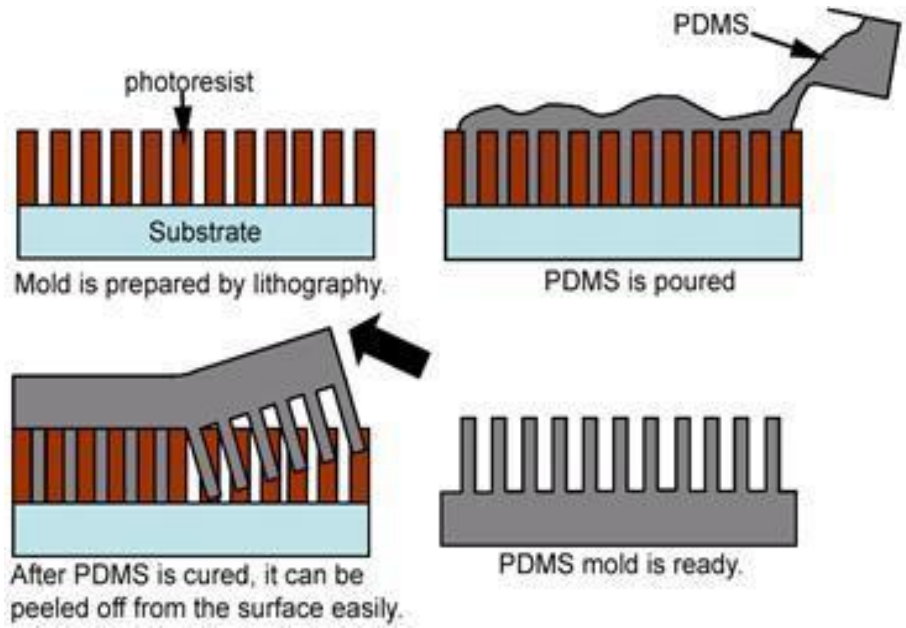
(b)



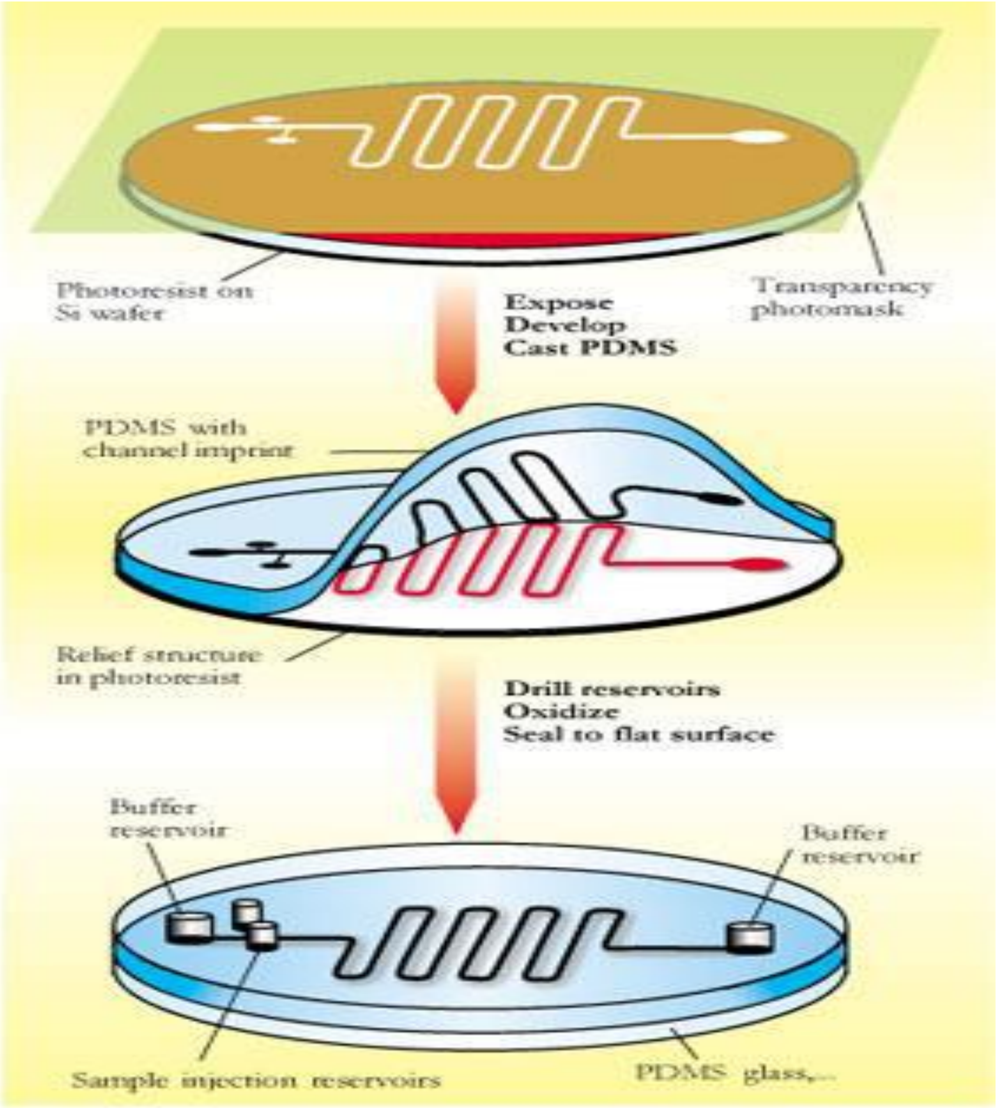


Soft lithography

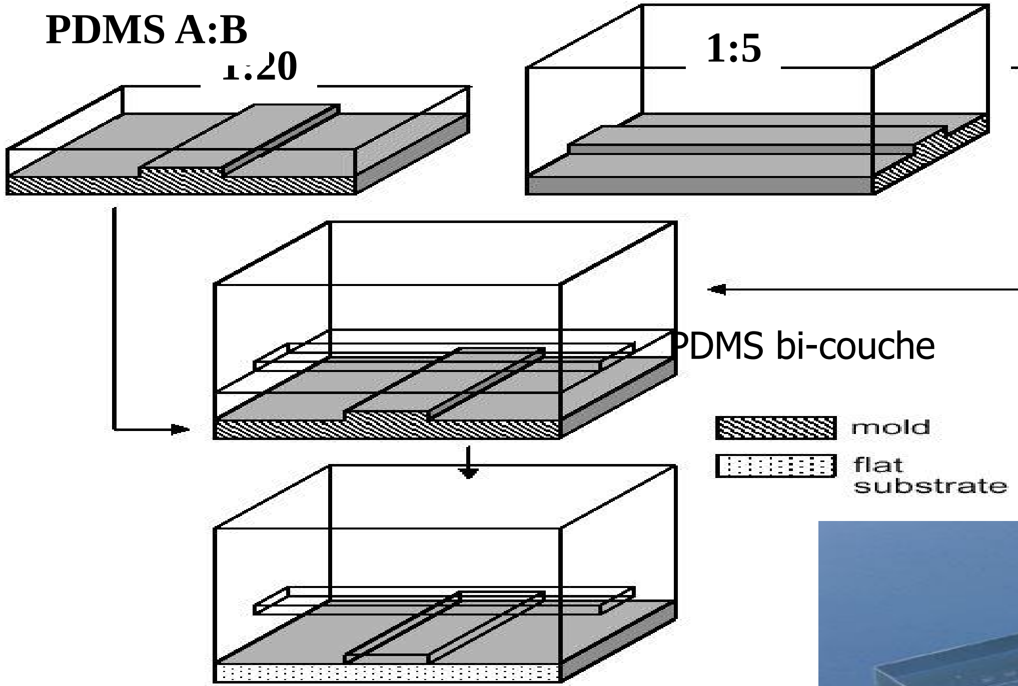
PDMS mold

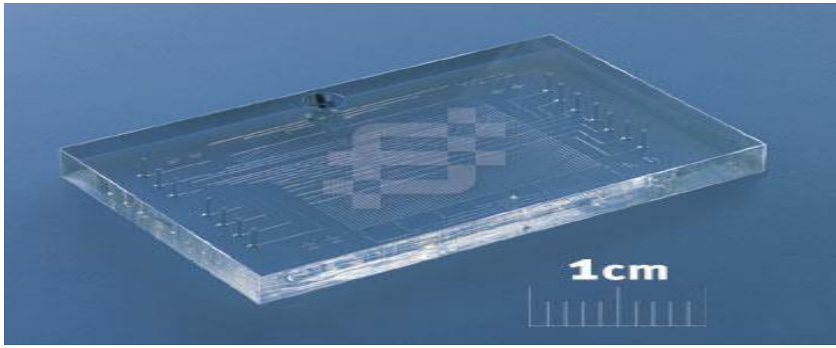


microfluidics



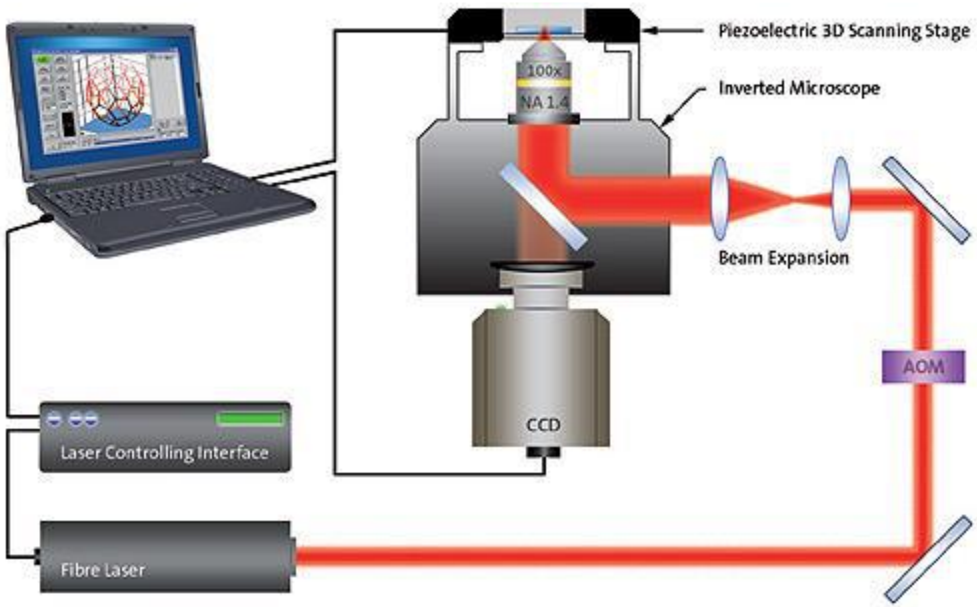
M.A. Unger, H-P Chou, T. Thorsen, A. Scherer, and S.R. Quake, Science 288, p.113 (2000)





