Nanofabrication Techniques

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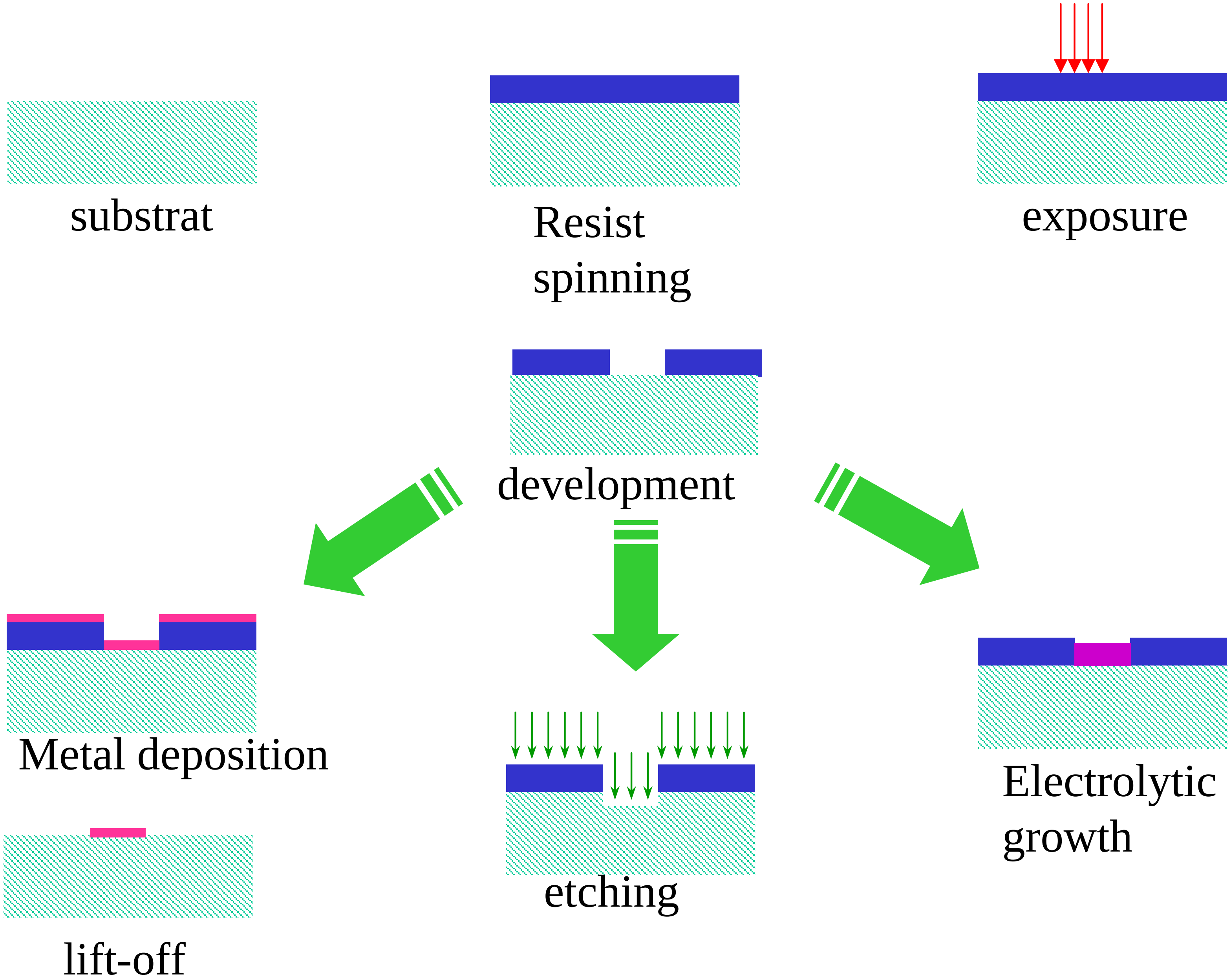
Marcoussis

Summary

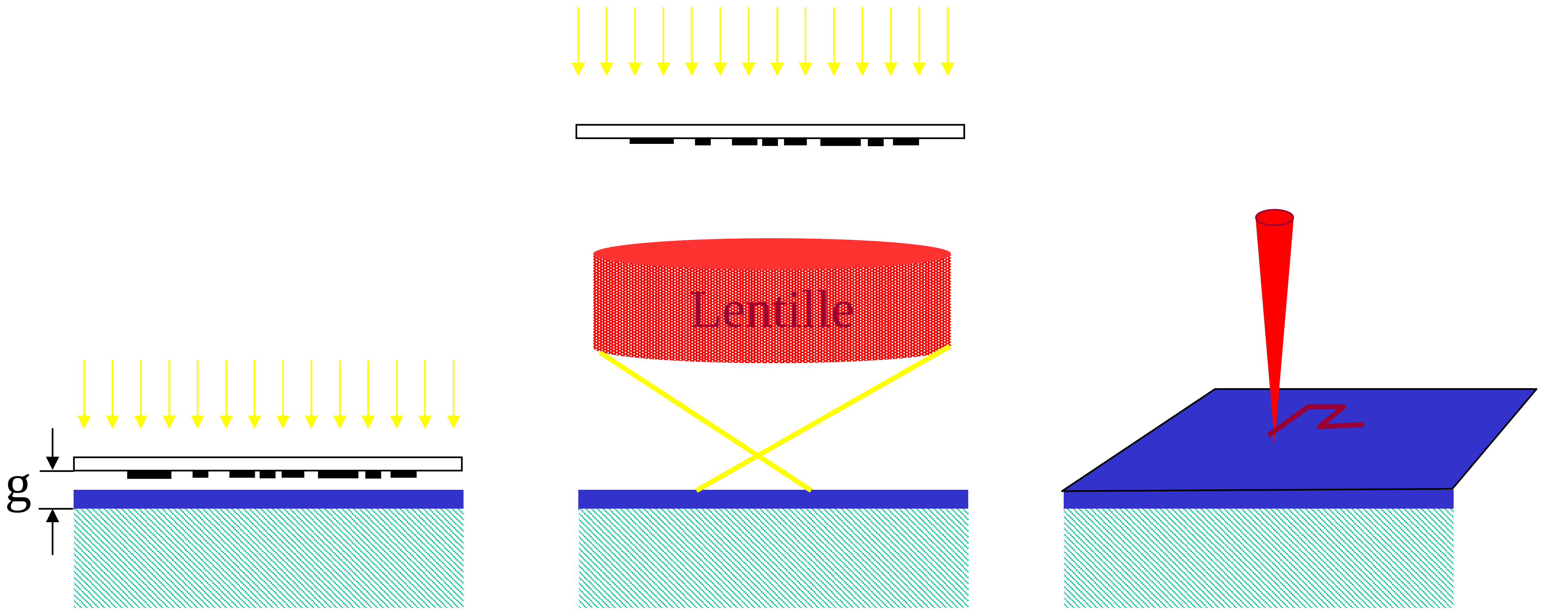
- Introduction
- Optical Lithography
- X-ray lithography
- E-beam Lithography
- Ion beam Lithography
- Near field Lithography
- Soft and Imprint Lithography
- Transfert techniques

Typical Flowchart for fabrication



lithography

Crucial step which will fix the size of the pattern

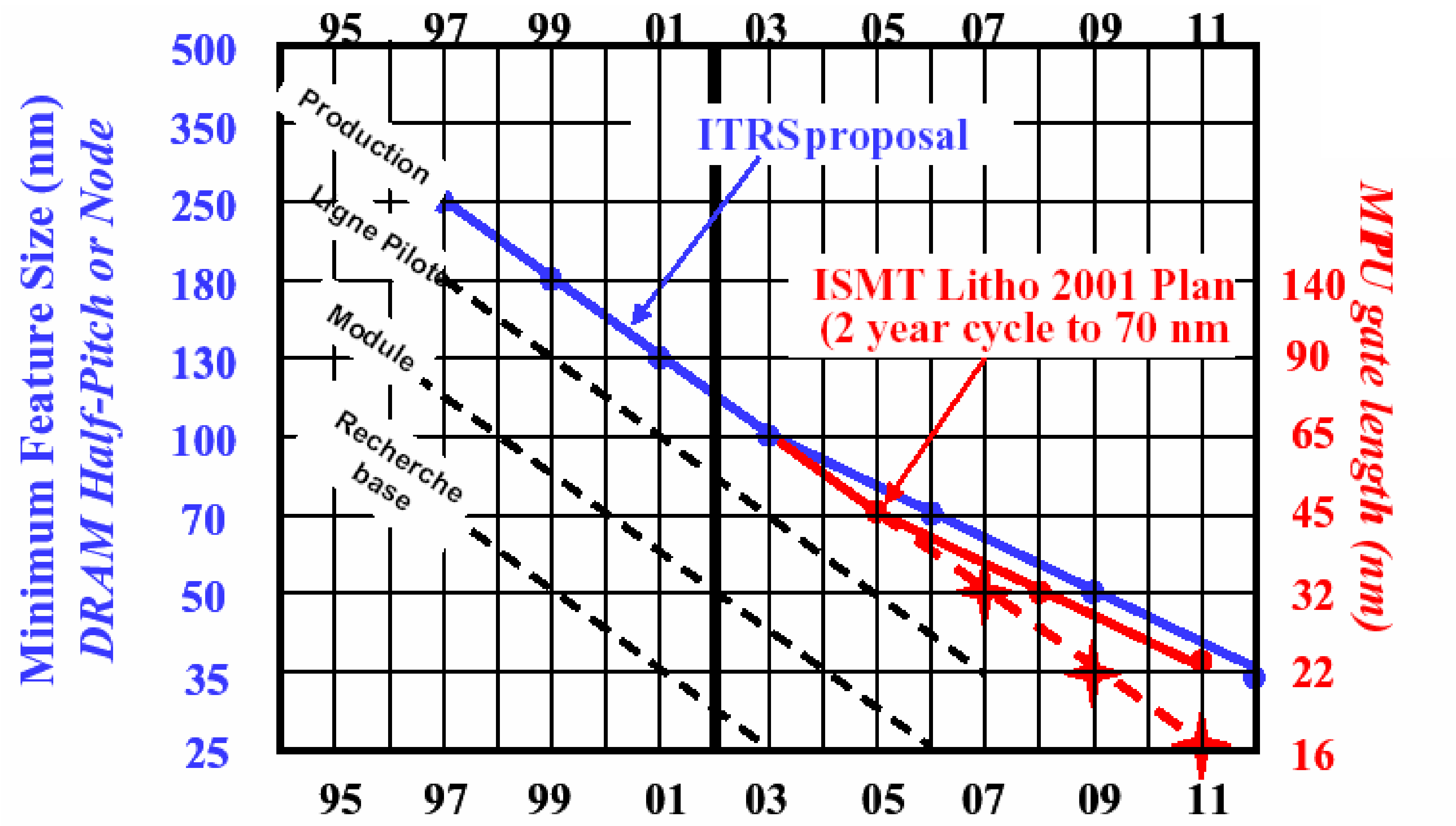


contact
1:1

projection
1:5 à 1:20

Focused beam writing

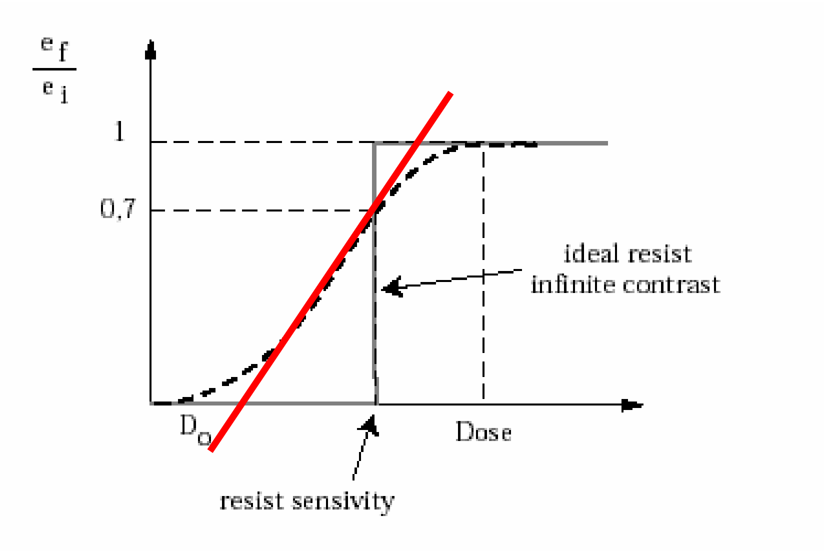
Moore Law



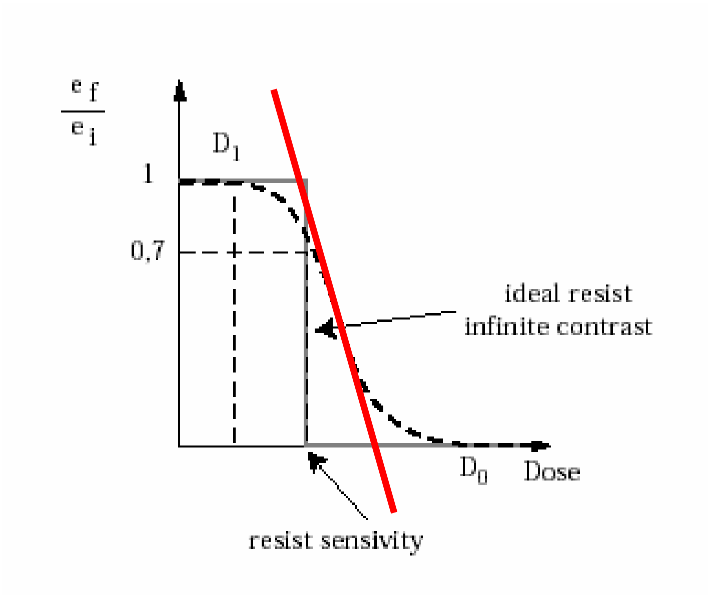
Minimum Feature Size (nm)
DRAM Half-Pitch or Node
MPU gate length (nm)
95
97
99
01
03
05
07
09
11
500
350
250
180
130
100
70
50
35
25
140
90
65
45
32
22
16
Production
Ligne Pilote
Module
Recherche base
ITRSproposal
ISMT Litho 2001 Plan
(2 year cycle to 70 nm

Resist and contrast

Contrairely to photography one does not want any gray scale
The highest contrast is the best.

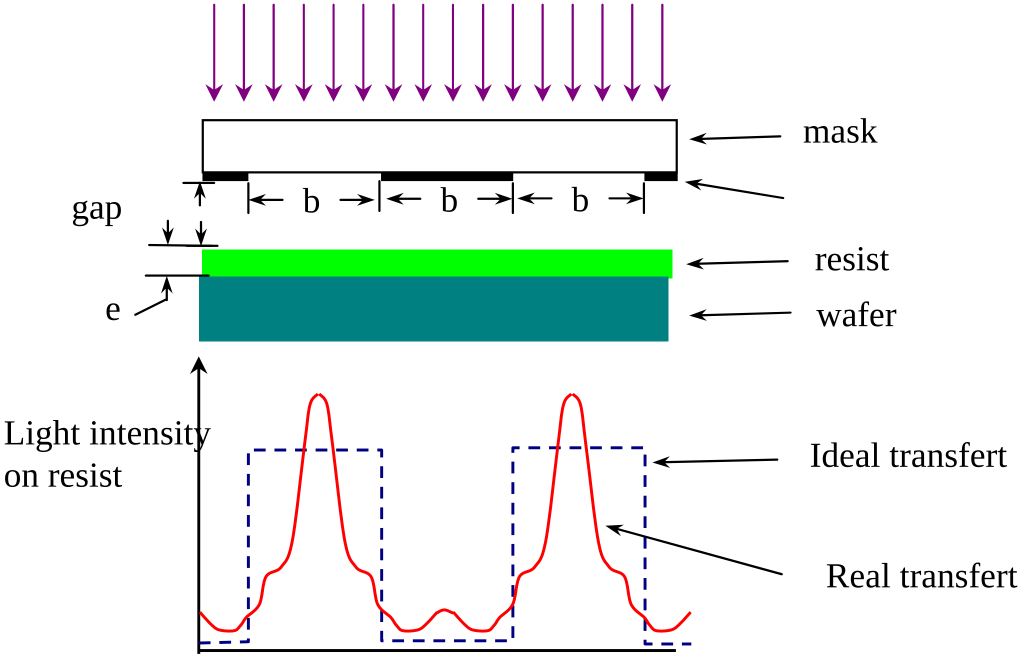


negative resist



positive resist

Optical lithography by contact or proximity



- resolution limited by diffraction:

$$t=\sqrt{\lambda g}$$

- gap minimum=resist thickness
- Substrats flatness
- Resist damage
- Mask damage
- mask1:1

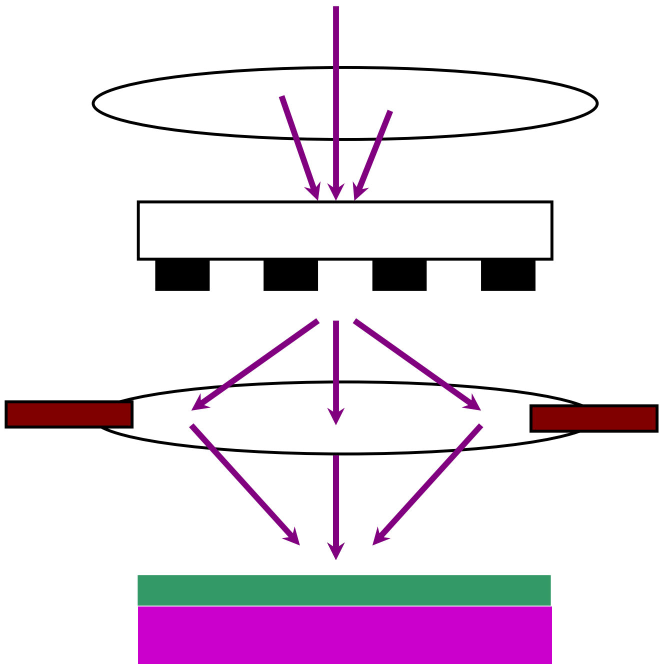
e.g. g=10µm, l=400nm t=10µm

Typically in a lab one can achieve 0.5µm and reach 0.2µm with conformal masks

λ >200nm for mask transparency

Simple and economical this is the popular lithographic tool for labs and R&D for intermediate resolution