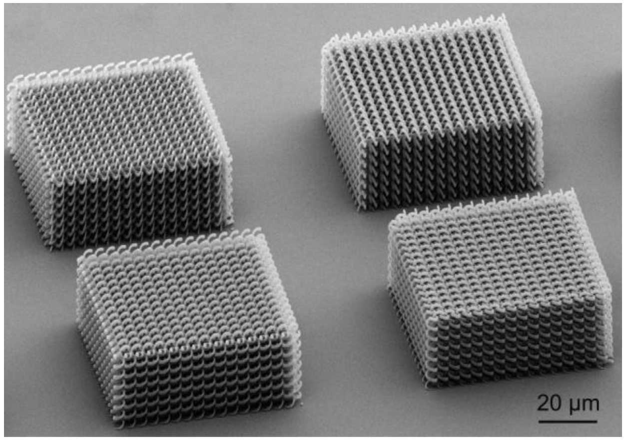
Fluidigm (USA)

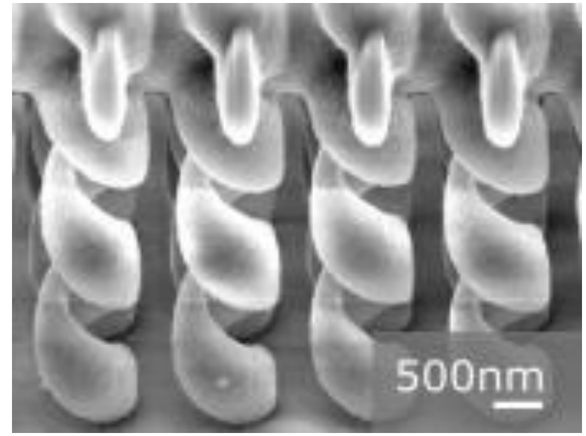
Litho 3D laser



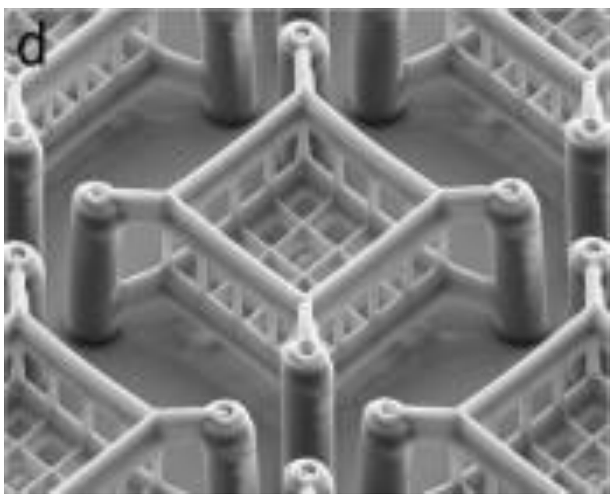
The wavelength of the LASER ido not produce any change in the resist
But at the focal point where the intensity is very strong
-> Two photons process
-> resist polymerisation

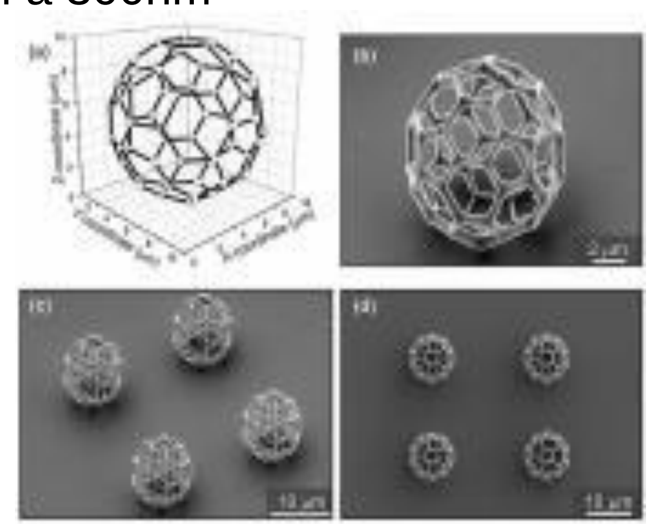
The sample is scanned under the focal point





Resolution 200nm à 300nm





Conclusions on lithography

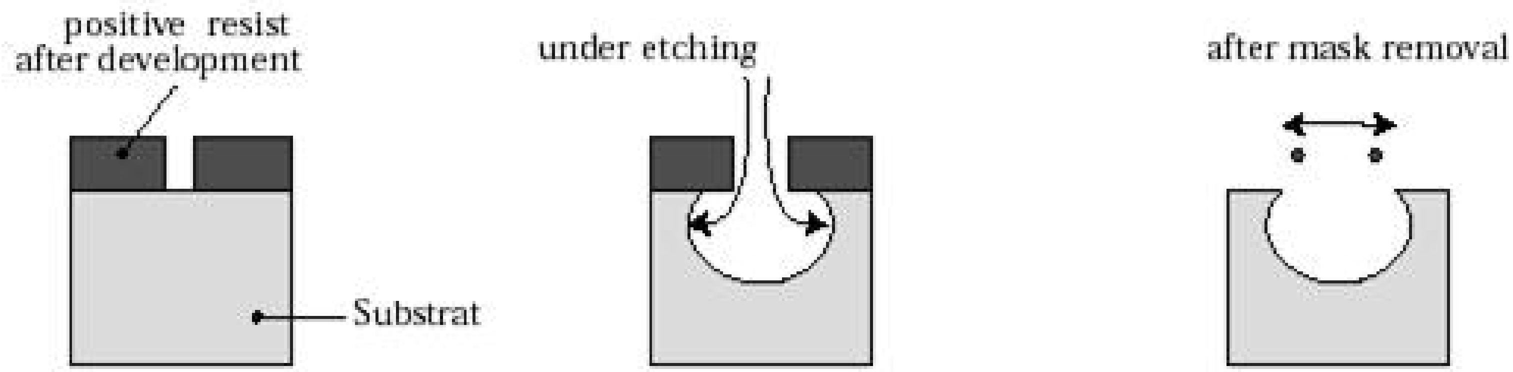
Technique		Resolution	Use	Remarks
Optical lithograpphy	contact	0.25µm	Labs et R&D	Cheap intermediate resolution
	proximity	2µm	Labs and R&D	Cheap but low resolution
	projection	20nm	Industry	Very expensive
EUV		<10nm?	Industry	Need some work 2020?
Ebeam lithography		1nm	Labs et R&D Mask making	Easy to handle no mask very high resolution Intermediate cost
Ion beam lithography		1nm	Labs et R&D	Milling and lithography diagnostic
Near field lithography		Atom 10nm	Labs	Very slow, cheap for specific appl.
Nano-imprint		10nm	Labs and industry?	Cheap, alignment issu specific

Transfert techniques

- Wet etchnig
- Ion etching
- Reactive ion beam etchnig

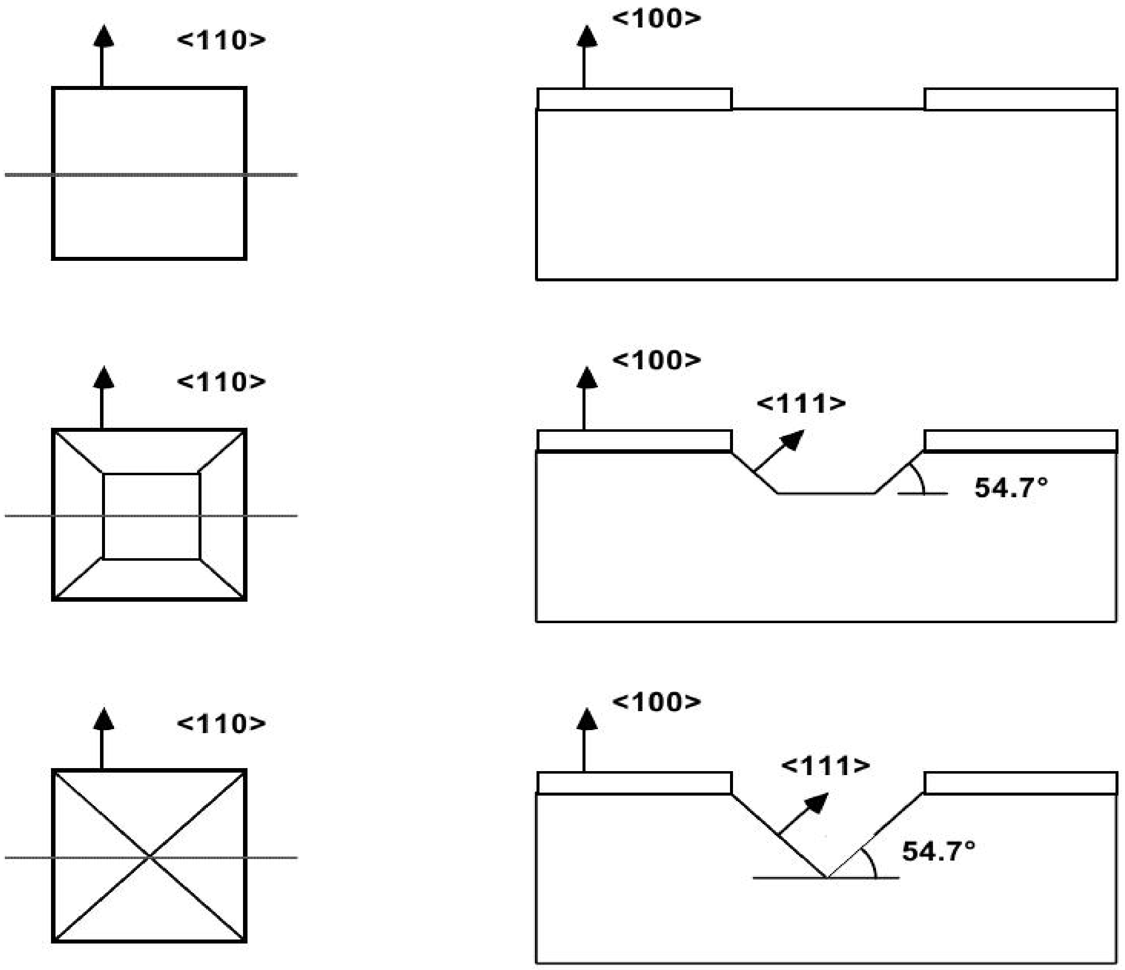
Wet etchnig

Isotrope etching (non crystallin materials)
•Simple
•Fast
•Pb of undercut

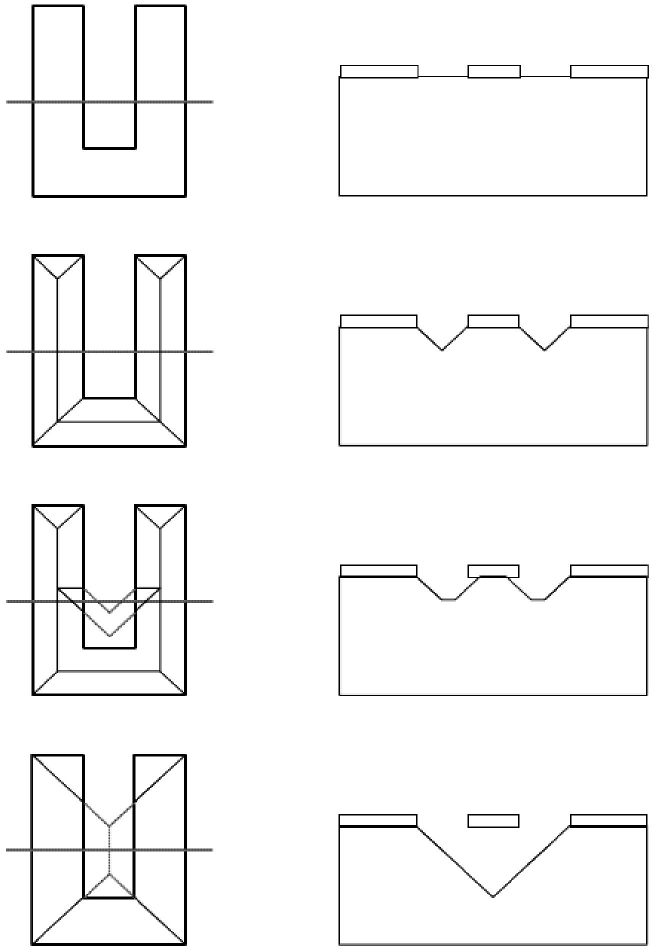


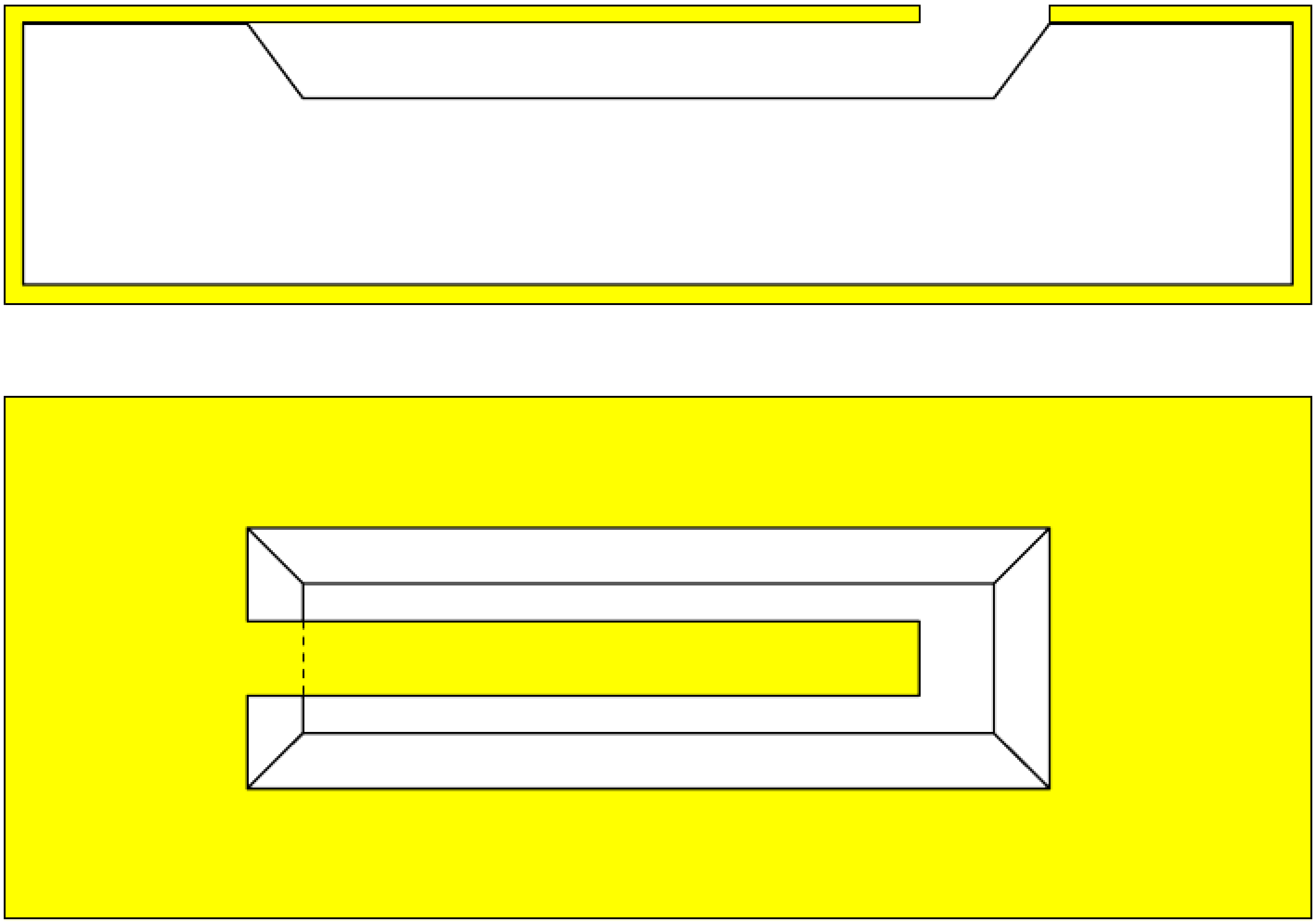
Difficult to control :
if weak chemistry long time but surface state important

Anisotropic wet etching (crystalline material)



MEMS suspended structures

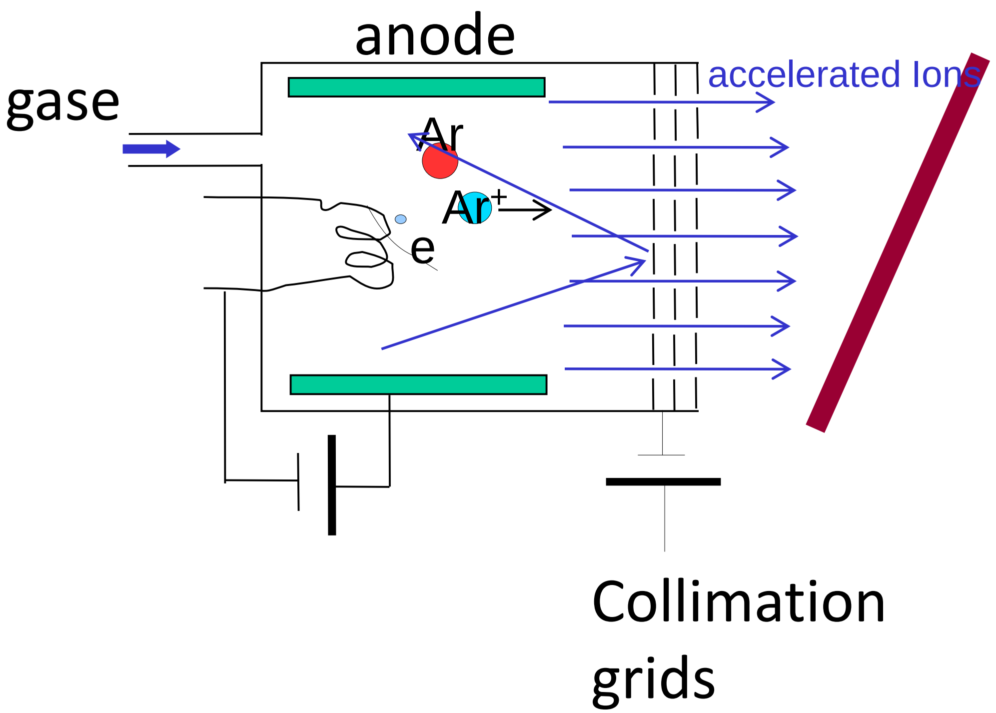




Ion Beam Etching (IBE)