Projection Lithography



1:5 to 1:20

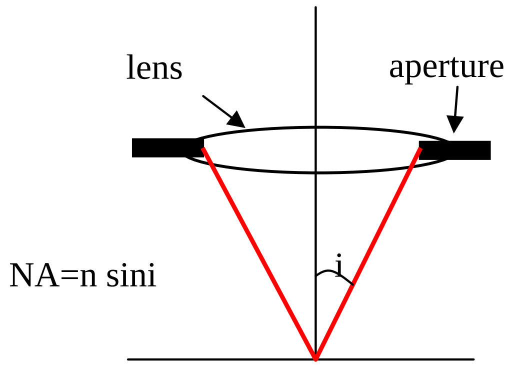
- Resolution limited by diffraction:

$$R = k\frac{\lambda}{N.A.}$$

N.A. numerical aperture

k technological parameter ⟶ process parameter

theoretical k=0.61 (Rayleigh criteria)



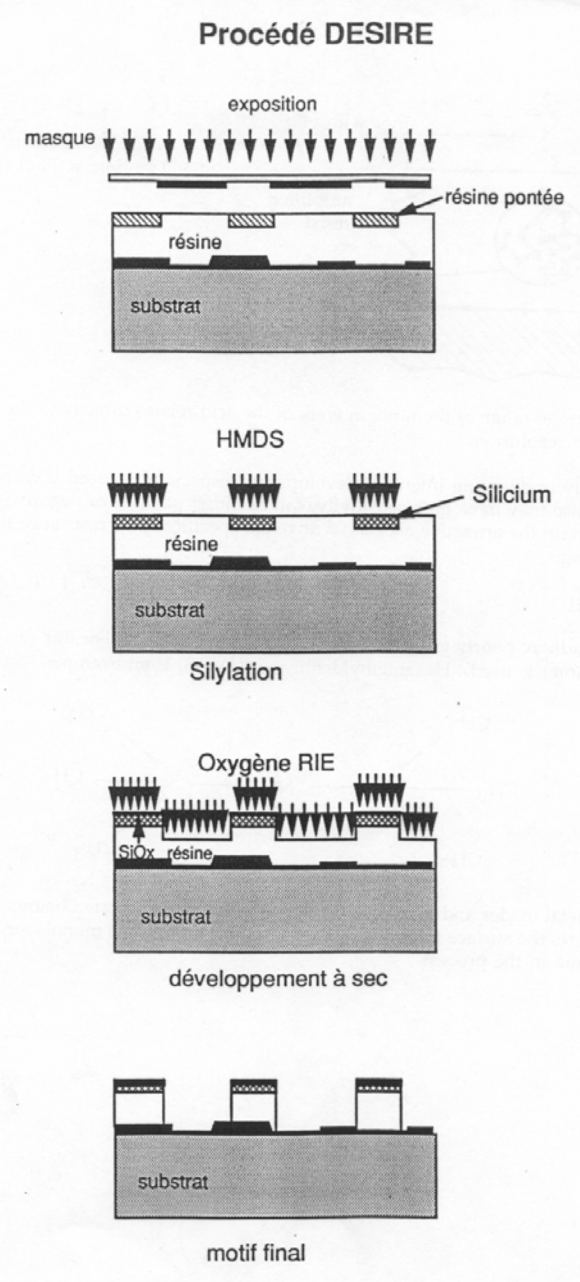
DOF$\propto$N.A.$^{-2}$

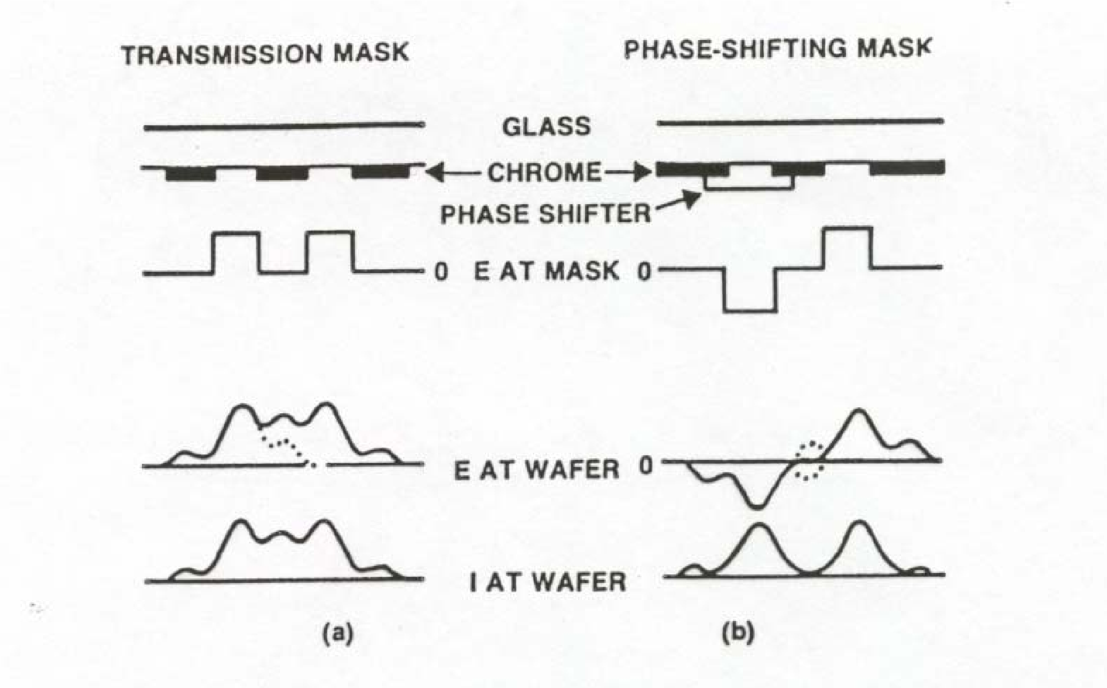
Evolution of projection lithography

Year	λ	N.A.	resolution	k
1980	436nm	0.28	1.25μm	0.8
1990	365nm	0.48	0.5μm	0.65
1995	248nm	0.5	0.3μm	O.6
1999	248nm	0.63	0.18μm	0.46
2003	193nm	0.6	0.090μm	0.49

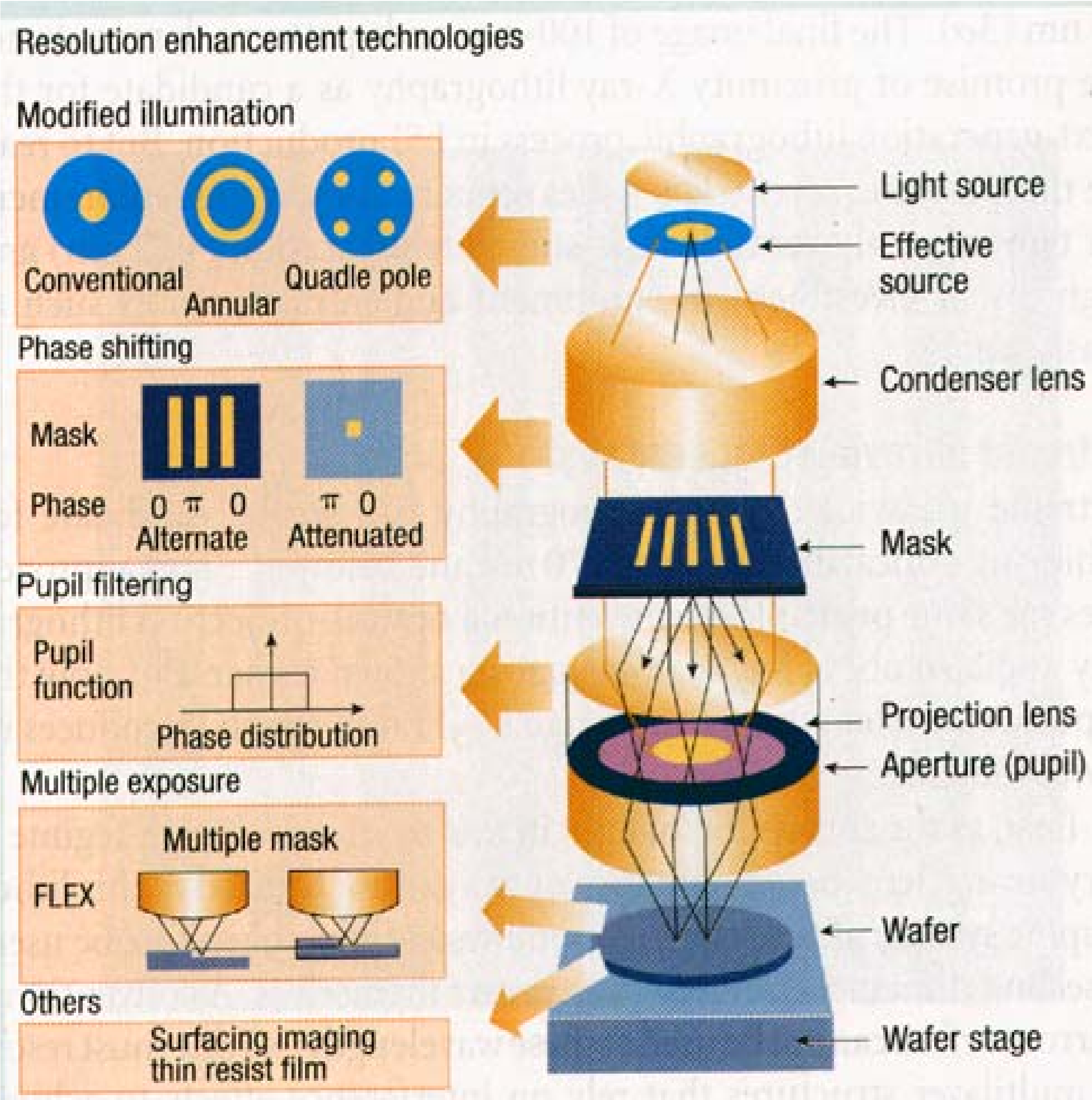
$k<k_{Rayleigh}$ top imaging technique and phase shift mask

Top imaging technique and phase shift mask





k : 0.61 ⟶ 0.4



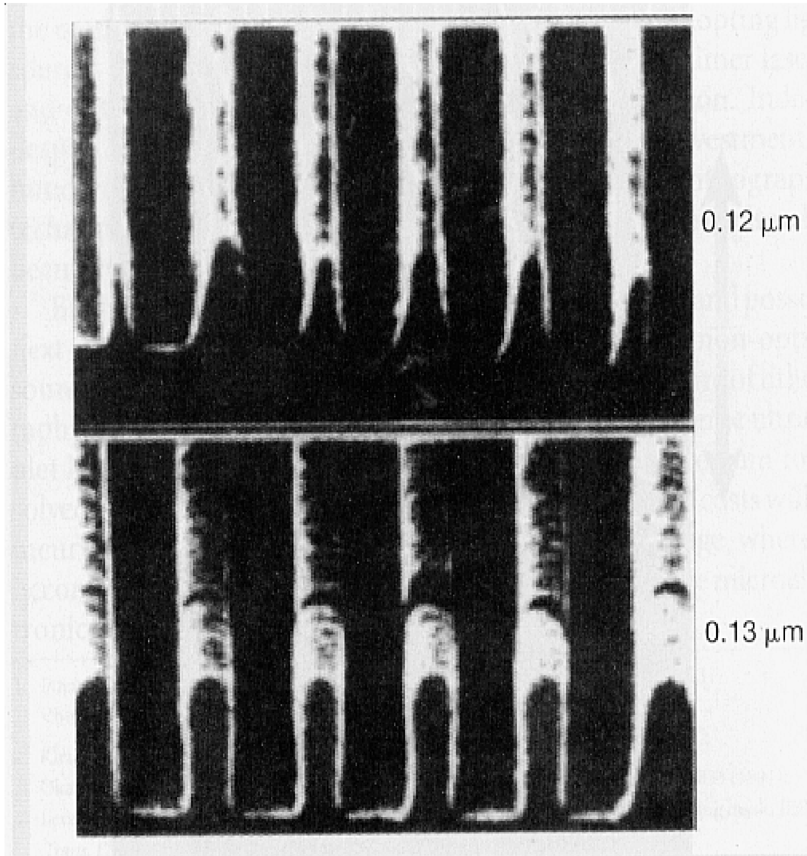
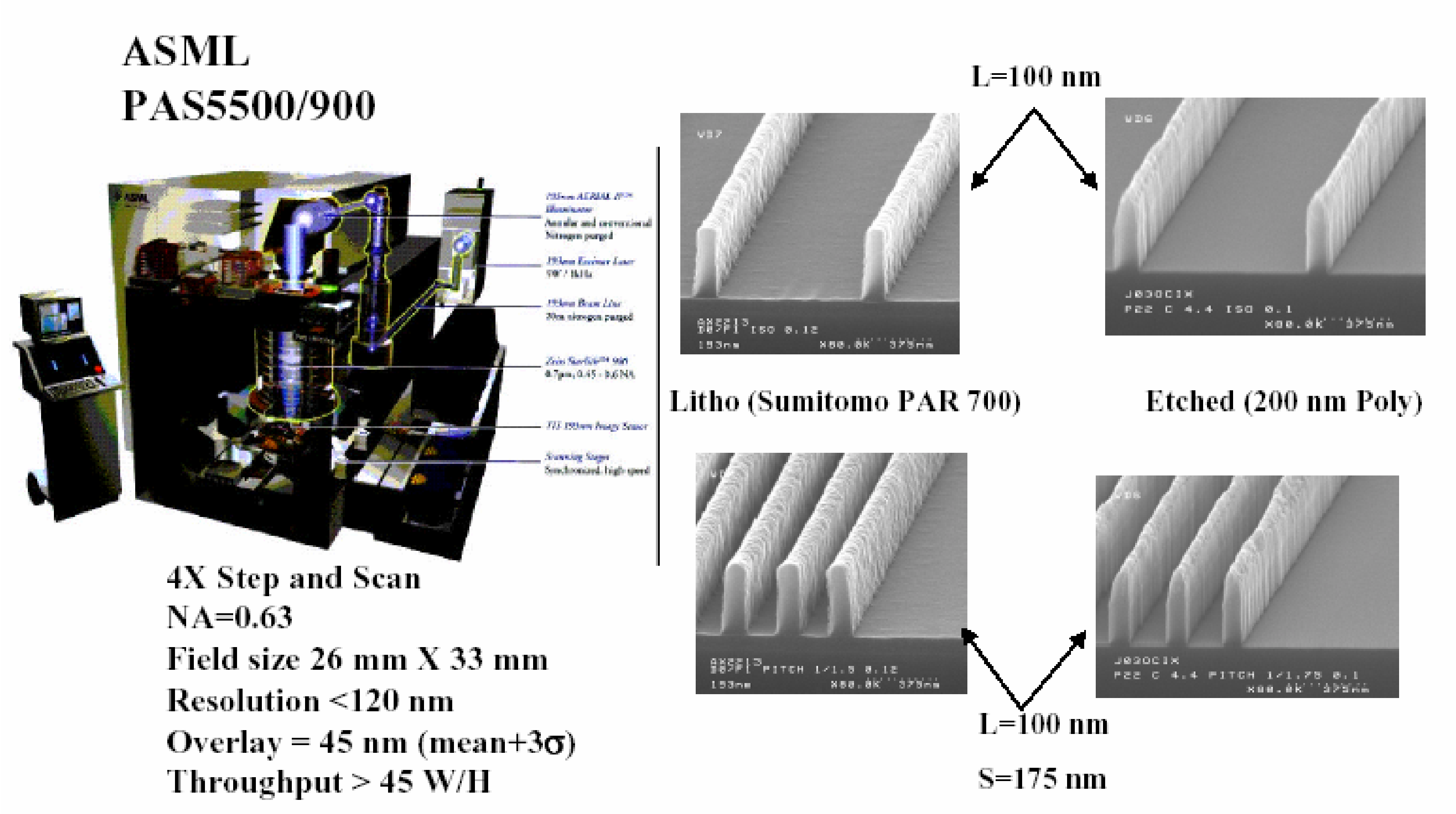


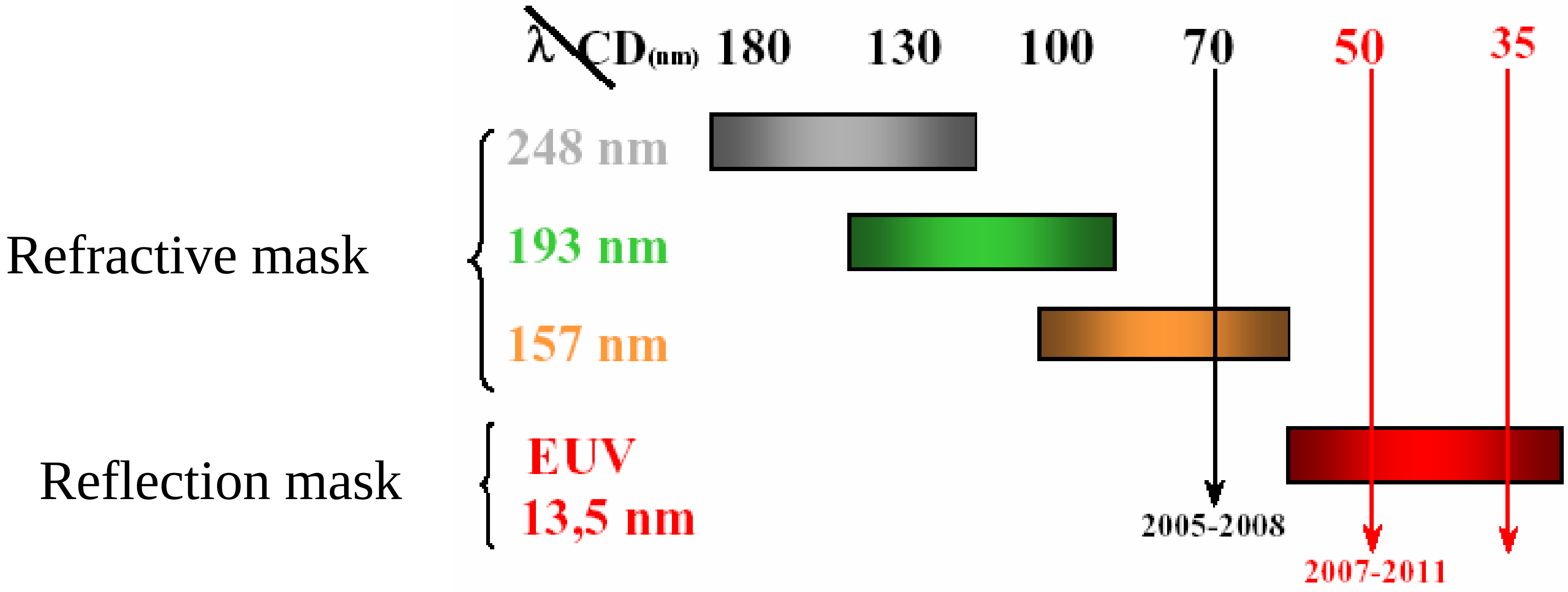
Figure 5 An example of resolution enhancement using phase-shifting technology. The exposure system uses a KrF excimer laser ($\lambda = 0.248$ μm; NA = 0.55; $\sigma = 0.3$) Structures having half the wavelength of the exposure light are clearly visible.