- Mechanical impact of the ions
- Etchnig rate T

$$T \propto \frac{E}{ZU}$$



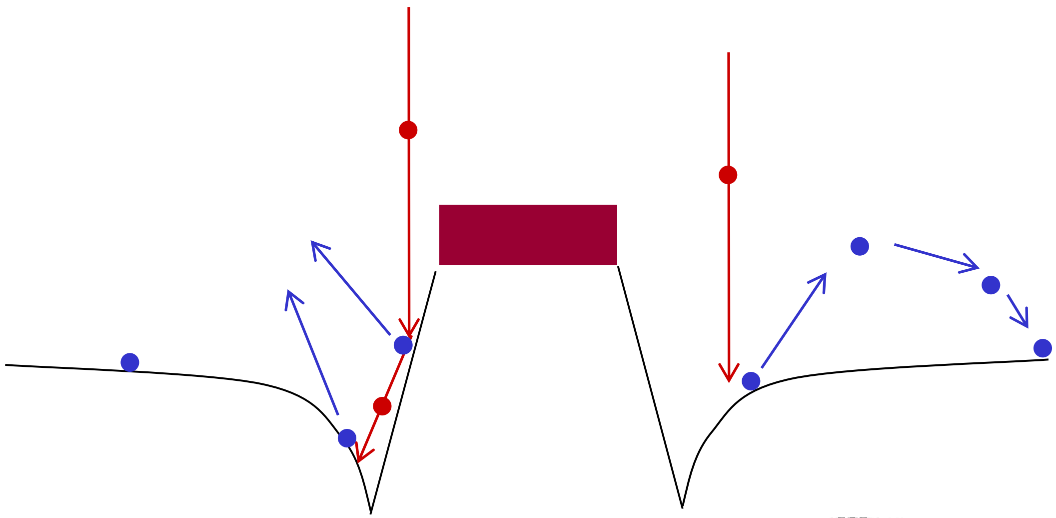
U Binding energy

Z atomic number

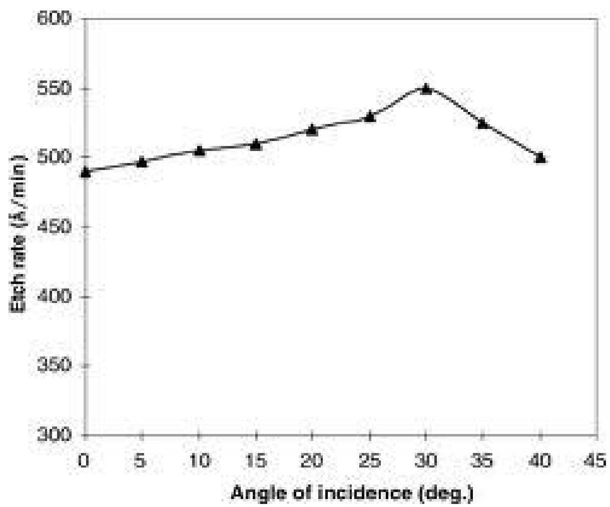
E ion energy x coeff (angle)

Typical energy: 100eV to 2kV

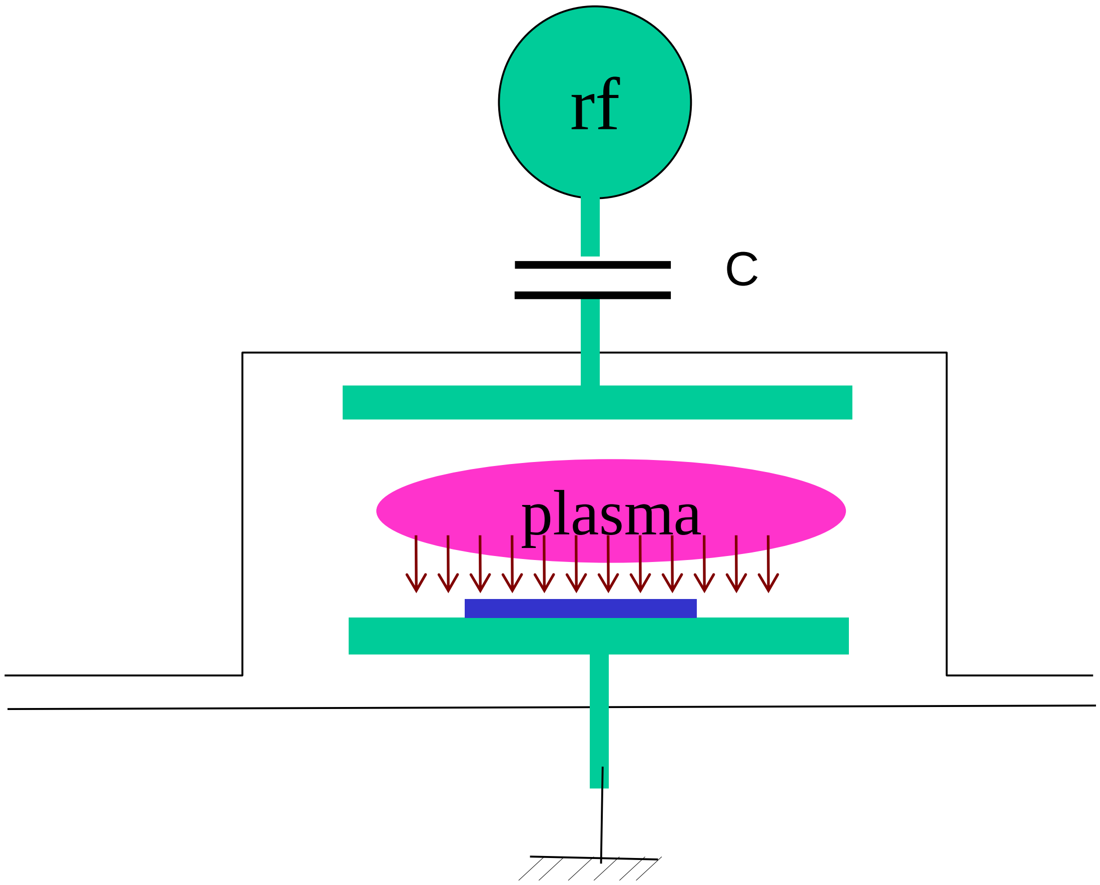
Ion beam etching



- Poor etching rate
- Not very anisotrope
- Not very selective
- Re-deposition
- Trenching
- Defect



Reactive ion etching: RIE



plasma

Plasma = partially ionized gase with ions (+or -) électrons and neutral species

Create by radiofrequency or microwave discharge at gase pressure typically 100Pa (1Torr)

Although the gase is at ambient temperature, the electron energy create very active ions radicals usually obtained at high temperature

Chemical reactivity of the surface is also modified by the impact of the ions.

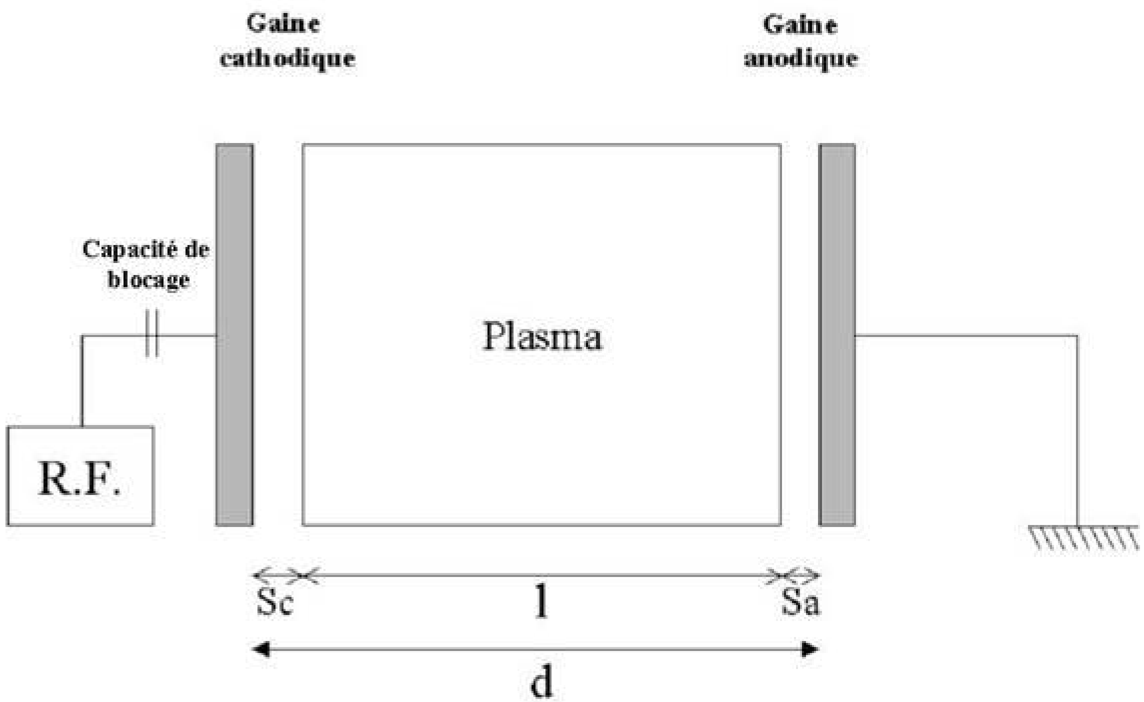
The interplay between chemical and physical effect give rise to very anisotropic and high rate etching.

Plasmas are quite complex systems and it is difficult to master all the parameters.

Autopolarisation

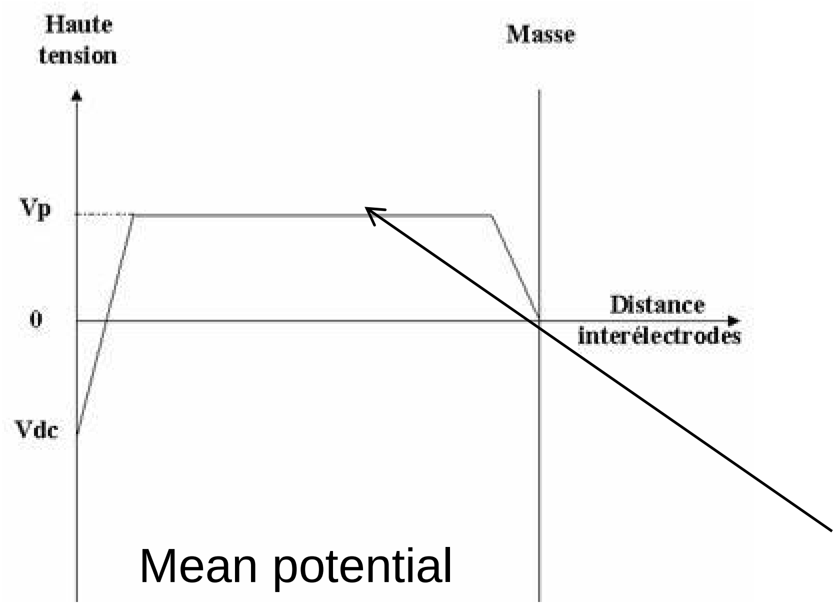
Speed of electron >> speed of ion because of mass difference
During an RF cycle all electrons reach the electrode but not all the ions
DC polarisation lock by the capacity
The ions are accelerated by this voltage to the sample

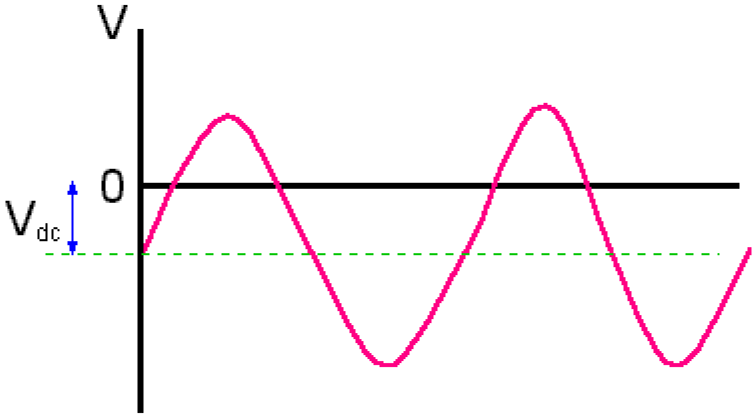
Zone neutre



Autopolarisation

At the first positive voltage an important flux of electrons arrive on the electrode but at the next negative one a much smaller number of ions arrive. A negative voltage built up and repell the electrons. The stationary state arise when the flux of electrons = flux of ions.