193nm lithography

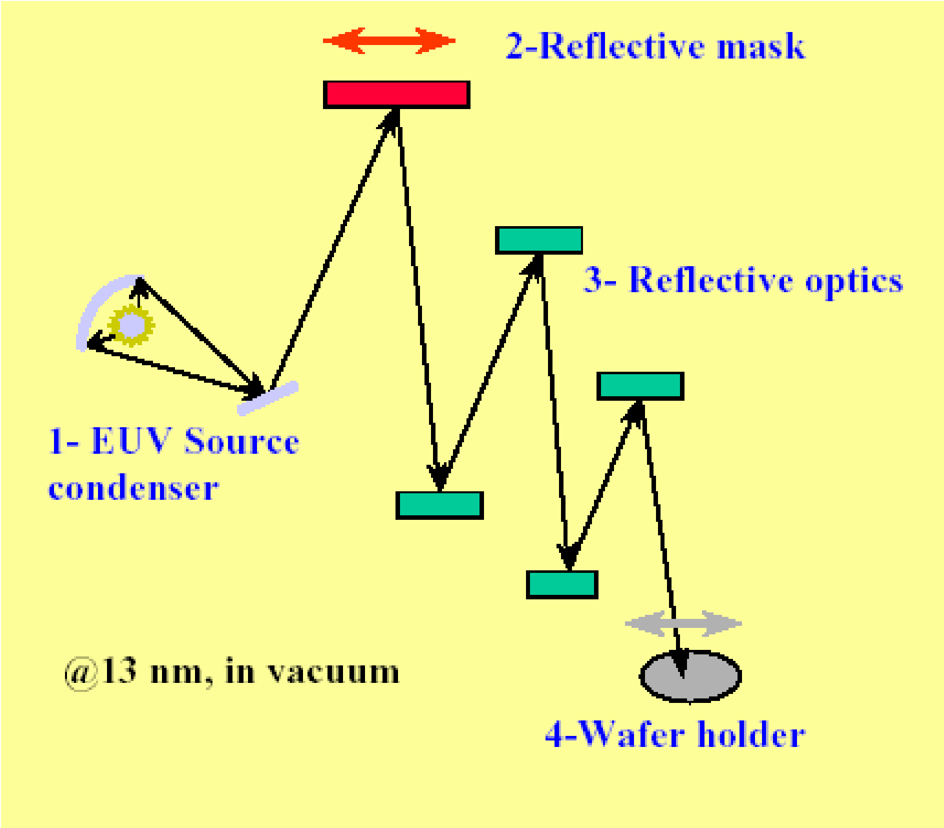


10M€!

« Photon for ever ? »



EUV Lithography



EUV are absorbed by all material and gases: need to be in vacuum

EUV reflective optics : requirements

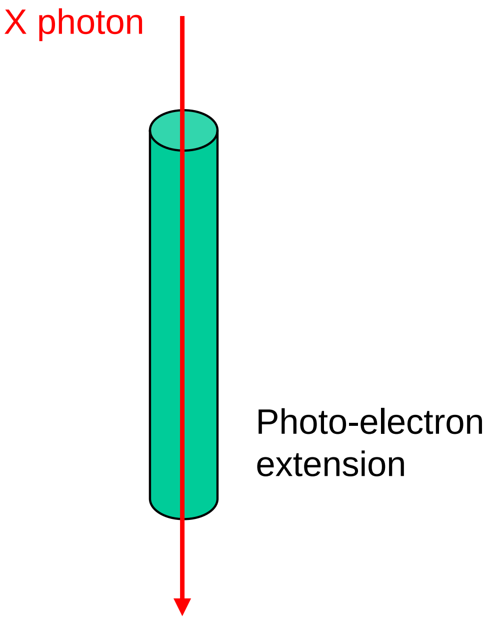
(For 70 nm CD)

- Aberrations
  - -> Surface figure : <0.2nm rms
- Flare (parasitic light => contrast loss))
  - -> Mid spatial frequency roughness : < 0.15nm rms
- Reflectivity loss
  - -> High spatial frequency roughness : < 0.10nm rms

- \+ Highest possible reflectivity
- \+ Aspherization
- \+ Graded multilayer thickness

At the moment the situation is not clear between 157nm/immersion lens and EUV

X-ray lithography



Choice of wave length:

- diffraction $t=(\lambda g)^{1/2}$
- mean free path of photo-electron: $l \propto \lambda^{-\alpha}$
- mask transparency
- absorber efficiency

$$0.8\text{nm} < \lambda < 1.6\text{nm}$$

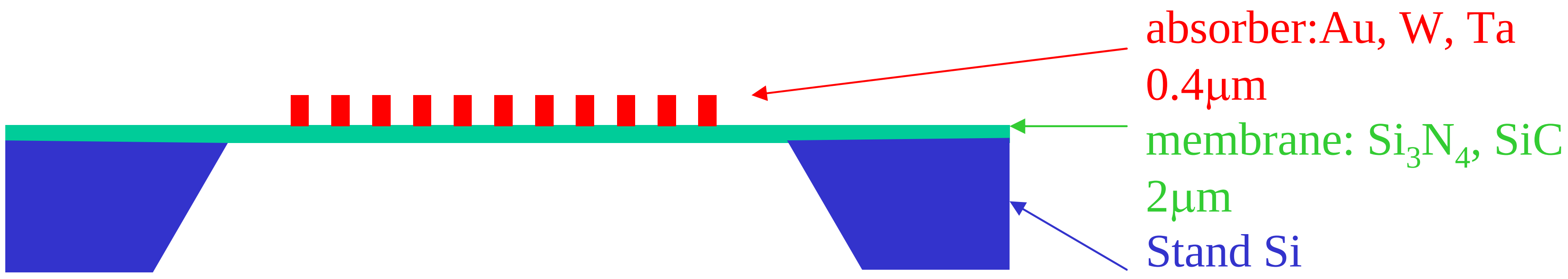
Not sensitive to dust particles
large process lattitude

diverging source → enlargment and shadow

Parallel source → synchrotron light

X-ray mask

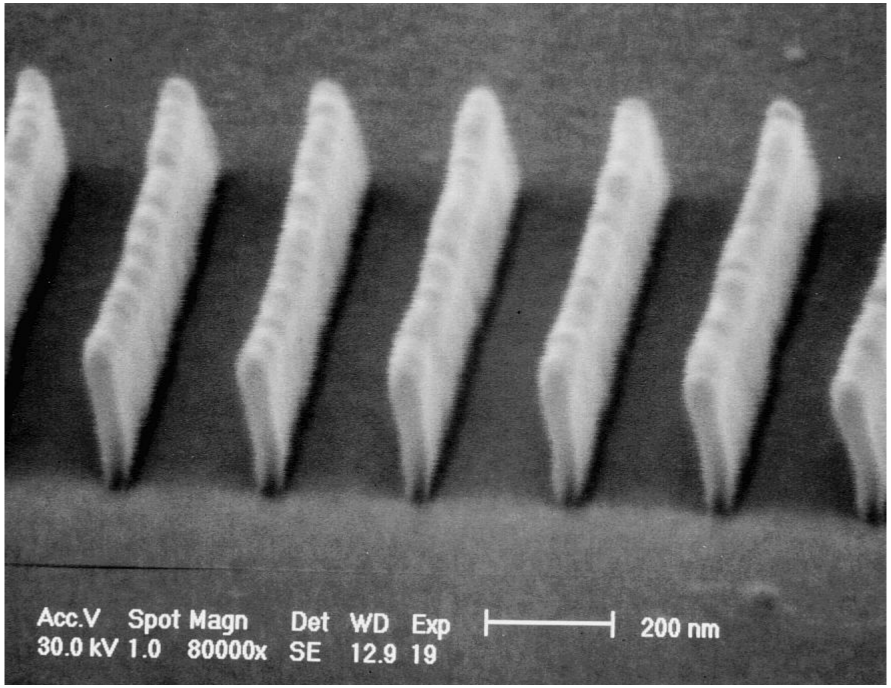
no X –ray optics ⟶ mask 1:1



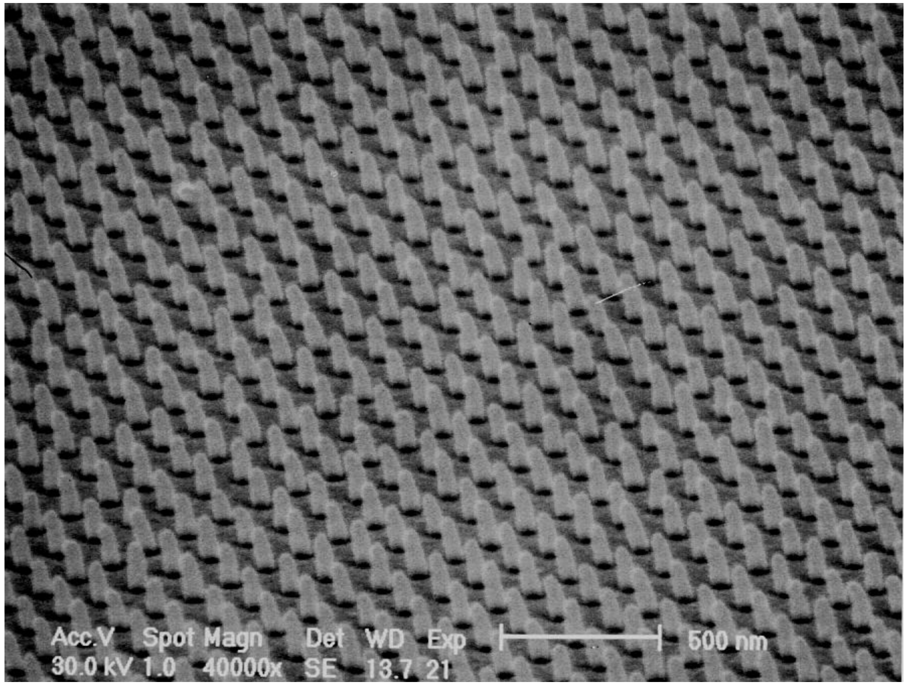
Need to control stress of membrane for flatness
No stress in absorber
Good mechanical stability

The major difficulty of X-ray lithography

Example of X-ray lithography



30 nm lines onPMMA

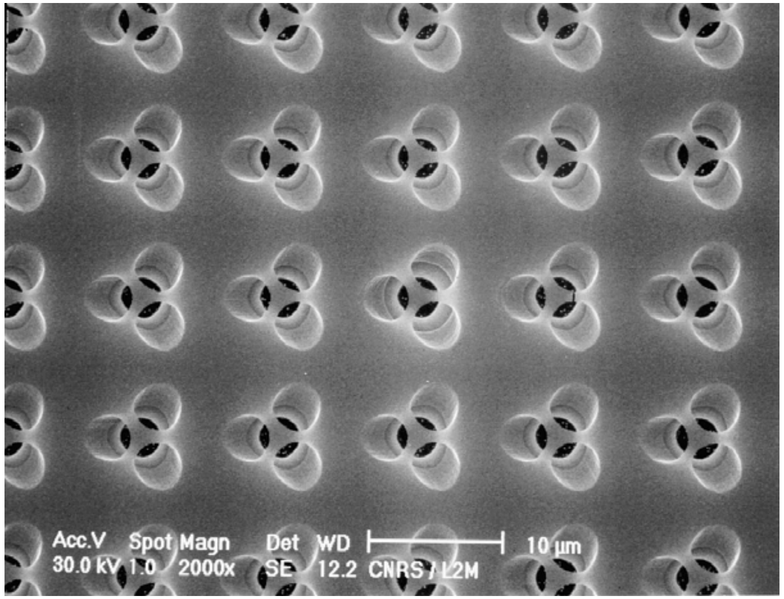


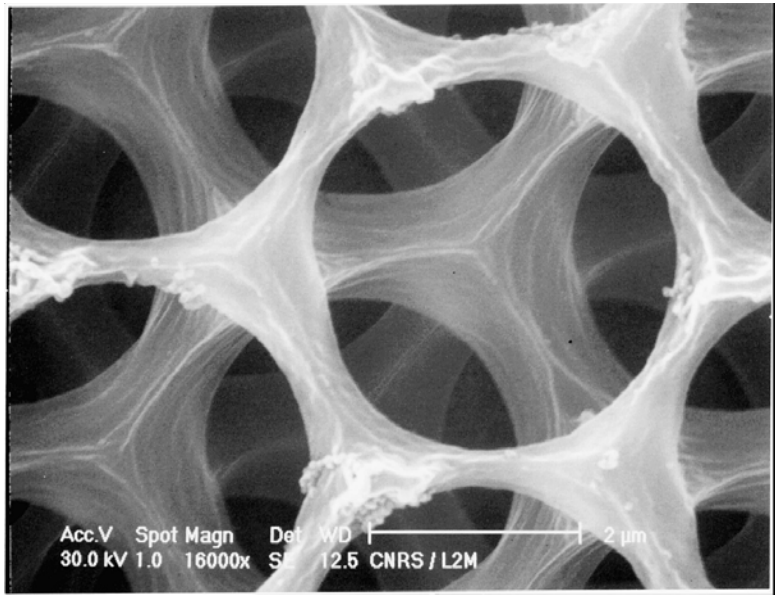
20 nm dots on PMMA

X-ray lithography versus EUV lithography ??????

3D X-ray lithography

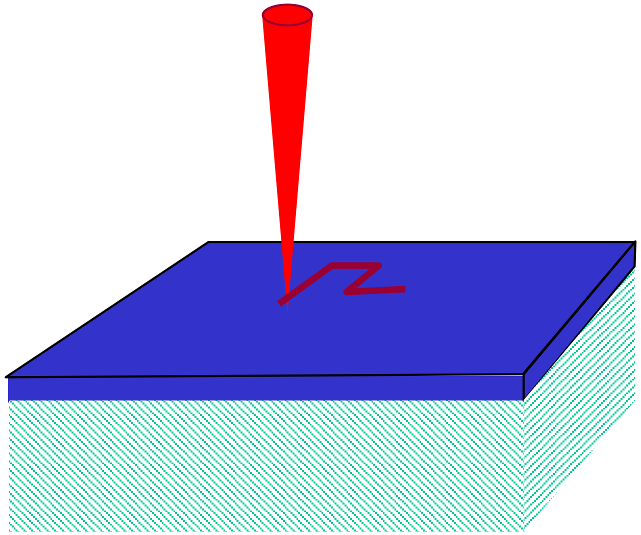
Multiple exposures with 3 different angles





Photonic crystal

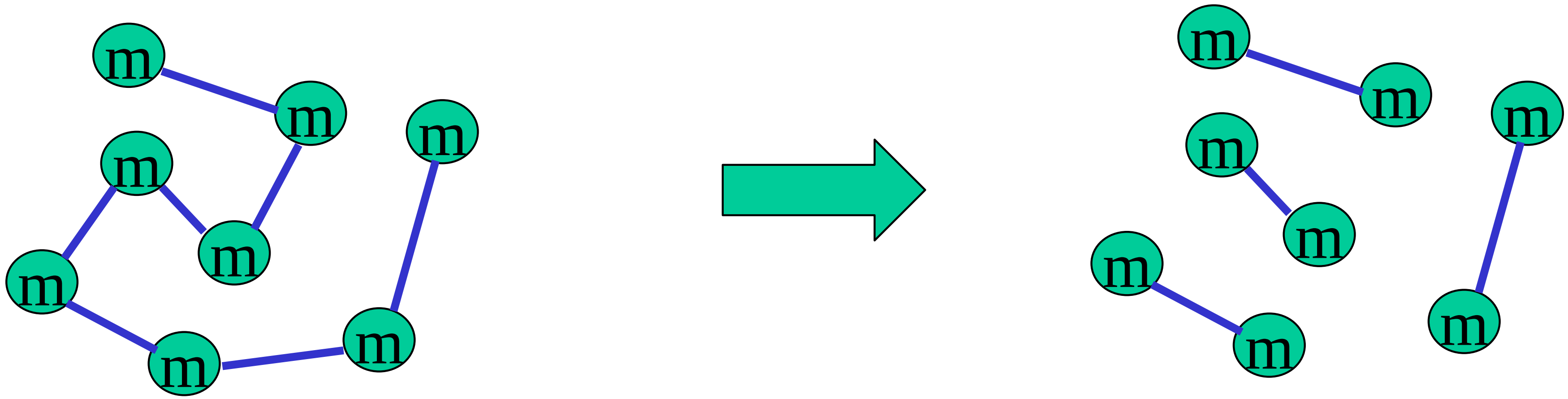
Electron beam lithography



- Since a long time one knows how to focus electrons beam spot < 10nm
- Very small wavelength: no diffraction limitation
- Direct writing: maskless
- sequential writing: small throughput
- resolution : depends on resist, one can reproduce the spot size i.e. 1nm

electron-resist interaction

organic resist (PMMA)