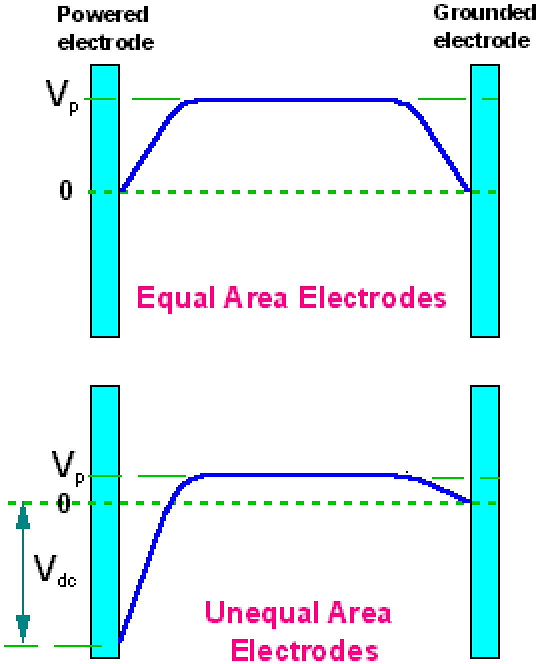




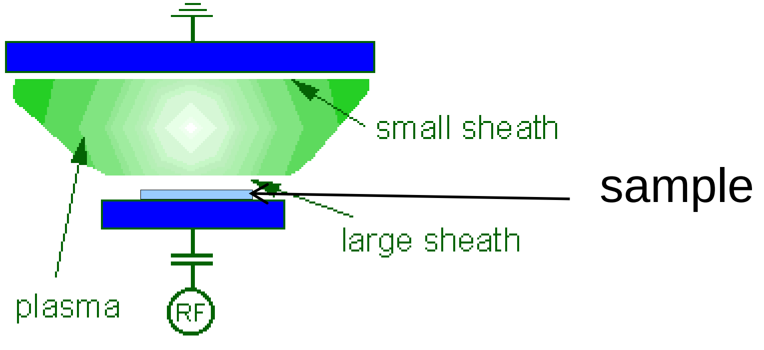
The plasma is at a positive potential since the electron are rapidely evacuated by the chamber wall. Vp allows to maintained the neutral charge of the plasma, This the most positive charge of the system.

autopolarisation

The polarisation depends on the ratio between the two electrodes. The mass electrode include the wall of the reactor and Vdc >> Vp

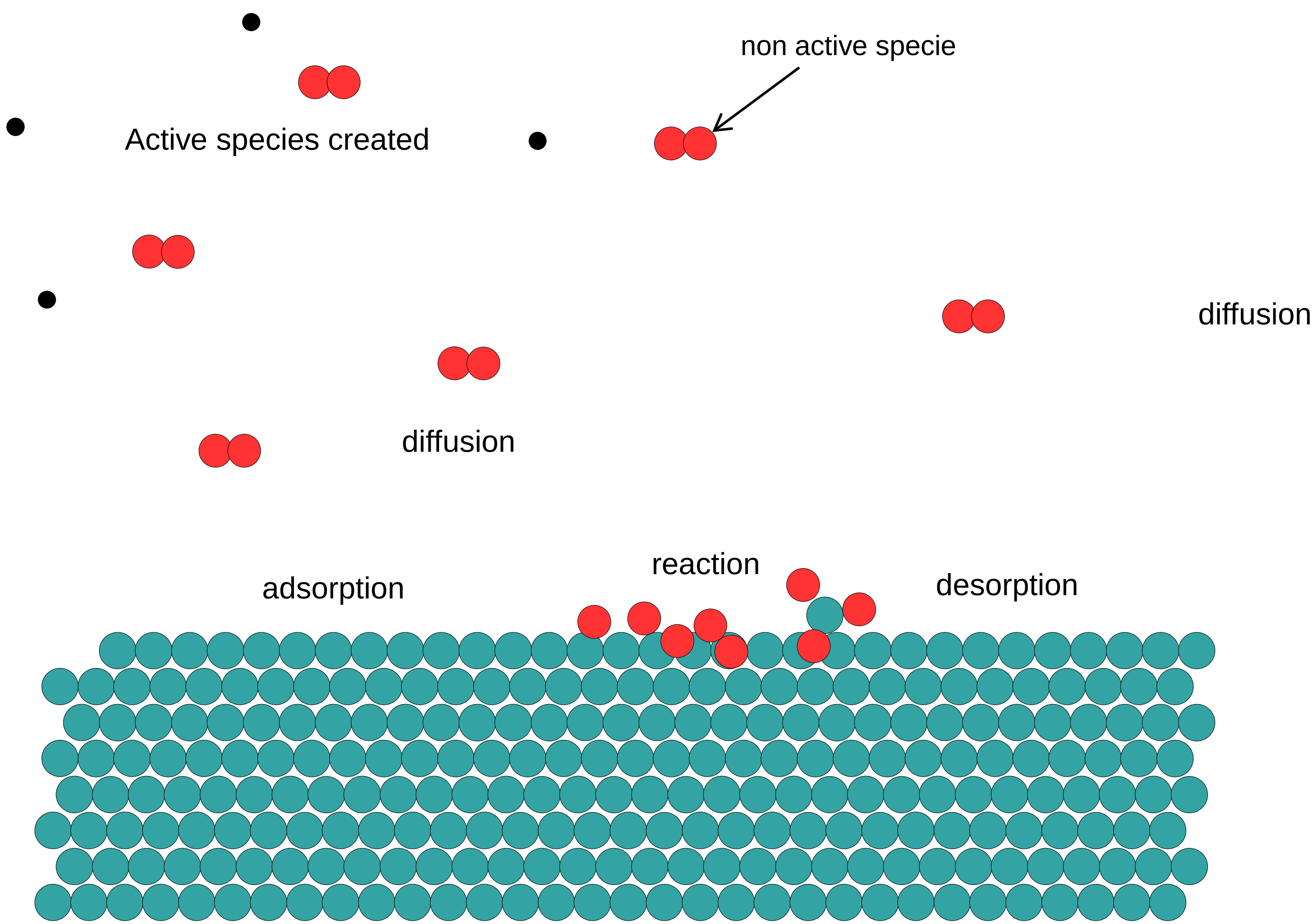


Time averaged values for the potentials in different RF reactors



The pollution of the reactor change the area of the mass electrode and the polarisation evolve with time

chemistry


non active specie
Active species created
diffusion
diffusion
reaction
adsorption
desorption

Chemical aspects

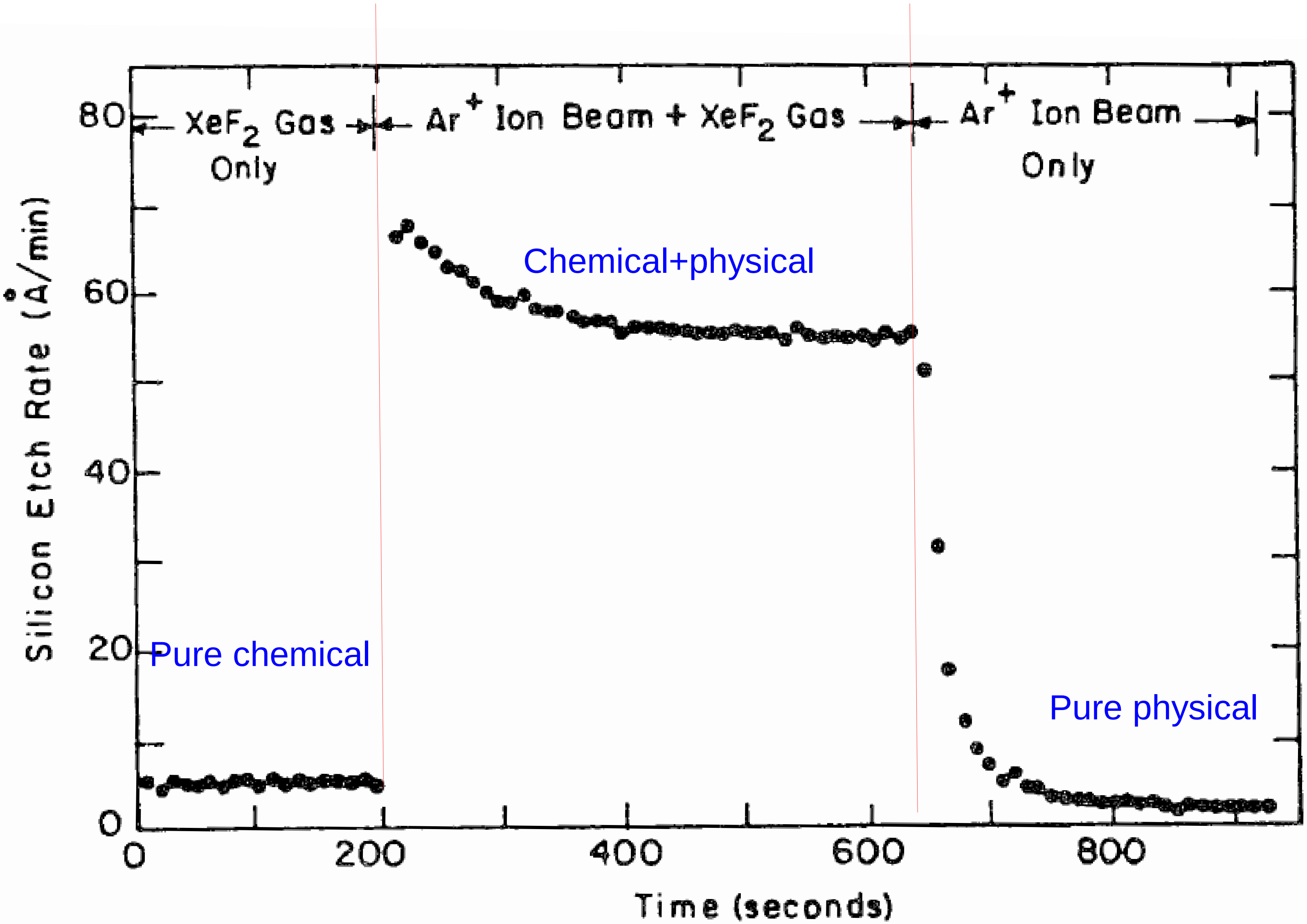
Example:
CF_4 is not active on Si but F is active

The desorption process of the chemical reaction is important otherwise the surface is passivated.