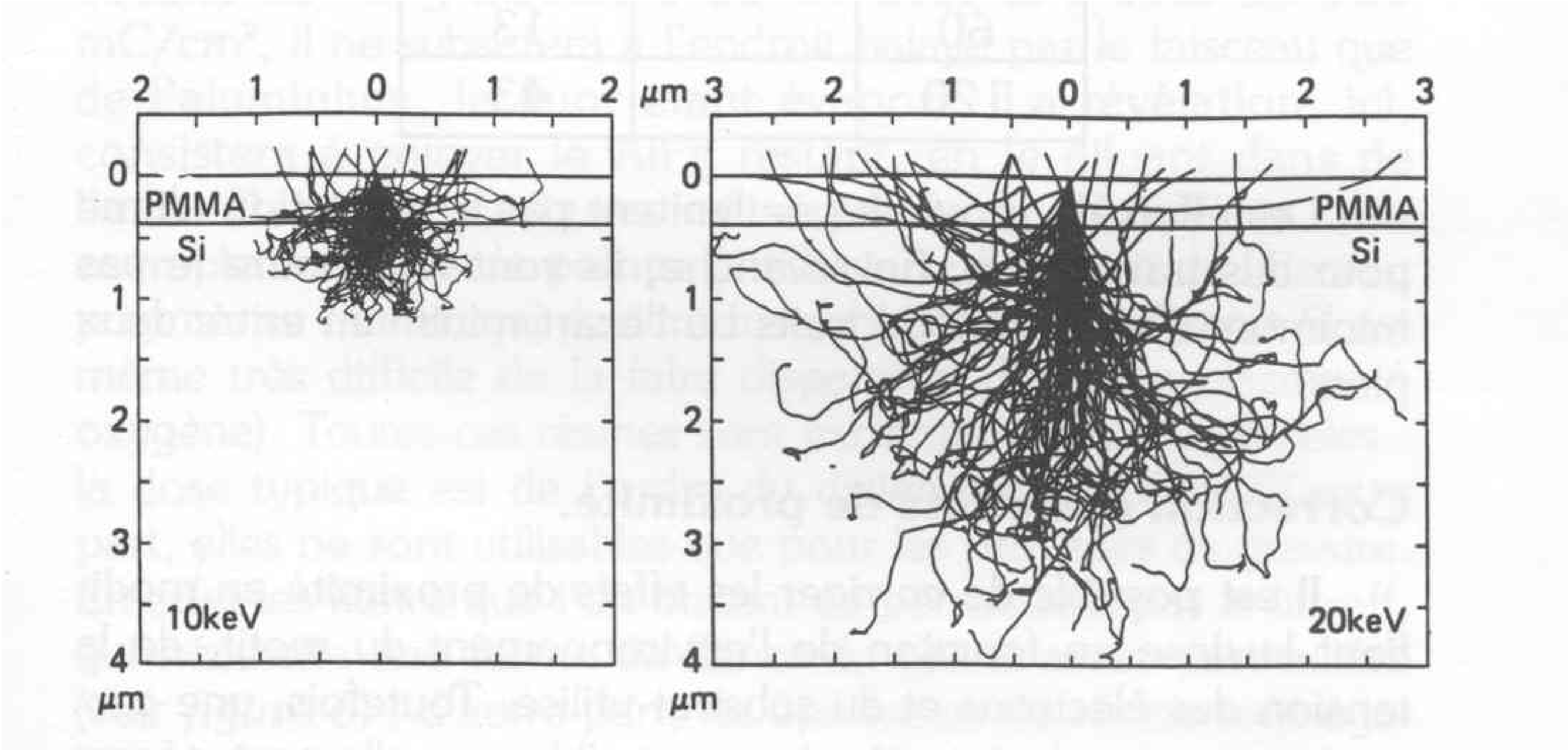
non soluble

soluble

Typical energy for breaking a bond: 10eV

Typical energy of the beam : several 10keV
(Problem of aberration at low energy)

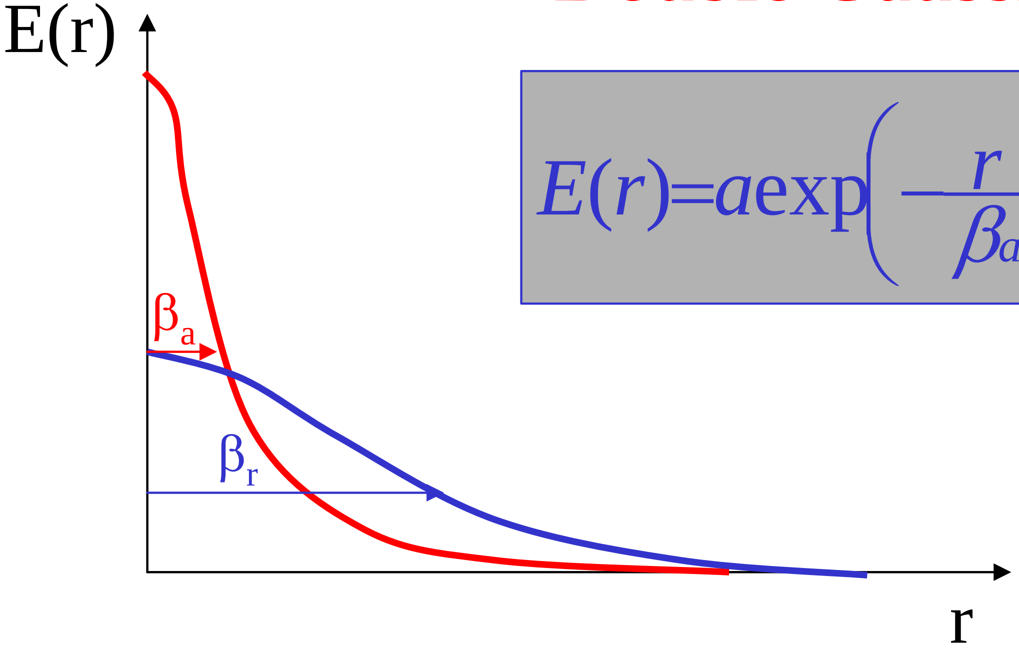
Monte Carlo Simulation to study energy lost



Forward scattering → Spreading of the beam , lost of resolution

Substrat backscattering → Energy far from the impact of the beam, proximity effects

Double Gaussian model



$$E(r)=a\exp\left(-\frac{r}{\beta_a}\right)^2+b\exp\left(-\frac{r}{\beta_b}\right)^2$$

Tension kV	β_a(µm)	β_r (µm)
20	0.08	2
50	0.04	9
60	-	13
120	-	43

Substrat Si

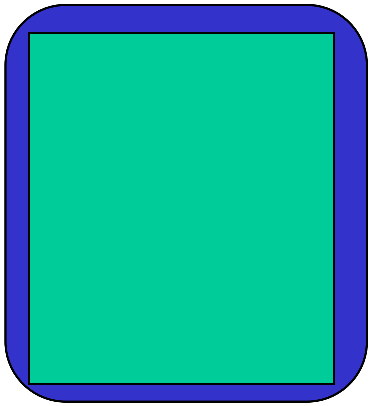
β_a forward scattering:
Essentially depends on the resist and the voltage

β_r backscattering:
Depends on the voltage and the substrat

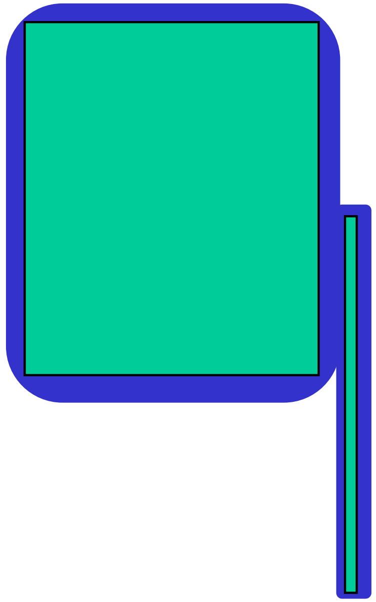
How to beat proximity effect

- Vary the dose depending on the pattern
- Use high energy: dilute proximity effect on a large area
- Use very small energy (STM) (but forward scattering)
- Use resist sensitive to high energy: inorganic resists
- Write on membranes

Proximity effects



Dose depends on the pattern
Intra proximity



Dose depends on the surrounding of the pattern

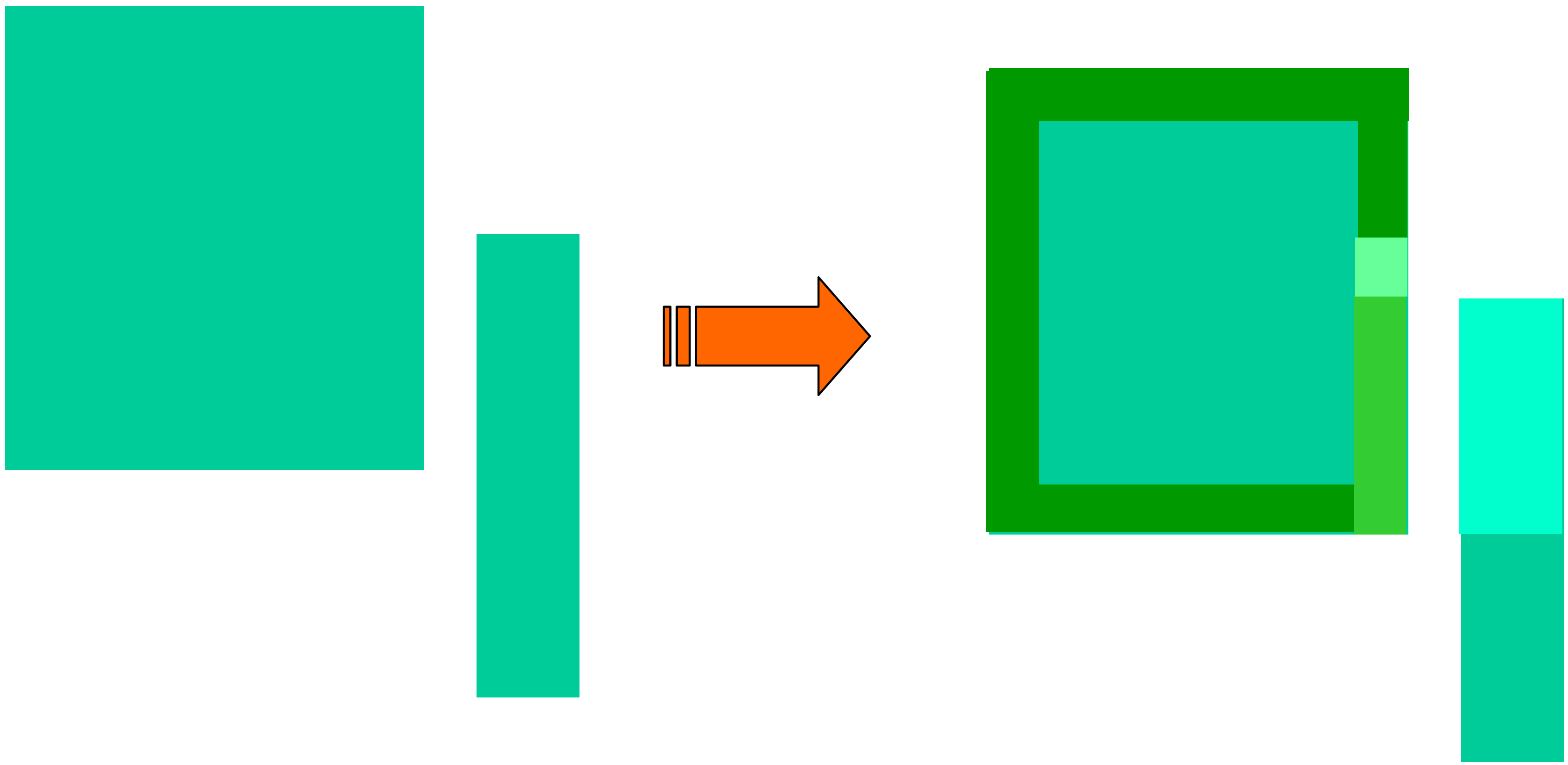
$$D=E(1+b)$$

Real dose

as exposed dose

proximity effect

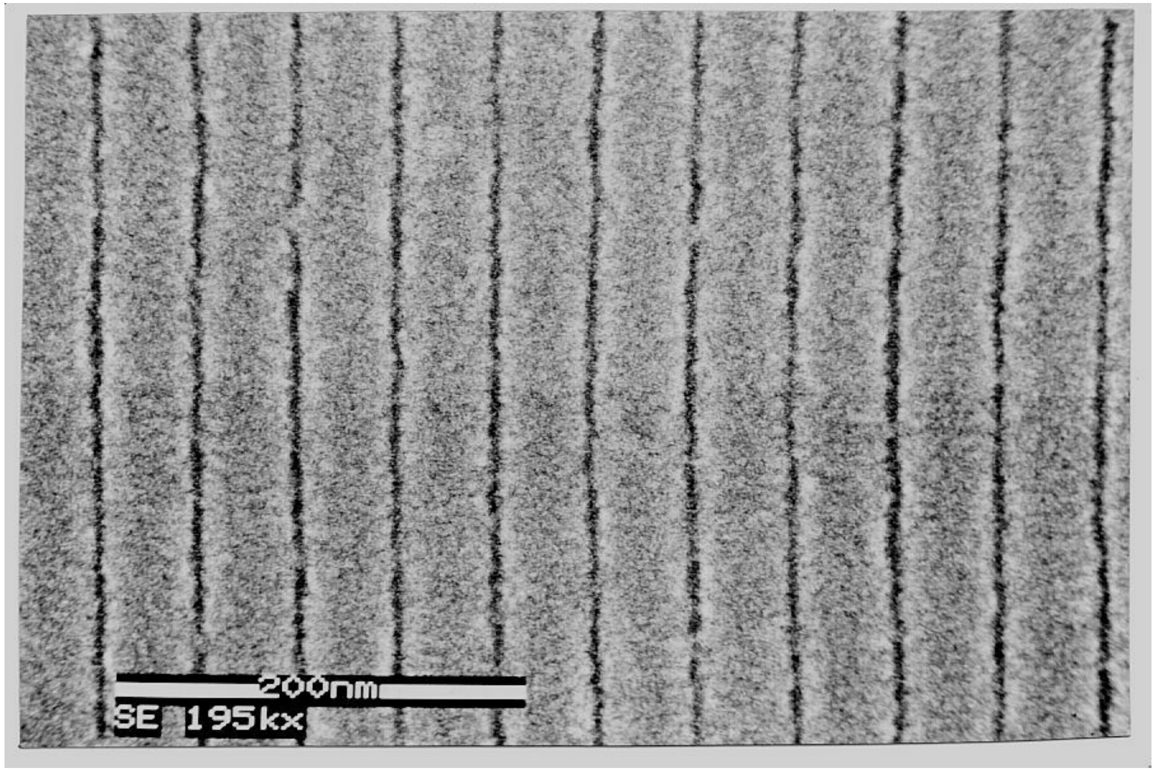
Software for proximity effect correction

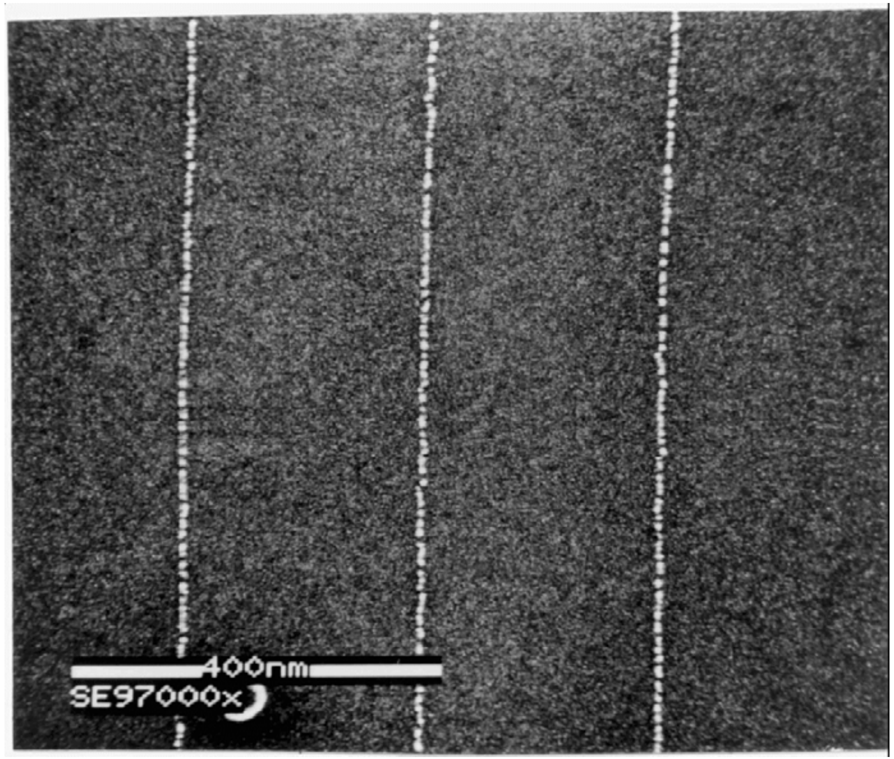


Commercial software exist (very expensive)
Correction may needs negative doses at some points!