Ex : Al react with F → AlF_3 but vapor pressure AlF_3 1 torr even at 1000°C

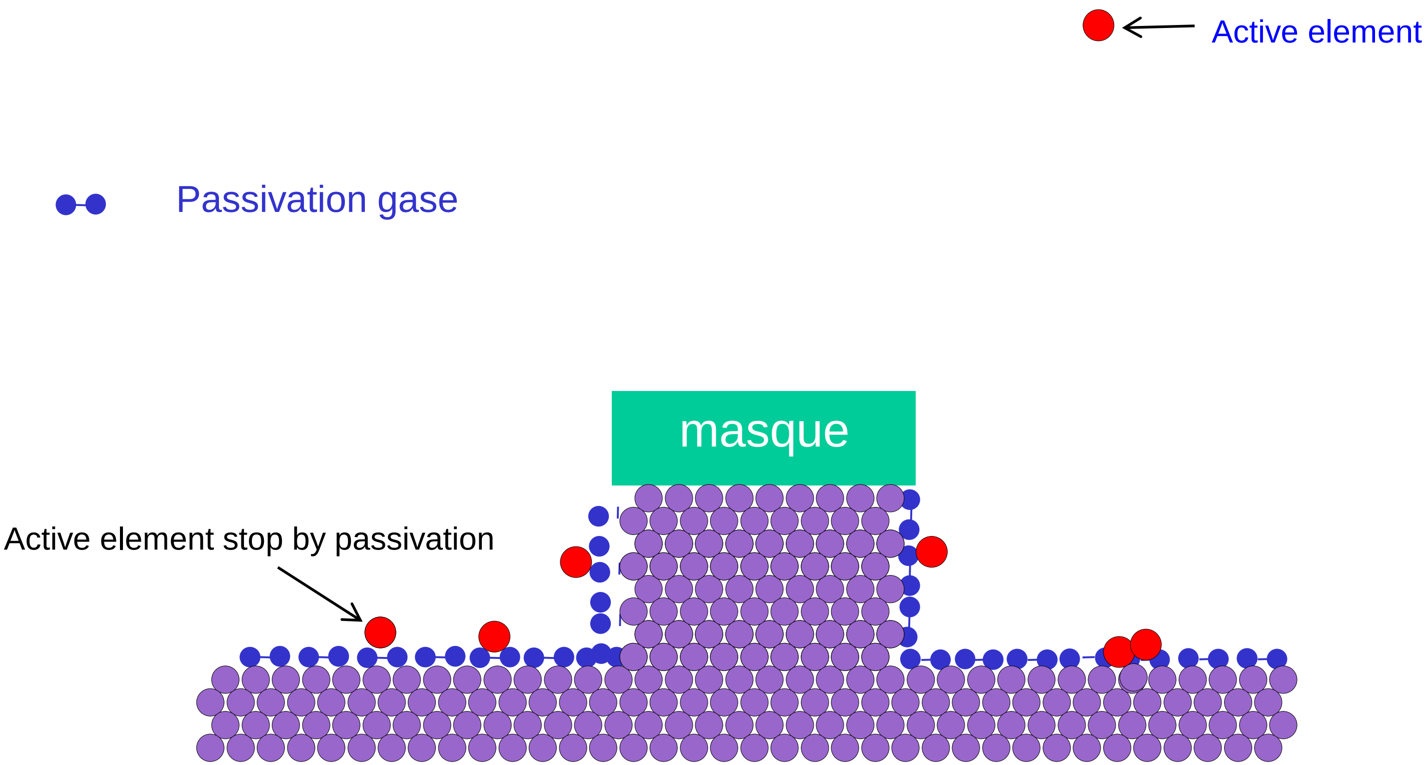
$Si + F \rightarrow SiF$ non volatile
$SiF + F \rightarrow SiF_2$ non volatile
$SiF_2 + F \rightarrow SiF_3$ non volatile
$SiF_3 + F \rightarrow SiF_4$ volatile

The chemical reaction are activated by electrons and ions bombardment creating active sites.



80
60
40
20
0
Silicon Etch Rate (Å/min)
XeF2 Gas Only
Ar+ Ion Beam + XeF2 Gas
Ar+ Ion Beam Only
Chemical+physical
Pure chemical
Pure physical
0
200
400
600
800
Time (seconds)

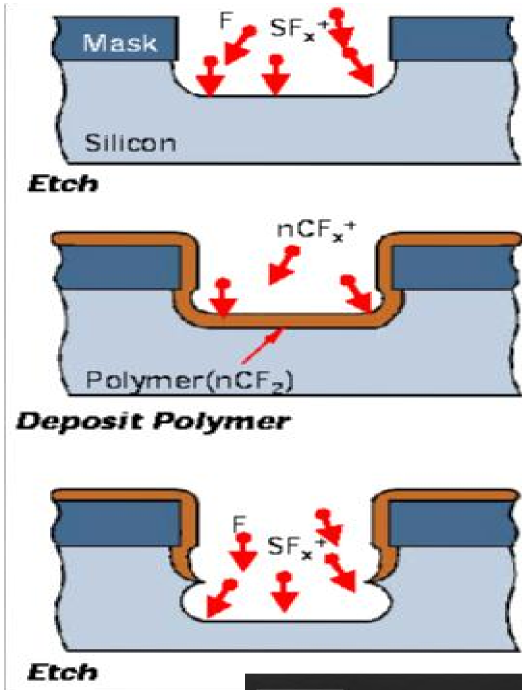
Anisotropy

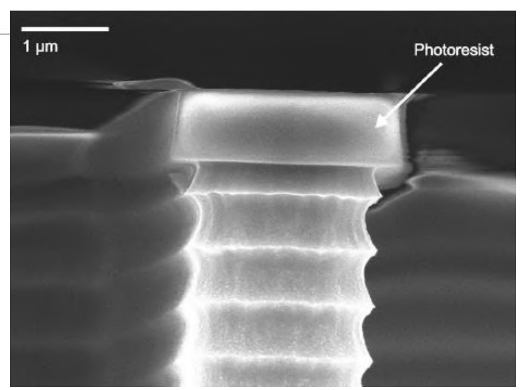


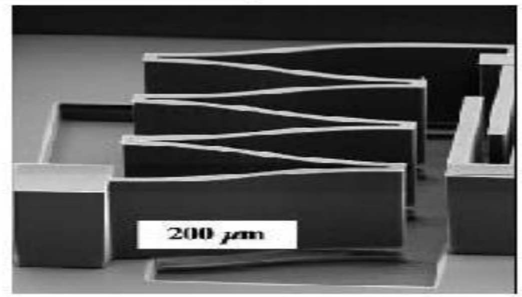
The edge which are less bombarded are protected

Bosch

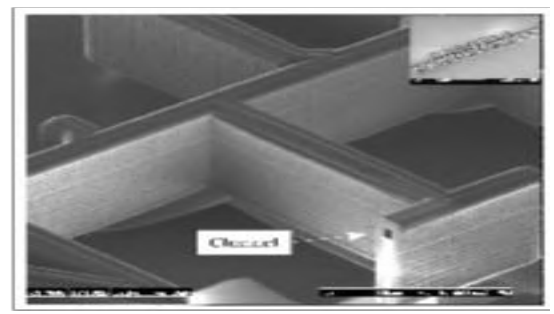
MEMS application

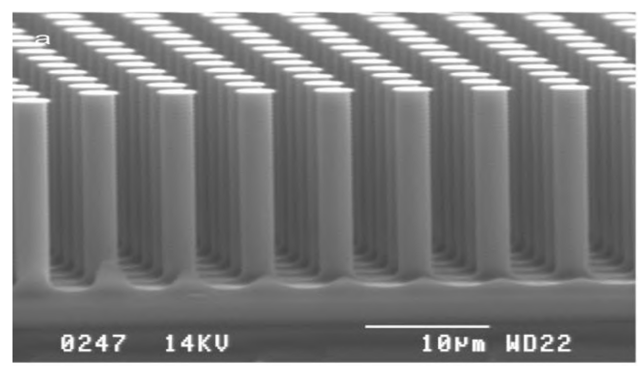






Spring - Klaassen, *et al*, 1995

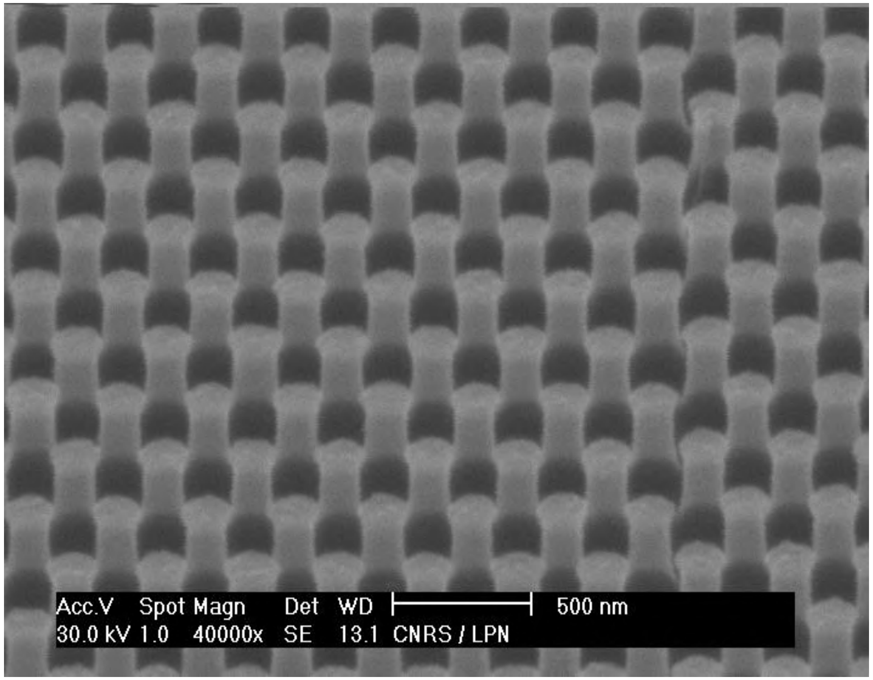




(Collège de France-LPN-ESIEE)