It is very difficult to produce arrays of line with a very fine pitch

200kV e-beam lithography on PMMA

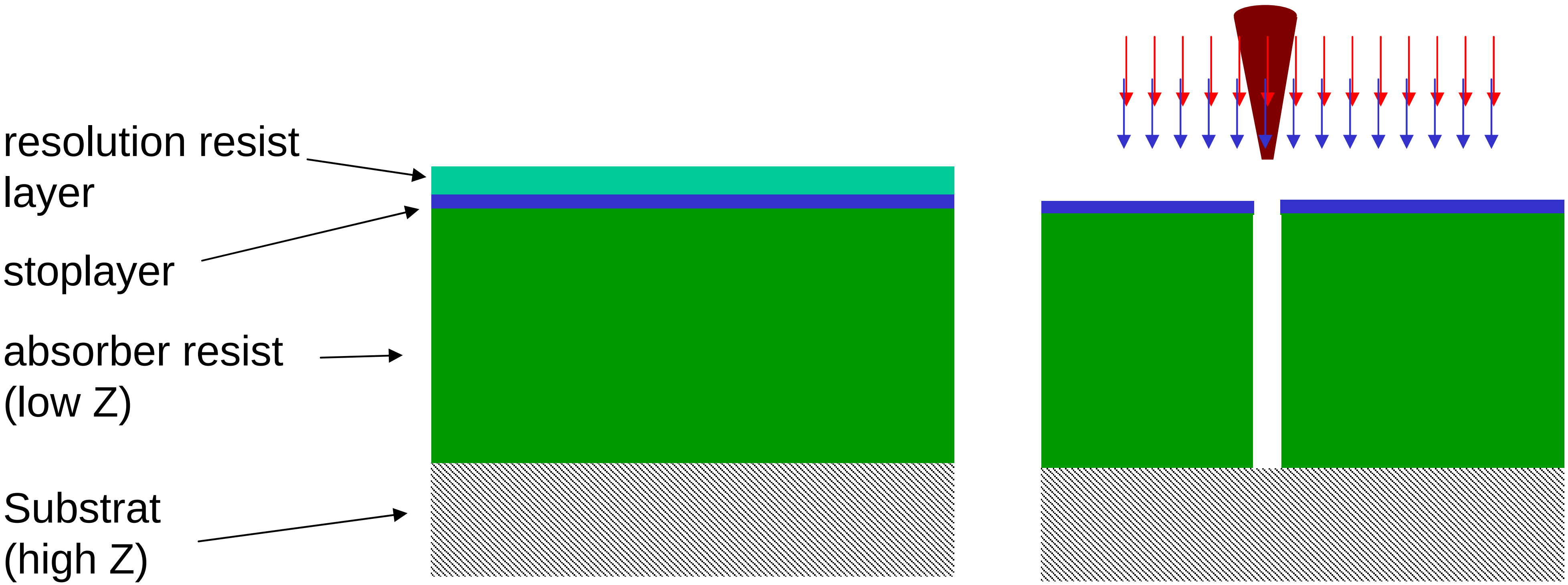




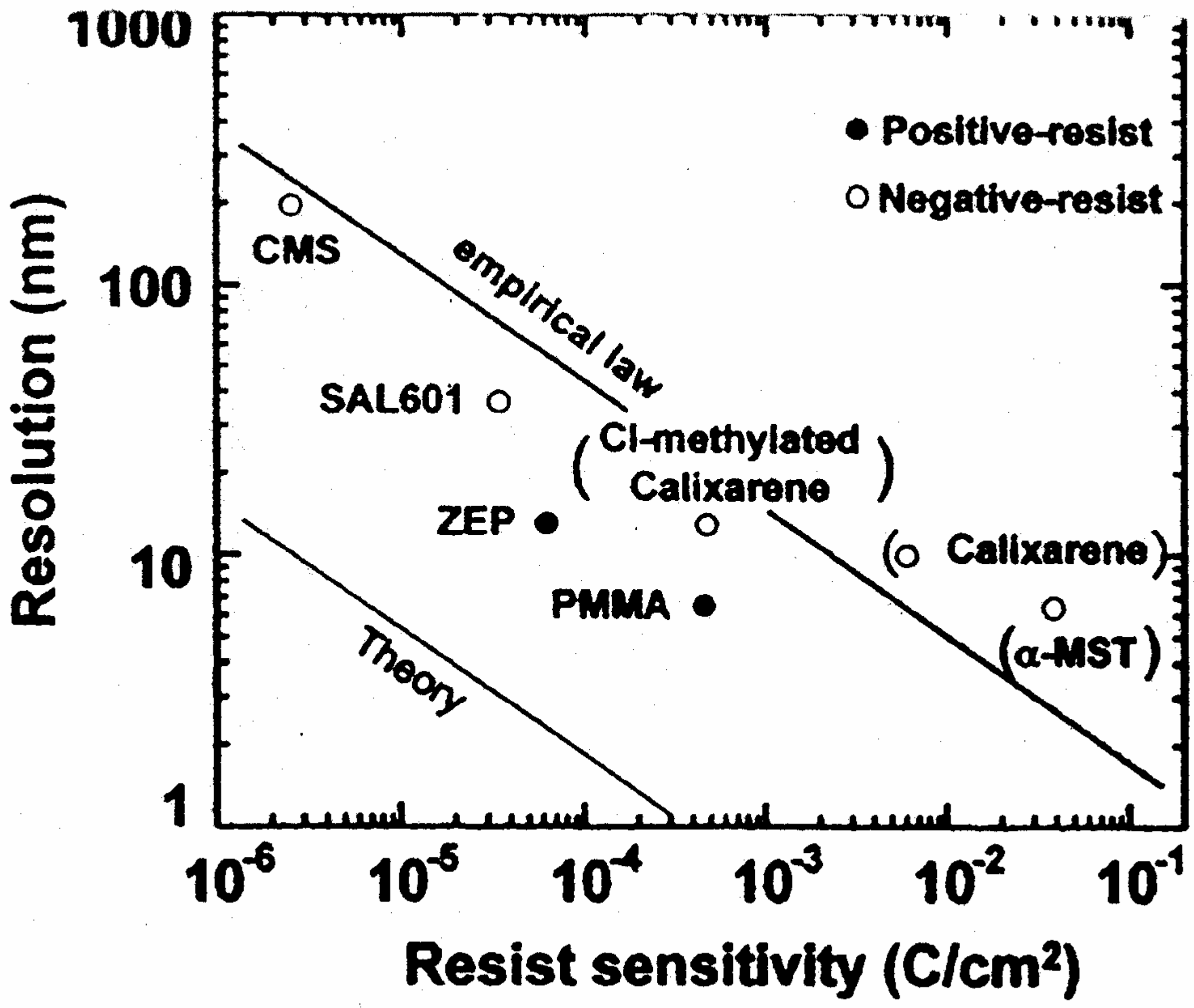
Line <10nm

Granular gold lift-off

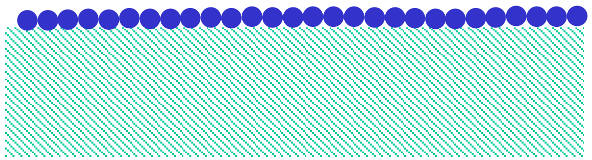
•Multilayer techniques



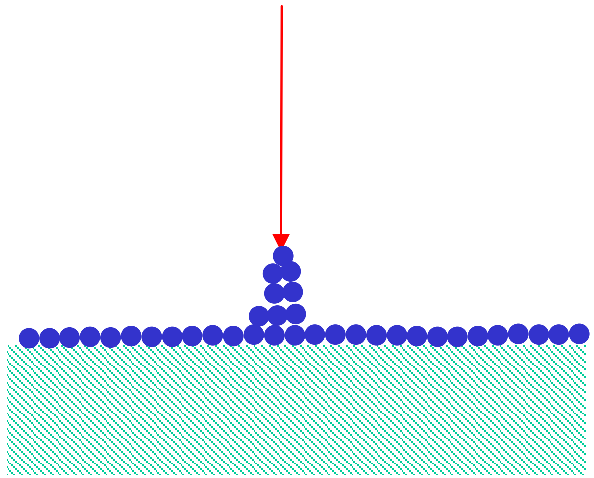
Resolution of organic Resists



Inorganic resist
sensitive to high energy



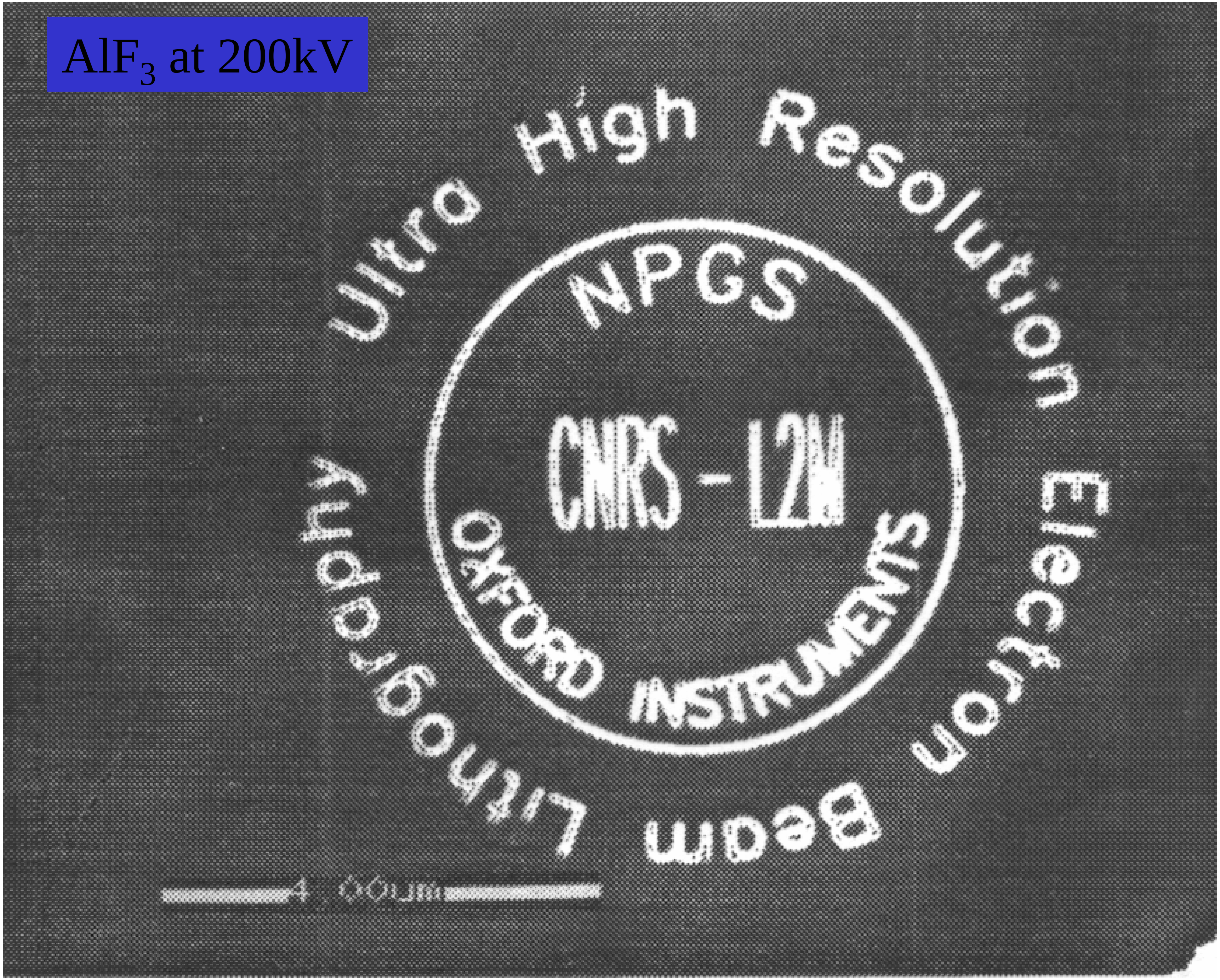
Diffusion pump oil



Polymerisation under the beam
Size few nm (hard to remove!)

Other inorganic resist: Al_2O_3, NaCl, AlF_3, …
problems: very thin resist :no lift-off
very high doses $\approx$ C/cm^2 i.e . 10^4s/μm!

AlF_3 at 200kV



The e-beam writer

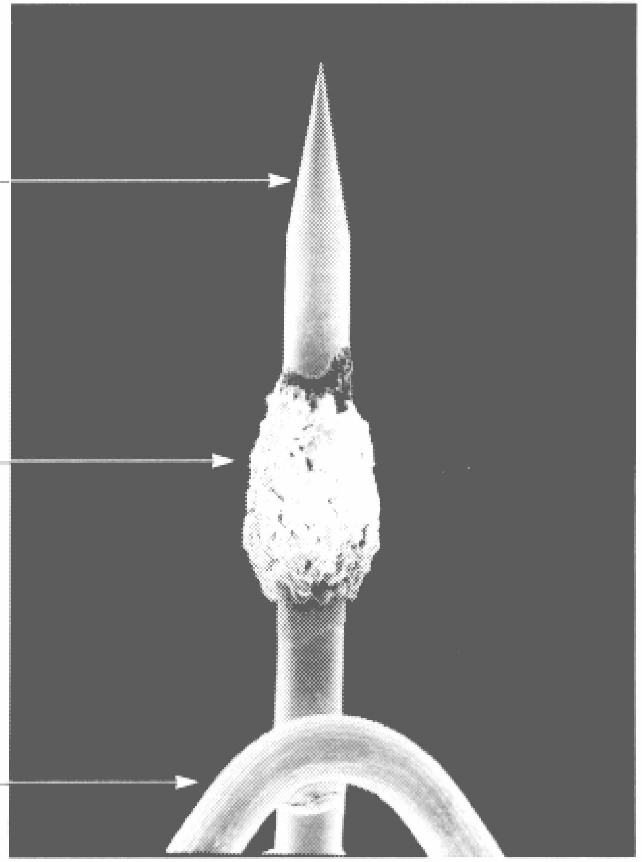
(example of the LEICA 5000)

Schottky Emitter Tip

<100> W Crystal

ZrO Reservoir

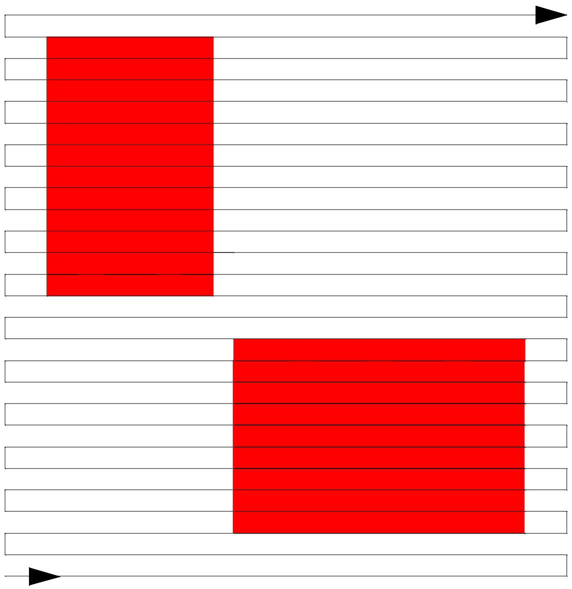
Polycrystalline tungsten heating filament



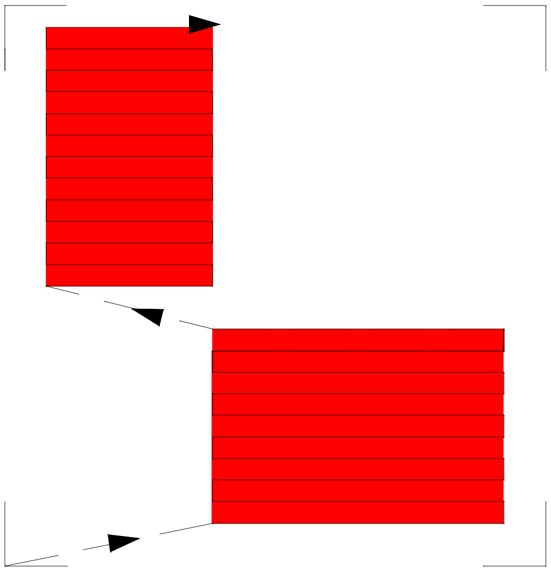
Brightness >>LaB6 cathode Spot size<5nm at 500pA

Scanning Techniques for E-Beam Lithography

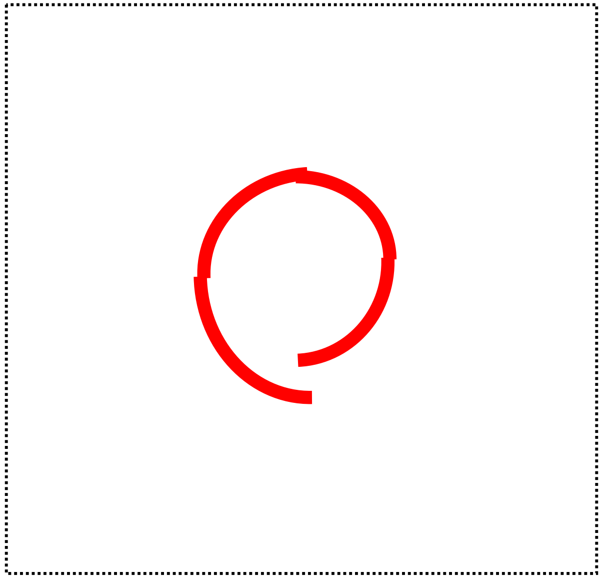
Beam Scan Area



Beam Scan Area



Stage Movement Limits



1. **Raster Scan**
The beam deflection system scans a fixed sized area whilst the beam is switched on and off to expose the local areas where shapes are required.

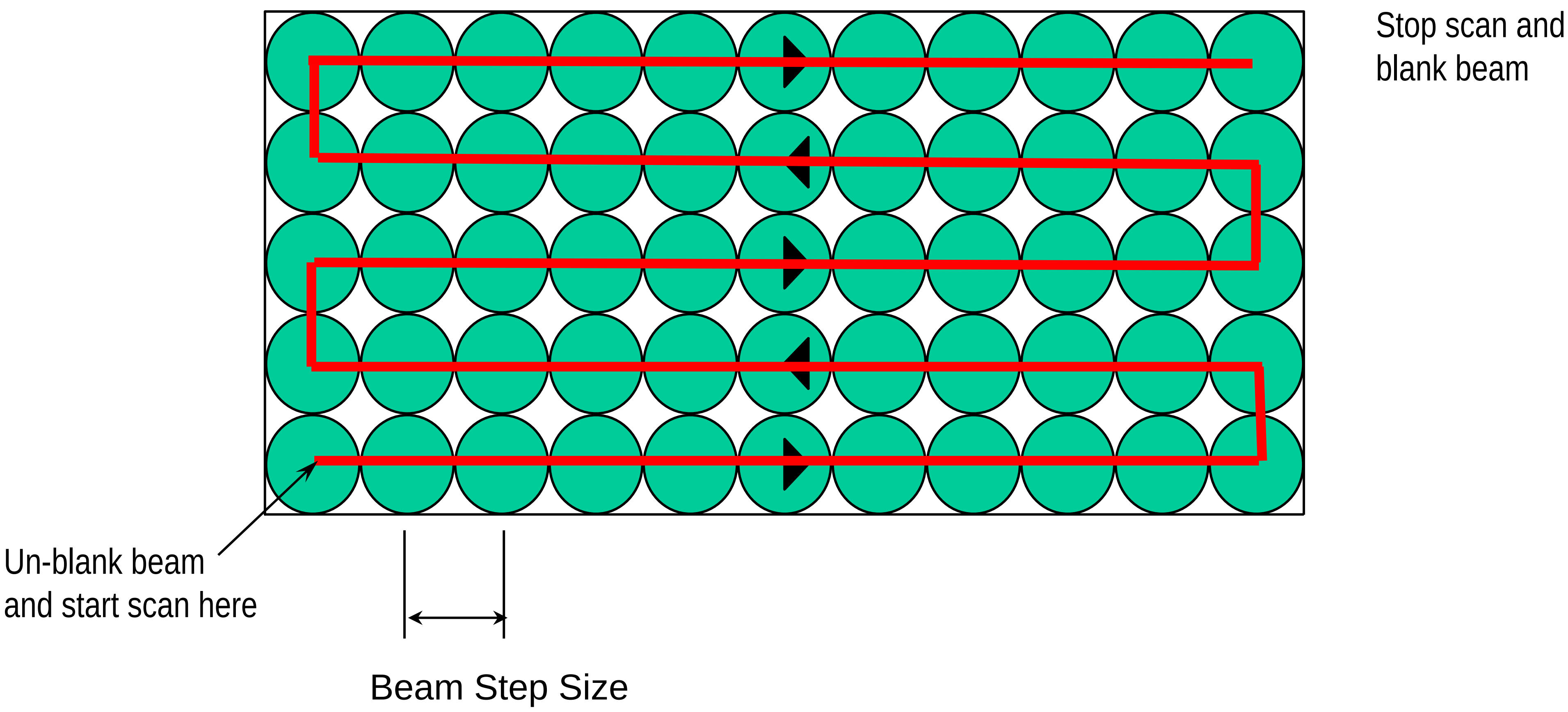
2. **Vectorscan**
The blanked beam is deflected to the lower-left hand corner of a shape. The beam is unblanked and the required shape area then scanned. The beam is again blanked and deflected to the next required shape.

3. **Stage Scan/ Static Beam**

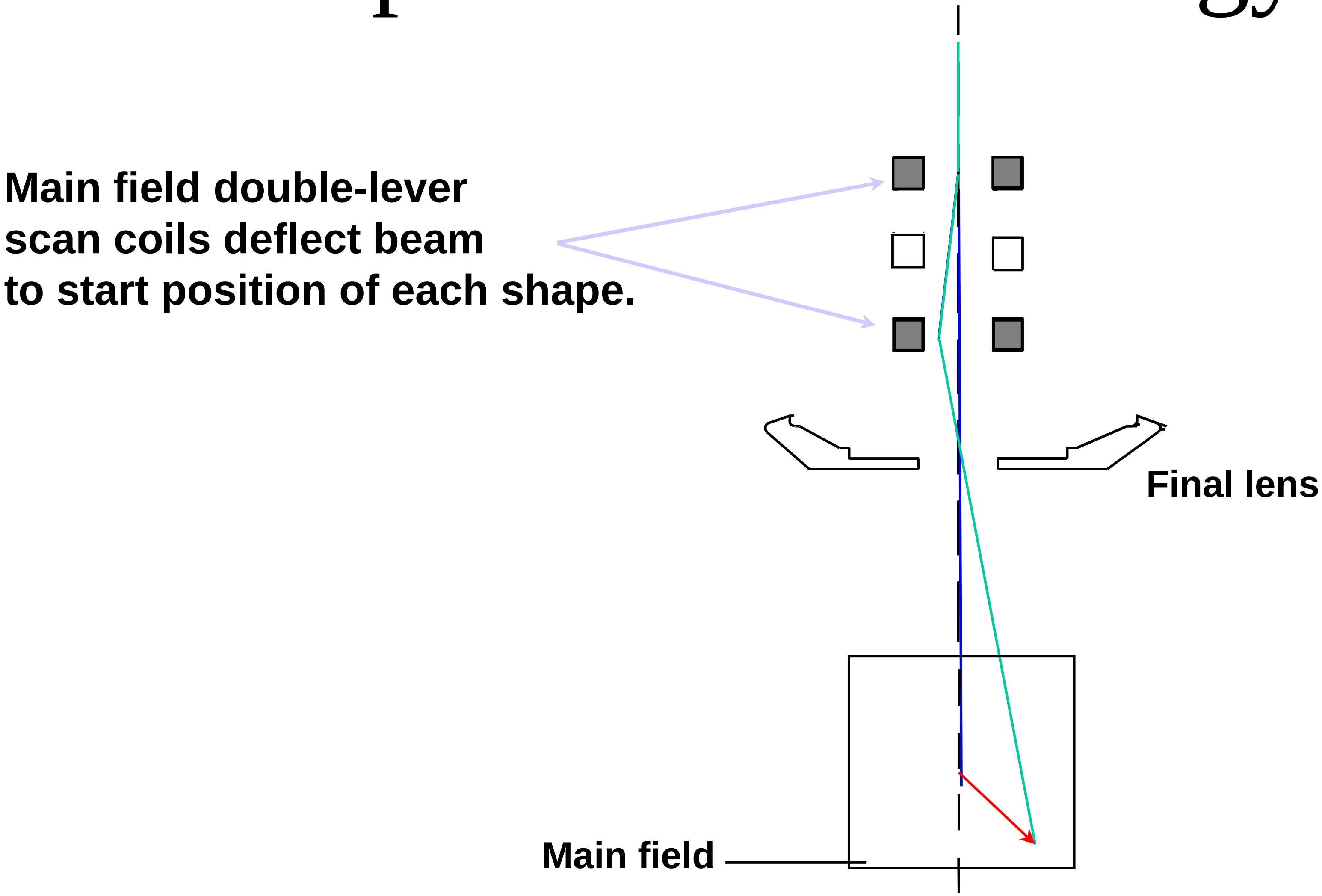
The stage is moved in the path required to create the lithographic shapes while the beam remains undeflected

Shaped beam for mask making machine

Vector Scan of Rectangle Shape

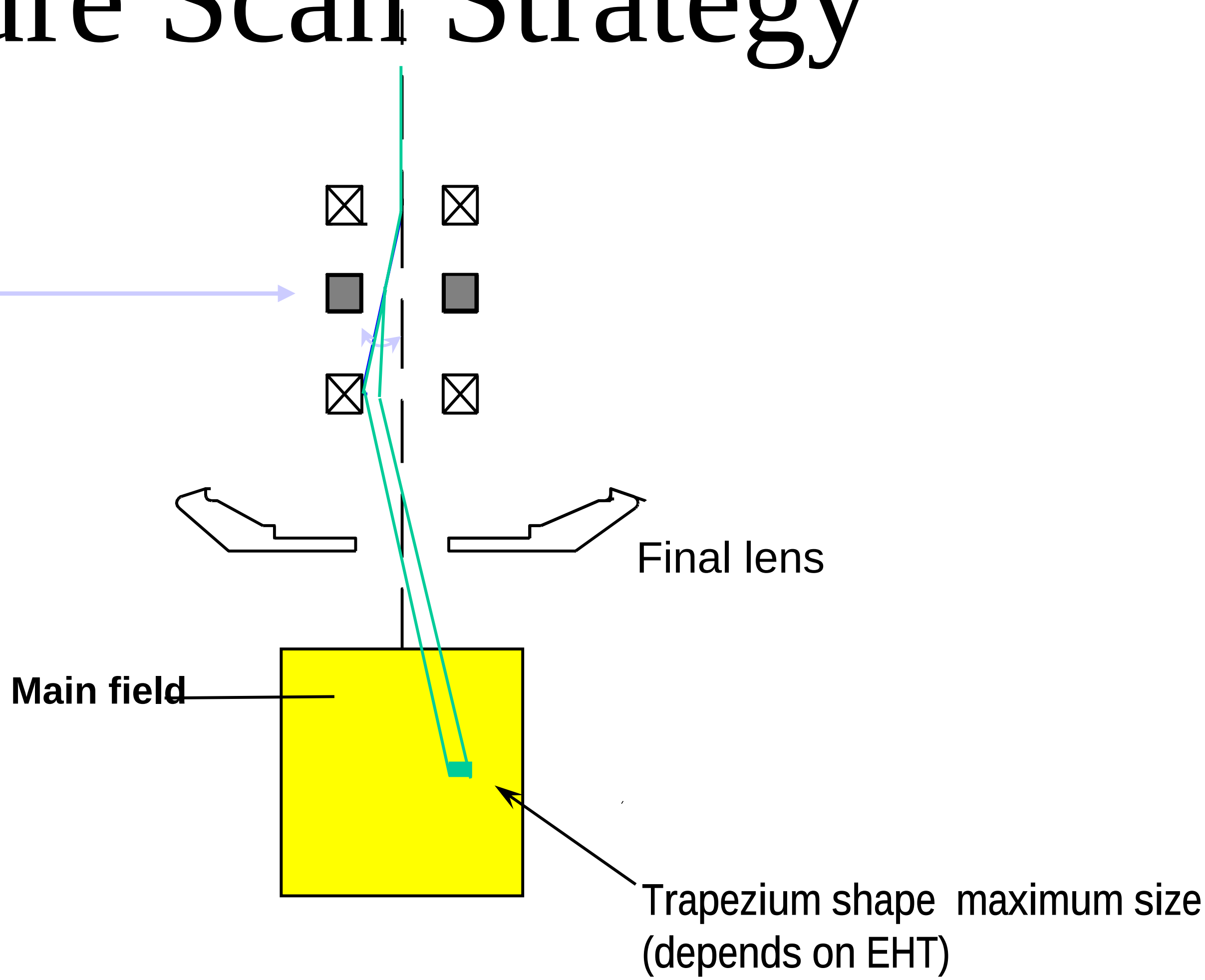


Exposure Scan Strategy



Exposure Scan Strategy

The Trapezium Deflector scans the required lithography shape at the position within the Main Field set by the Mainfield deflector coils.



Trapezium Field

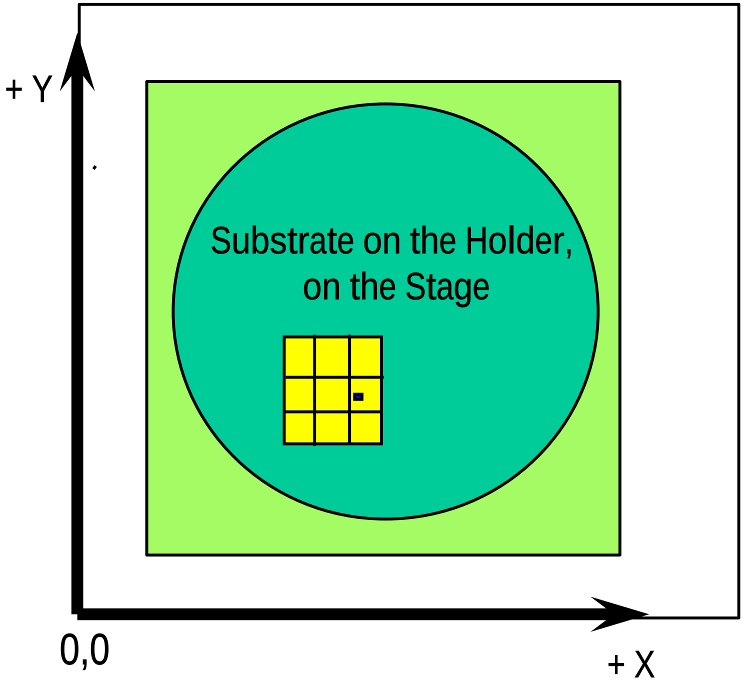
- **The main reason for the Trapezium deflection system is speed.**

- **It is not possible to deflect the main beam with 25Mhz stepping frequency.**
- **Large current changes in inductive deflection coils require long settling times**

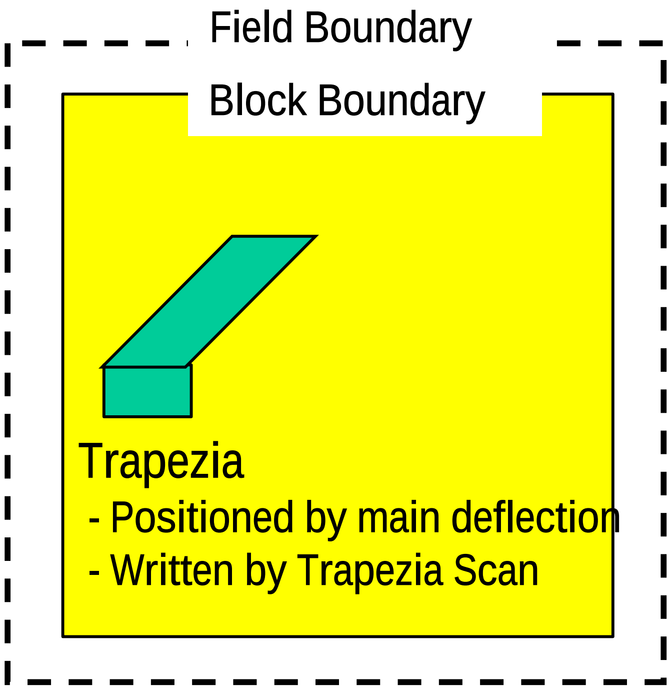
- **To achieve very fast deflection**
- **Use a coil with low self-inductance**
- Limit the range of deflection currents

- **Disadvantages:**
- The deflection range is limited (12.8µm max but depends on EHT).
- Large shapes require fracturing into Trap deflection range sizes.
- **Advantages:**
- High speed deflection possible
- Exposure lost time for settling greatly reduced

Writing Strategy



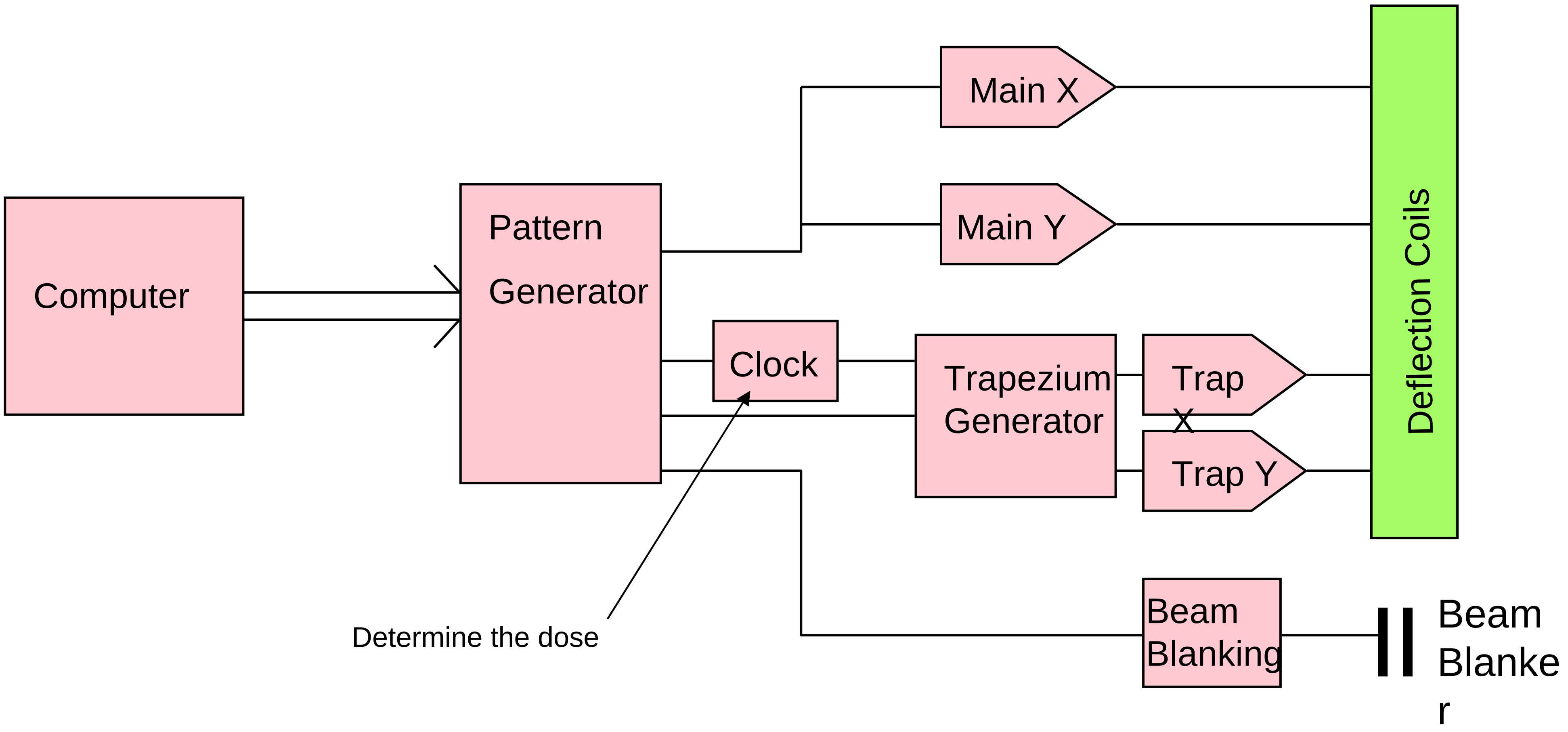
Fields/Blocks positioned
by stage movement



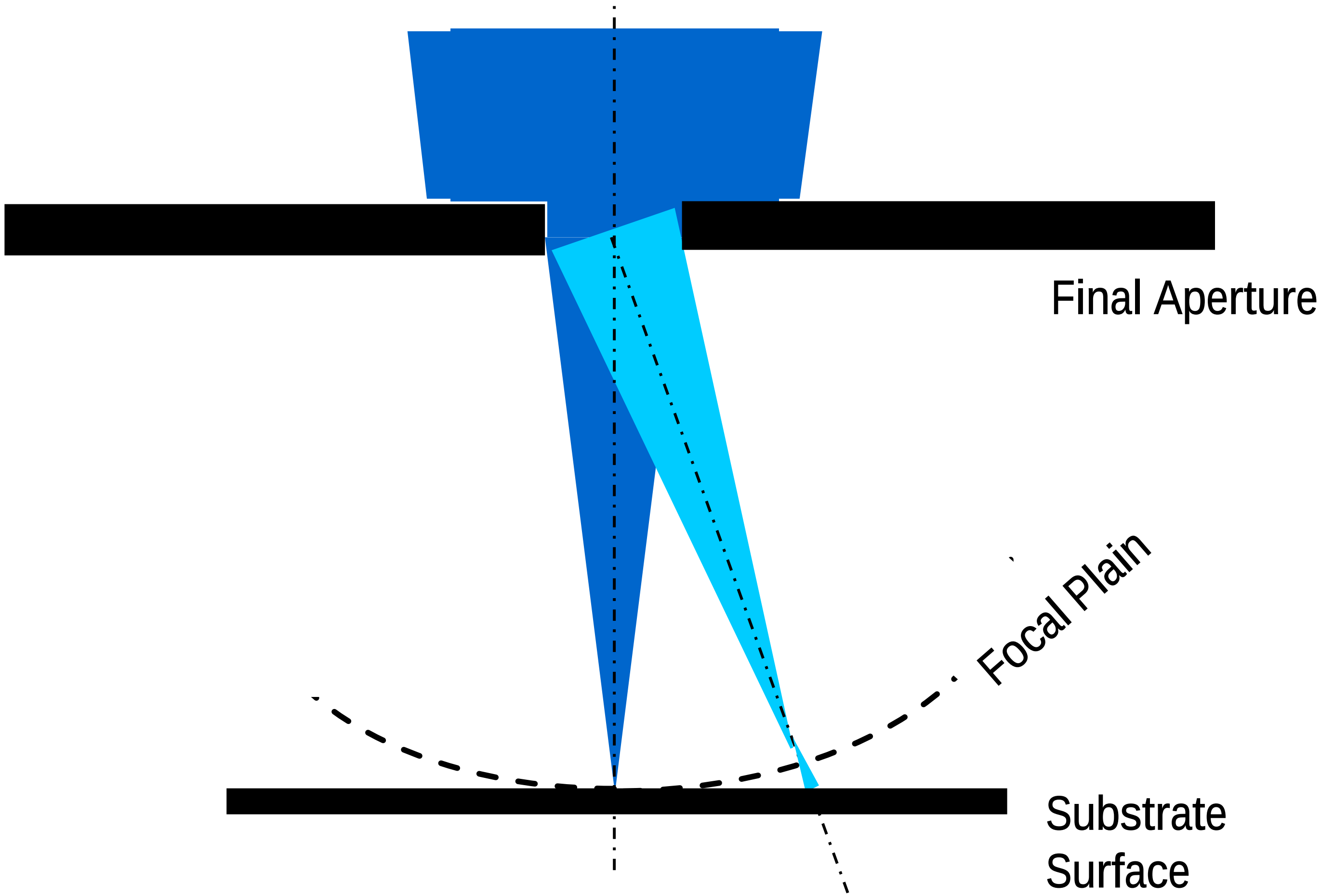
Shape positioning Resolution $= \dfrac{\text{Field Size}}{32768}$