RIE Pros

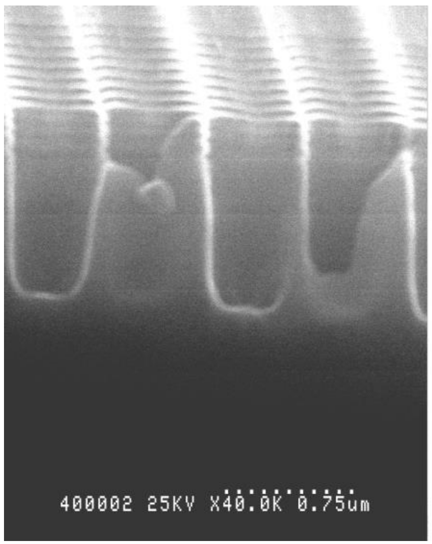
- Easy to handle
- High rate
- Selectivity
- Anisotropy
- No redeposition



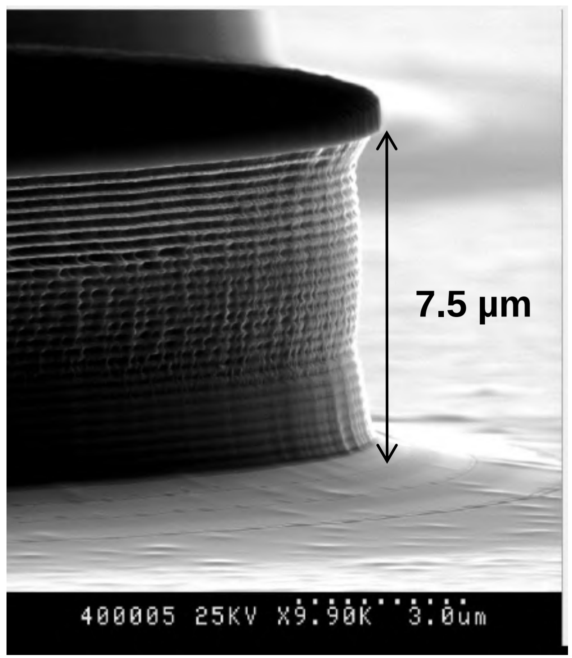
RIE Cons

- Sensitive to pollution drift in etch rate
- Plasma density quite small 10^{10} cm^{-3}
- Energy and pressure are linked difficult to separate physic to chemistry

Examples RIE



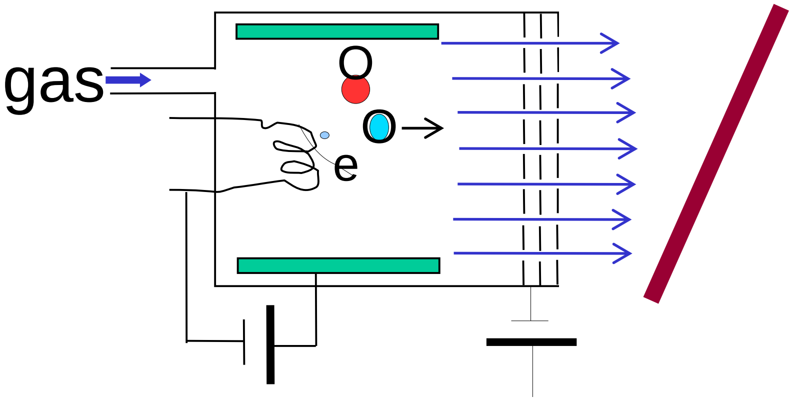
depth 1.2µm
diameter0.4µm

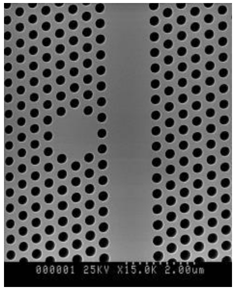


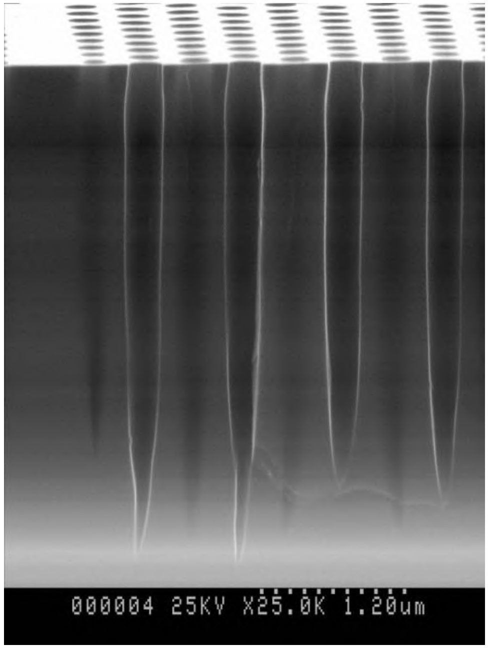
1,94µm x 6,25µm

AlAs/GaAs micropillar

Reactive Ion Beam Ething:RIBE

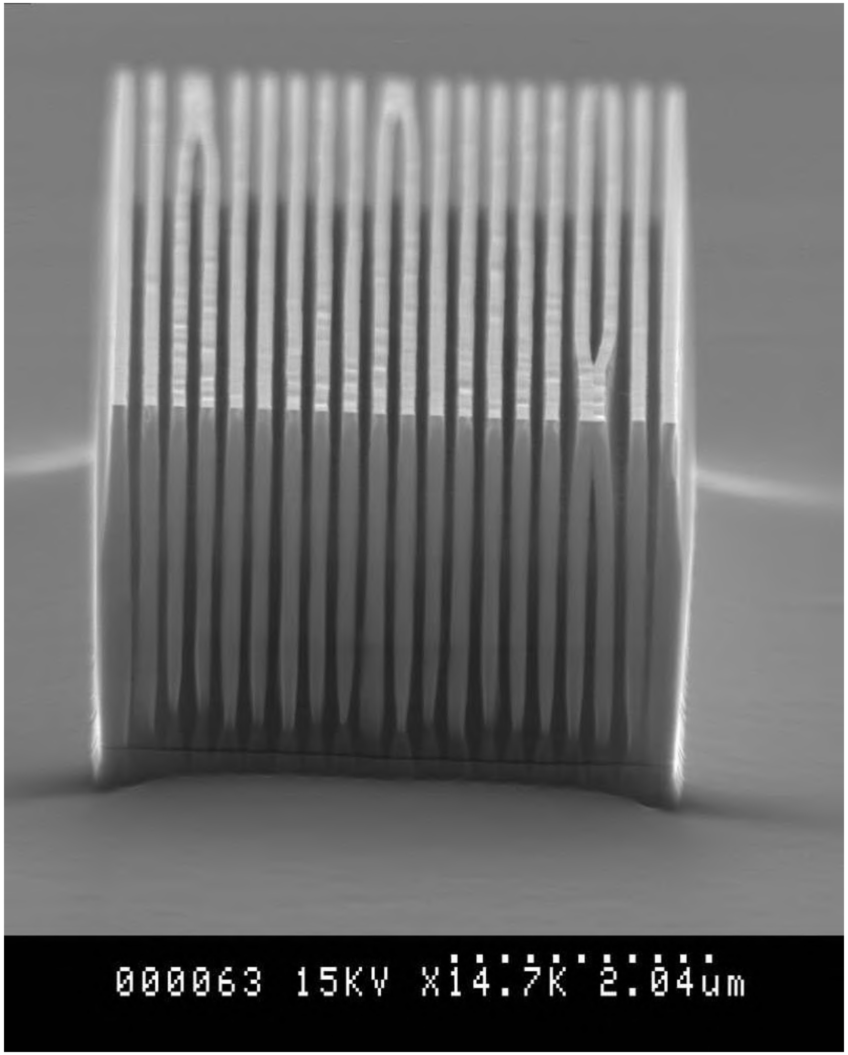






- ➢Idem IBE but with chemical ions instead of Argon
- ➢Complete separation between energy and chemistry
- ➢Give impressive aspect ratio
- ➢Quite high voltage → defects
- ➢Needs plasma electron source (filament burn)

Example RIBE

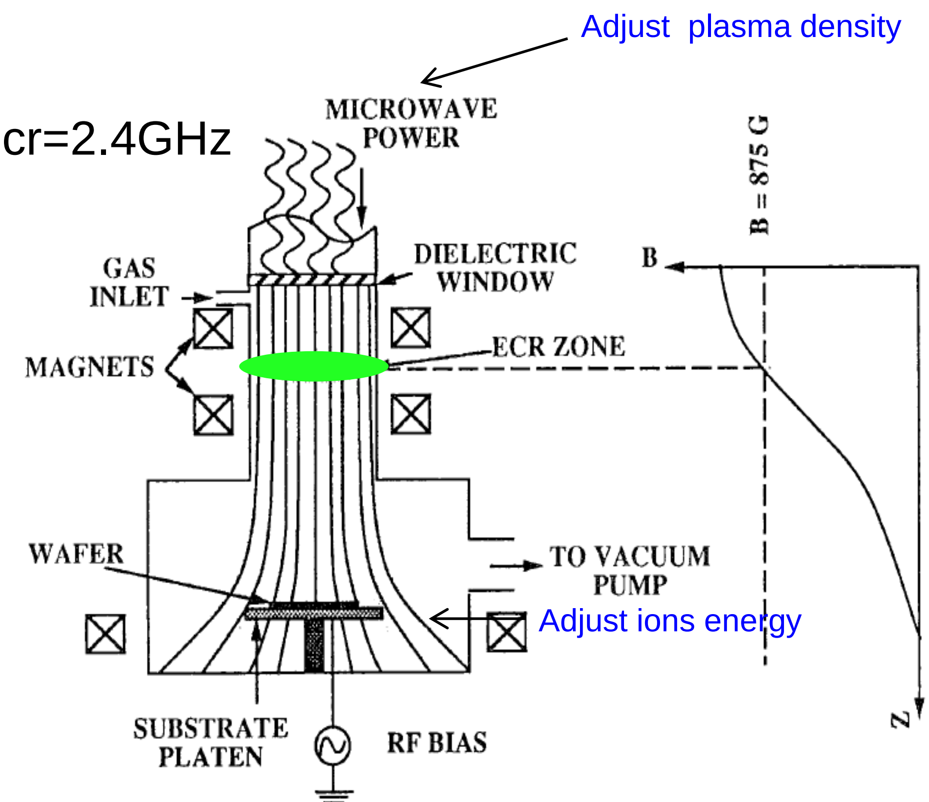


Electron Cyclotron Resonance

Very dense plasma (high rate) at low energy (less defects)