Beam Step Size interval defines Trapezia size

Basic Deflection System

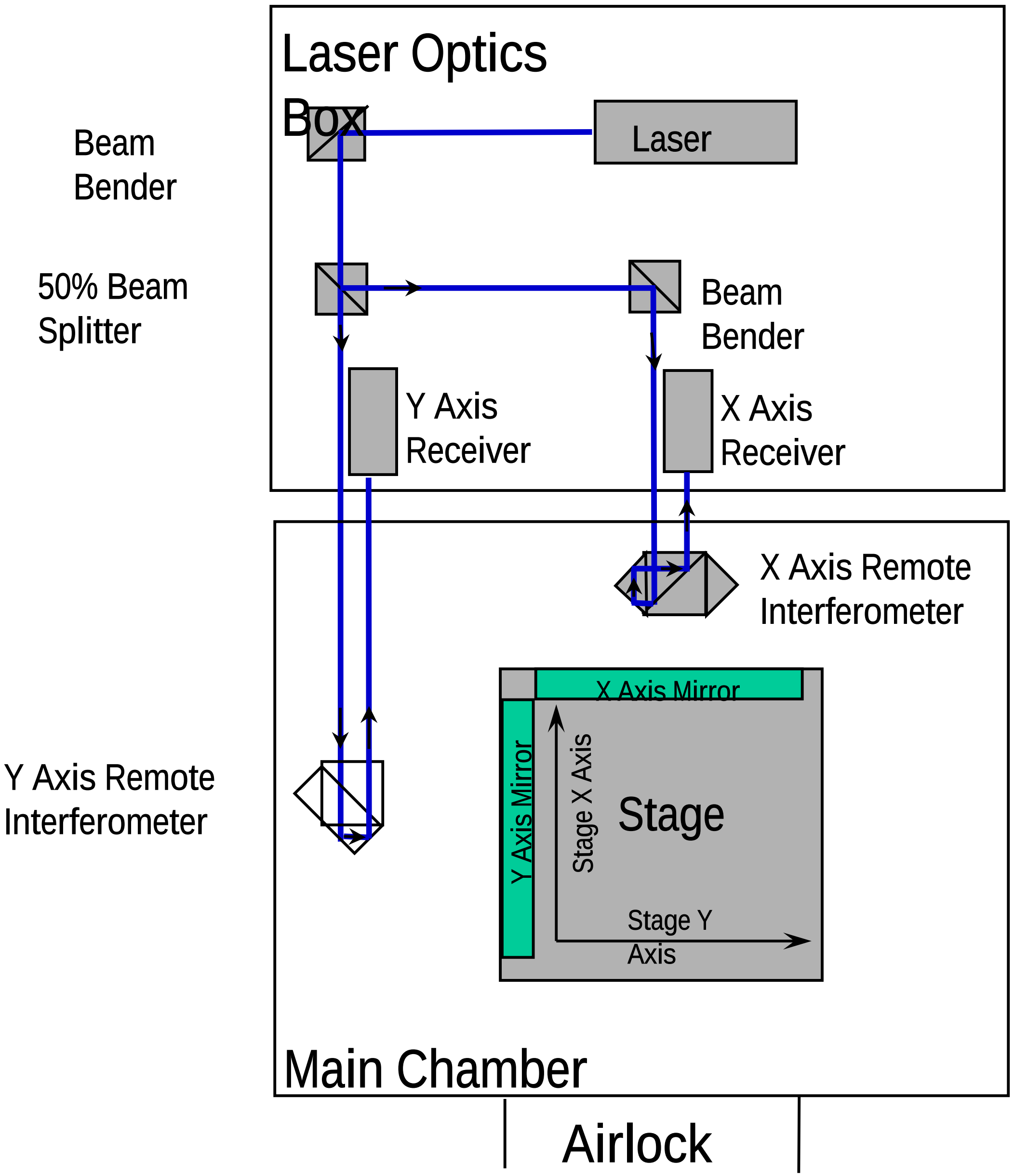


Effects of deflection on the Beam



the pattern has to be divided into field

Laser Interferometer Optics



The Laser emits a second beam for each axis which is polarized at 90^0 to the first.

This beam travels through a different path as shown. It is reflected back to the Receiver by the Remote Interferometer optics and does not “see” the Stage.

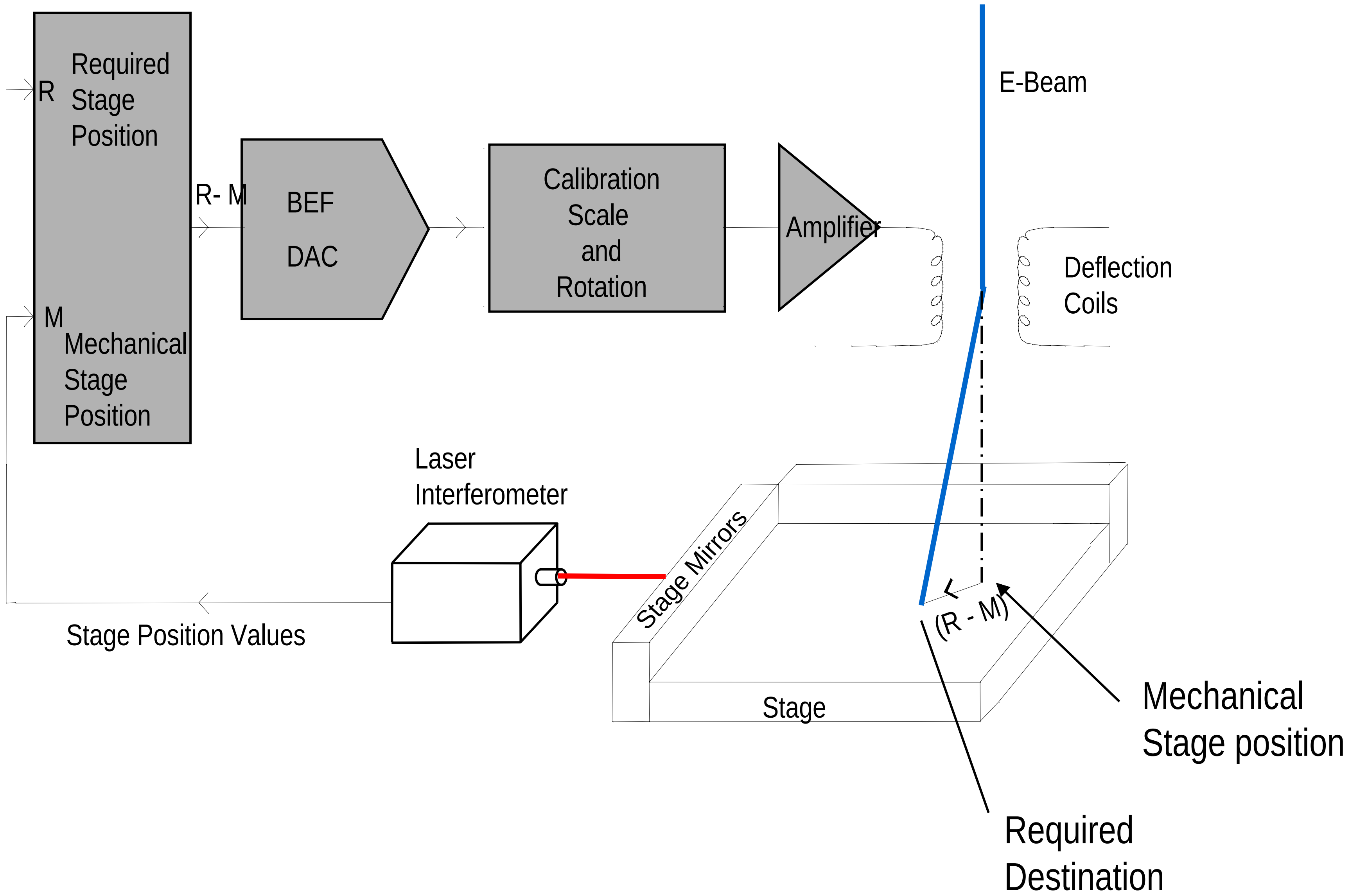
This beam measures any changes of path length between the Laser and the Remote Interferometer units.

The measurements of the two beams are combined and the resultant signal output provides an accurate measurement of the position of the stage relative to the remote interferometer units.

Hence changes of room temperature affecting the path length in the Laser Optics Box do not affect the accuracy of the measurement of the Stage position.

Accuracy about 2nm

Elements of Beam Error Feedback (Pull-in)



e-beam lithography:

- Highest resolution

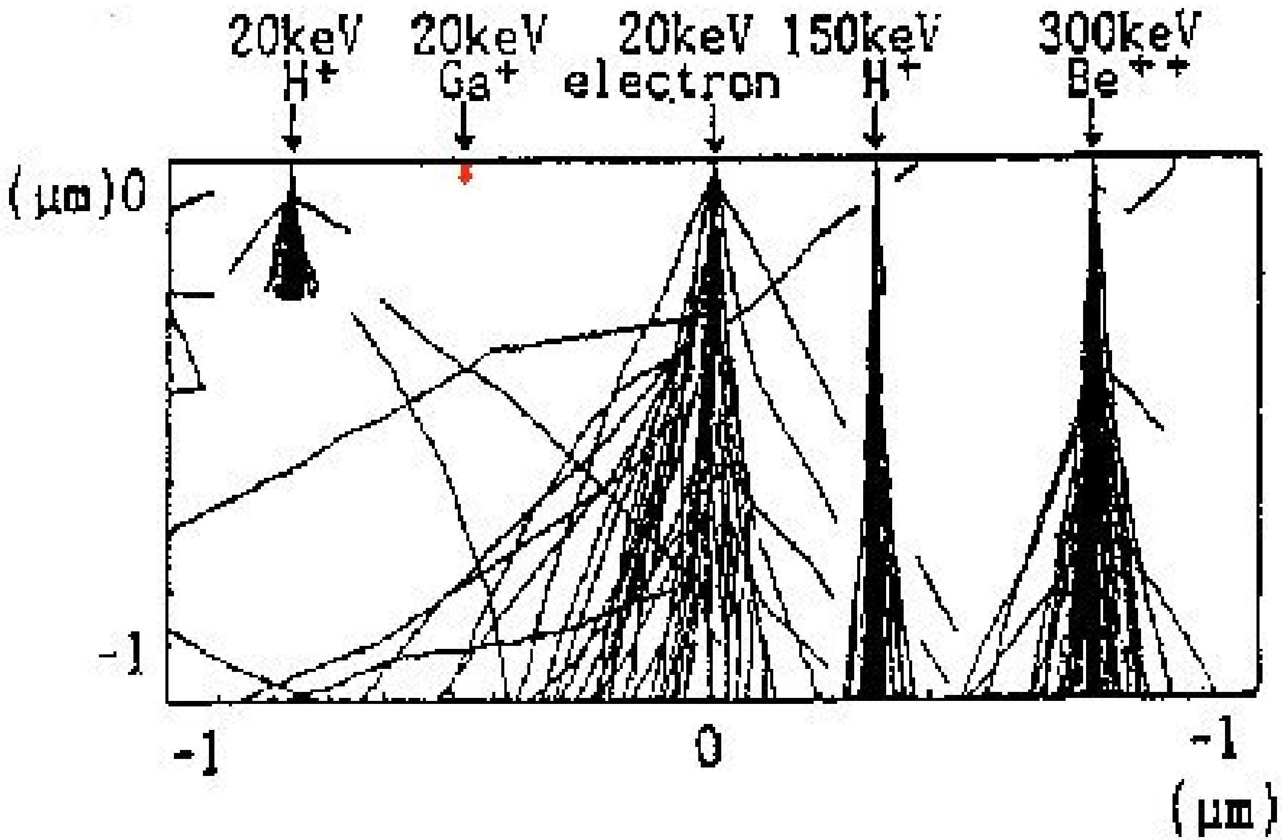
- Low process - not for industrial purpose (for all processes)

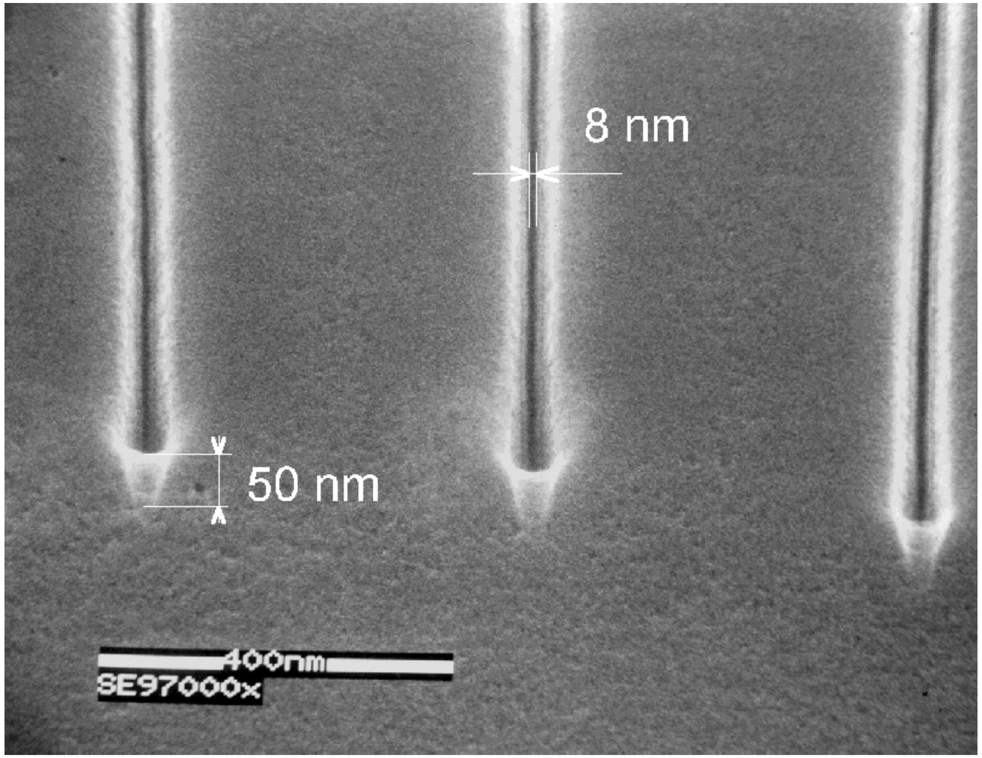
- Intermediate cost :
  - 150k€ for SEM based equipment
  - 3M€ for e-beam writer

Ion beam lithography

- Revival of ions beam – spot size < 10nm
- Ions are rapidely absorbed – no proximity effect
- Small doses
- Tridimensionnal structures
- Direct writing (without resist) through etching or implantation.