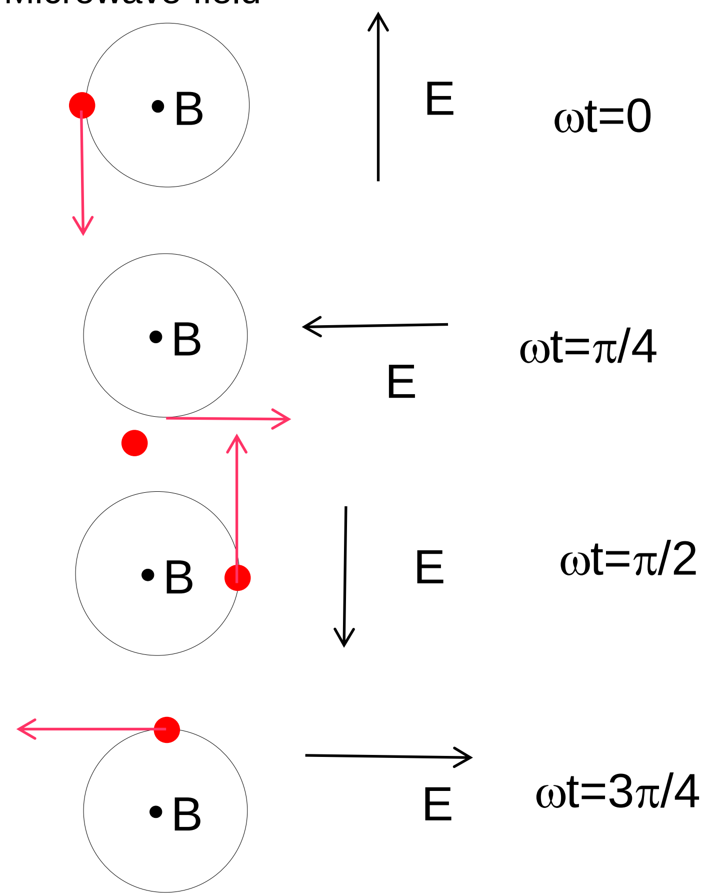
Independent control energy/density of ions

fecr=2.4GHz



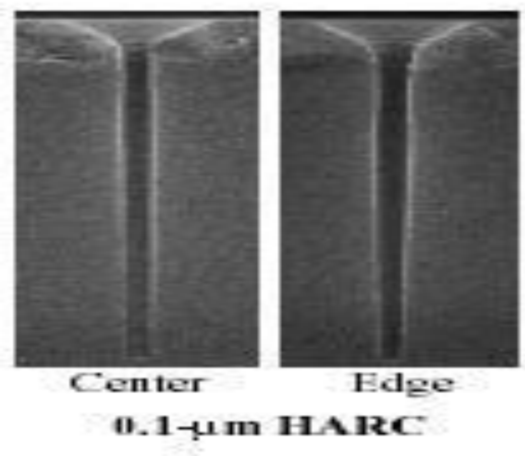
There is a space slab where
cyclotron and microwave are in phase

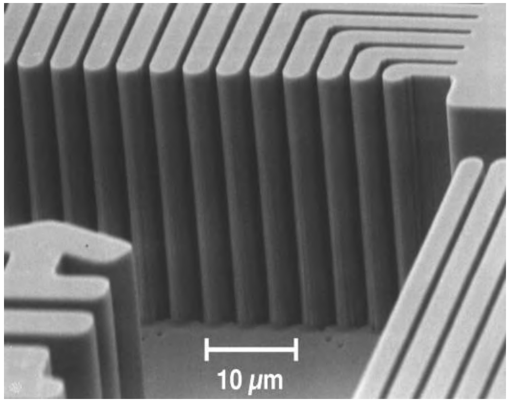
ECR : cyclotron 2π f = eB/m in phase with
Microwave field

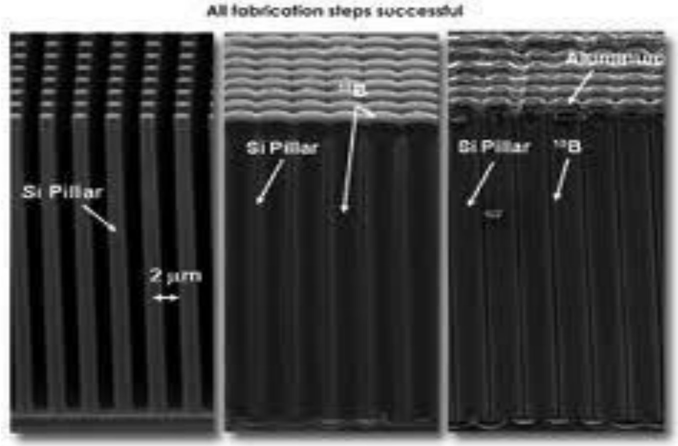


Plasma density $10^{13}cm^{-3}$

Example ECR etching

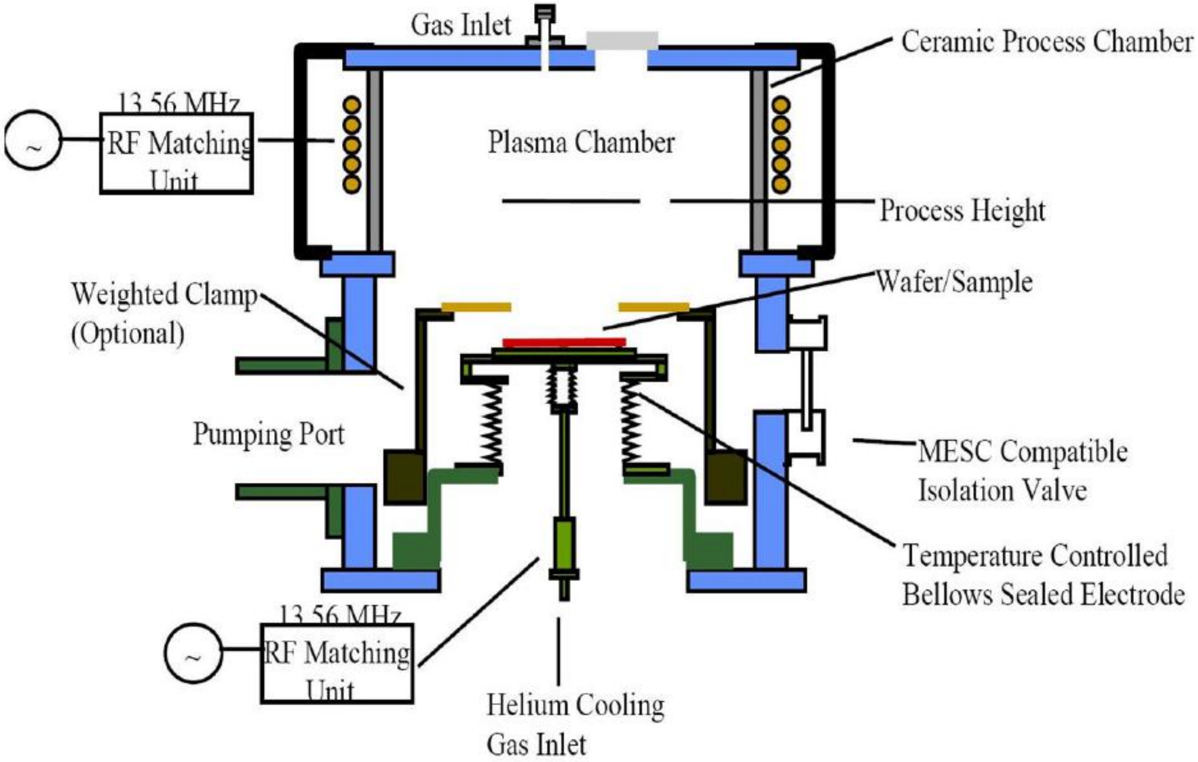


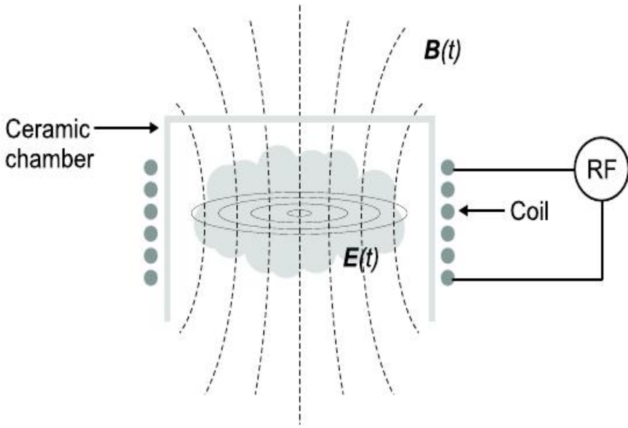




ICP : inductively Coupled Plasma

The plasma is create by a oscillating magnetic field





The oscillating magnetic field create an electric field :cf Maxwell $\overrightarrow{\mathrm{rot}}\vec{\mathrm{E}} = \frac{-\partial \mathrm{B}}{\partial \mathrm{t}}$

The plasma is better confined than with condensator plate

A voltage applied on the substrate holder allows to control the energy of the impining ions

density10^{12}cm^{-3}