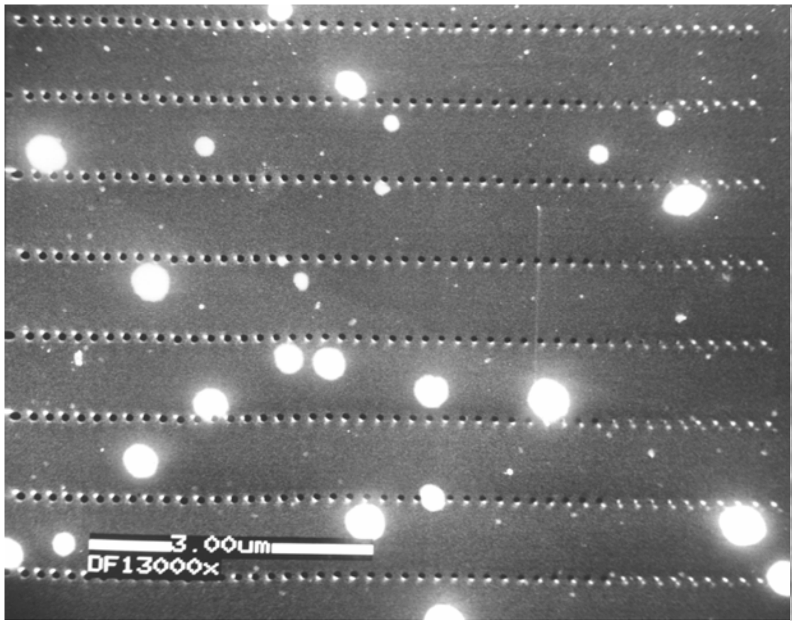
Ion trajectories

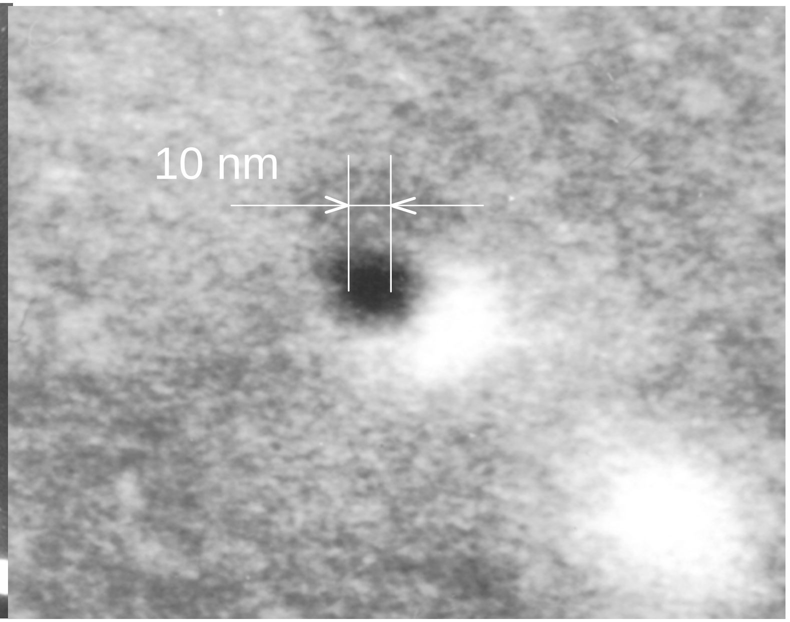




30kV Gallium ions

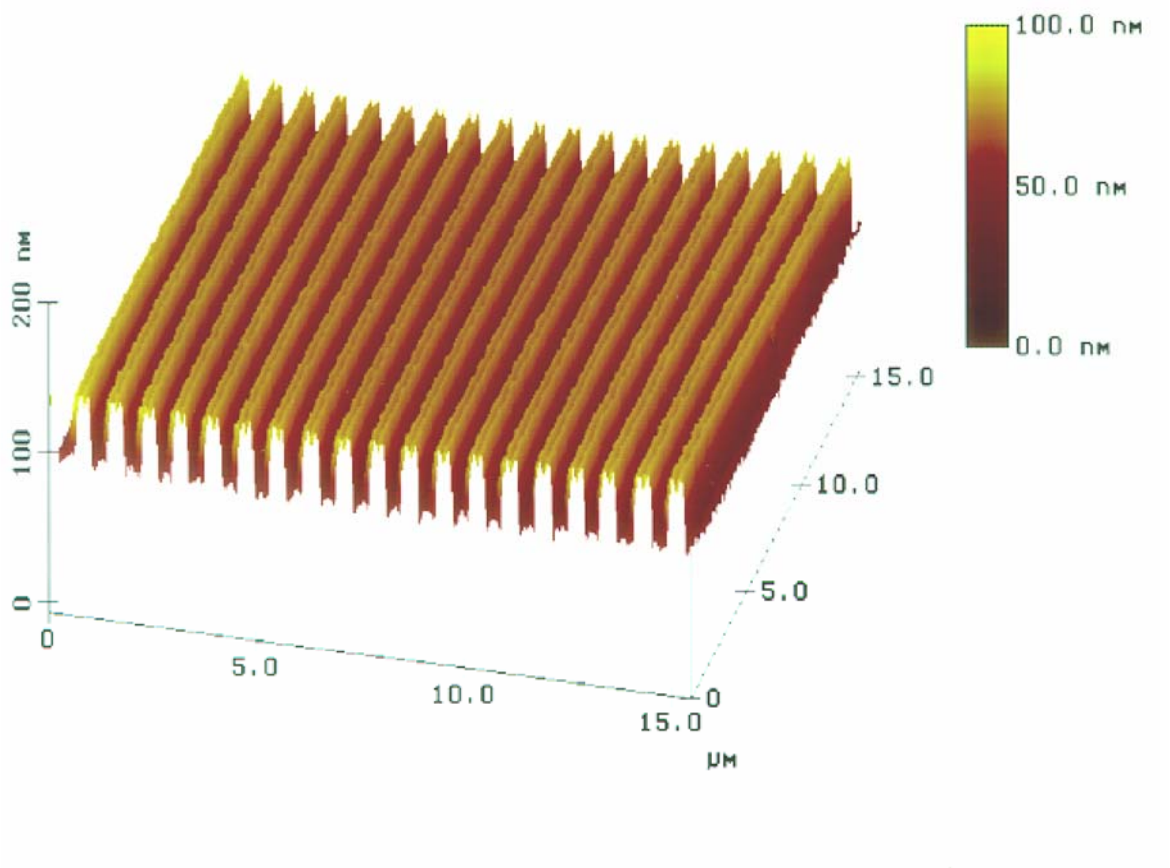
Holes in a Si_3N_4 membrane



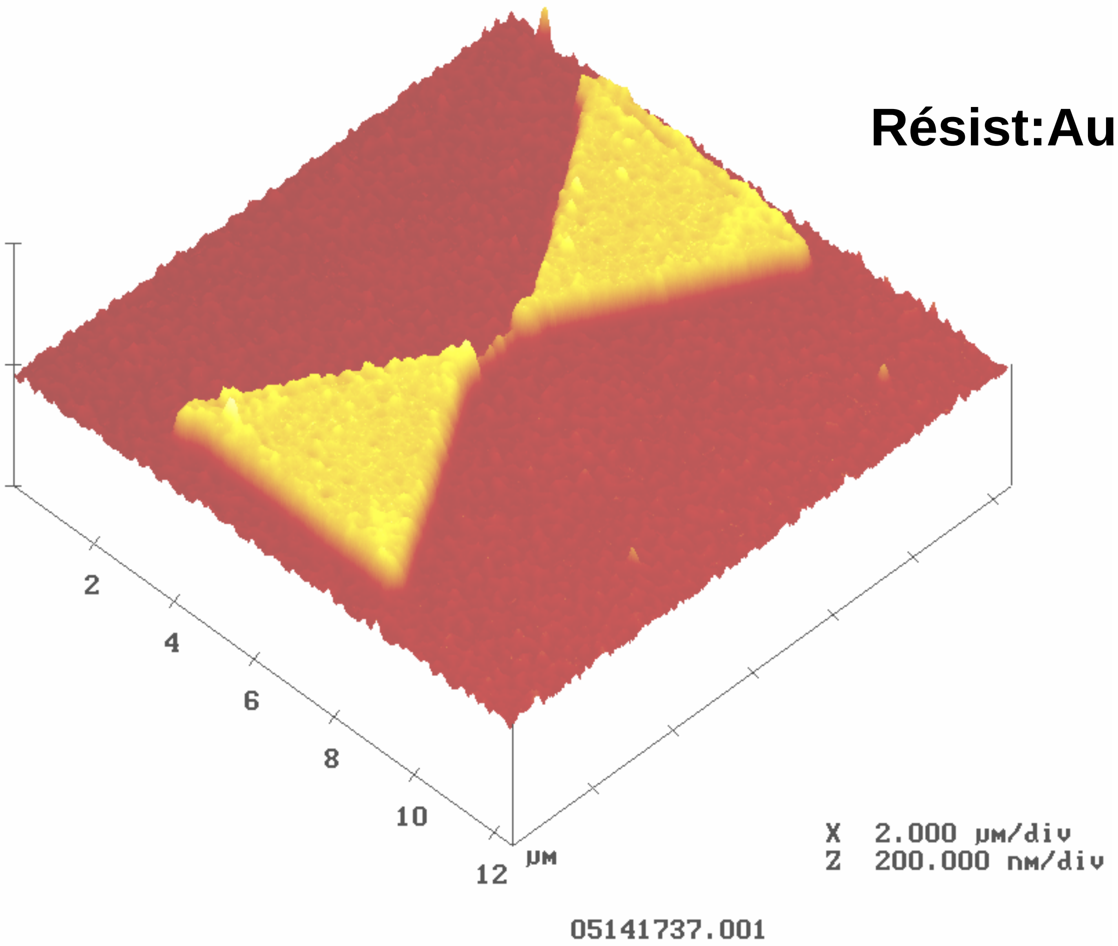


LPN Marcoussis

Ion beam lithography on AlF3 resist
30kV Ga ion



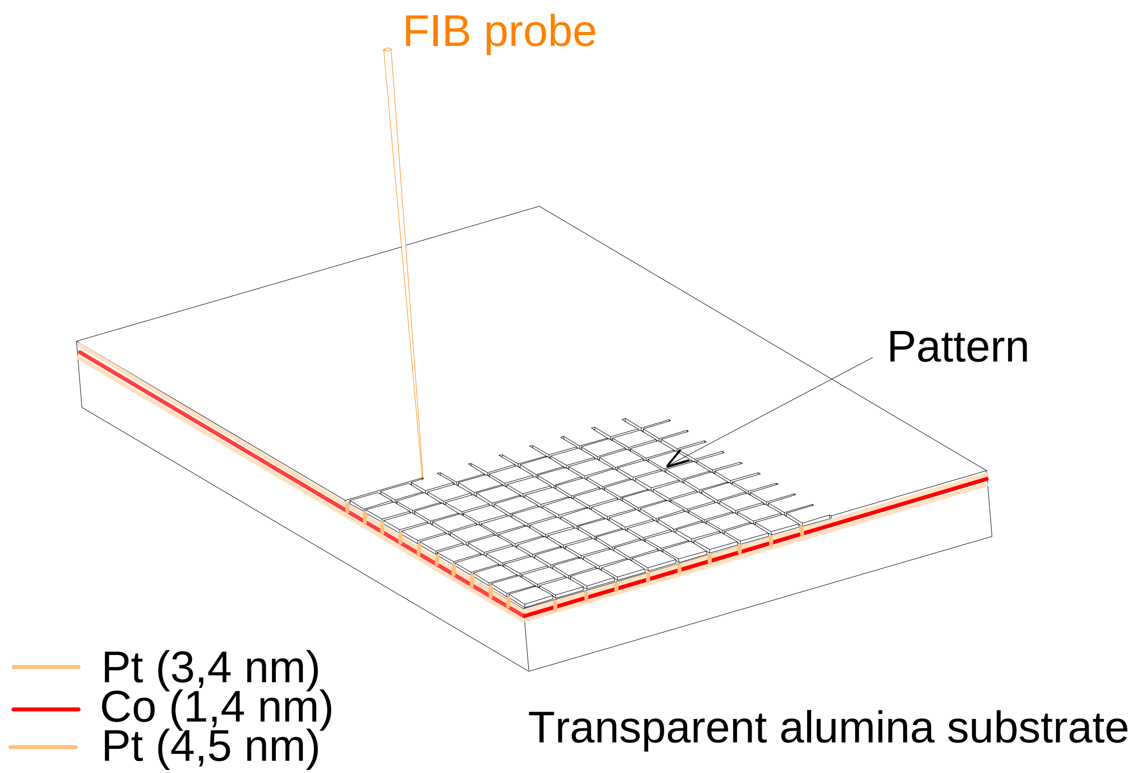
3D lithography on organo-metallic gold composite

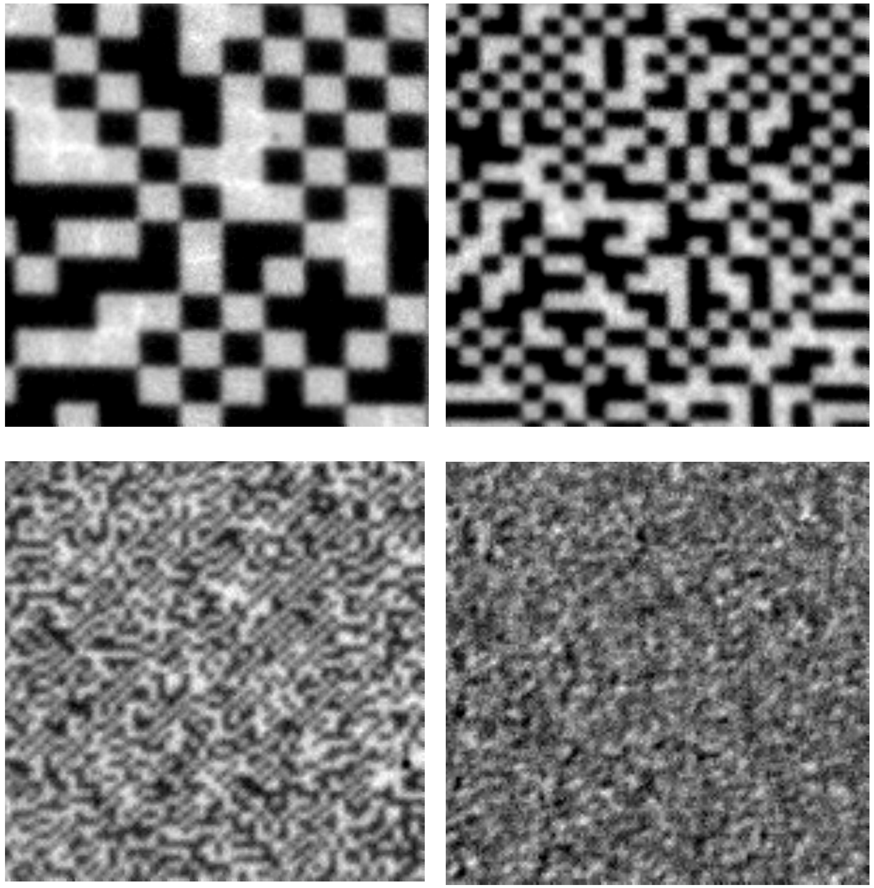


Résist:$Au_{55}(PPh3)_{12}Cl_6$

Dimensions : 30 nm wide, 20 nm height : 1.5 µm long.
(Ga ions , energy 30 keV, initial thickness 50nm)

Local FIB induced mixing - Thin magnetic films patterning

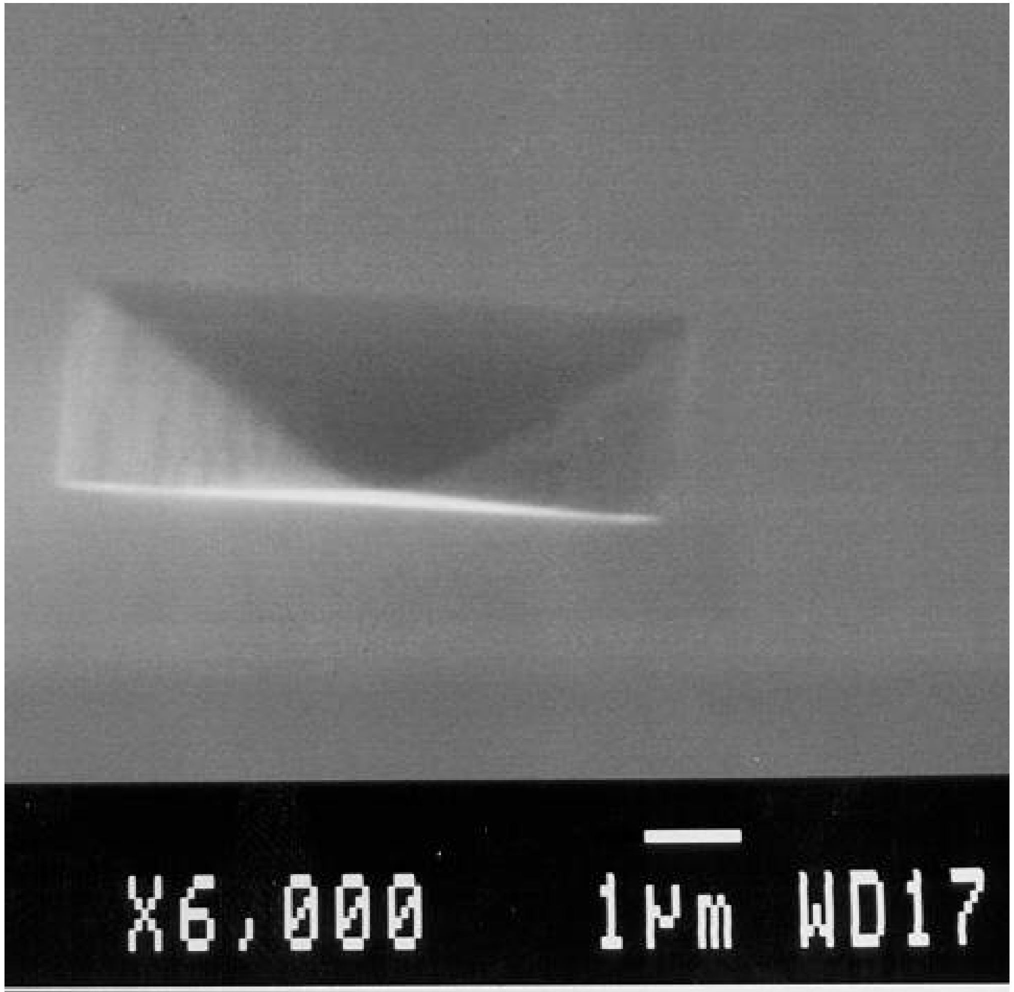




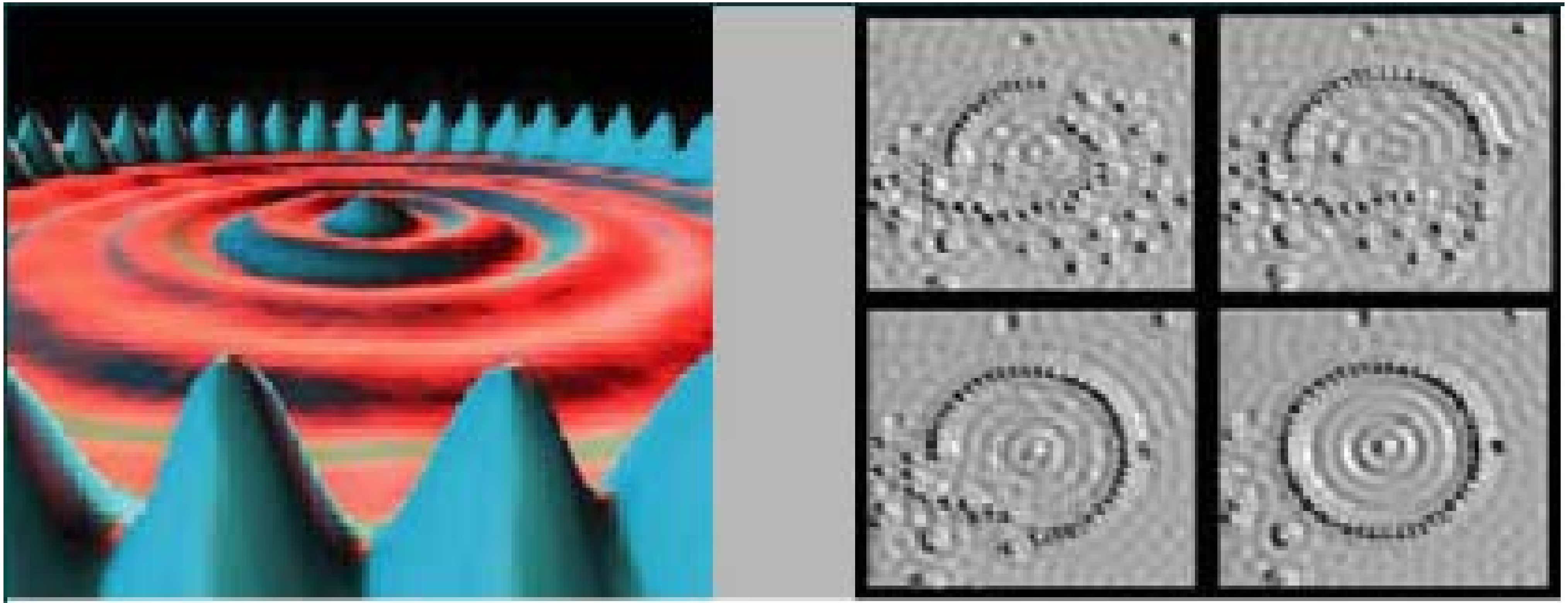
Magneto-optical image of magnetic domains defined between irradiated ***lines***
(Ga^+ ions, 30 keV, 5×10^{15} ions/cm^2).

$\Rightarrow$ Arrays of stable magnetic dots 1500 nm, 750 nm, 300 nm, 50 nm

Tridimensional etching



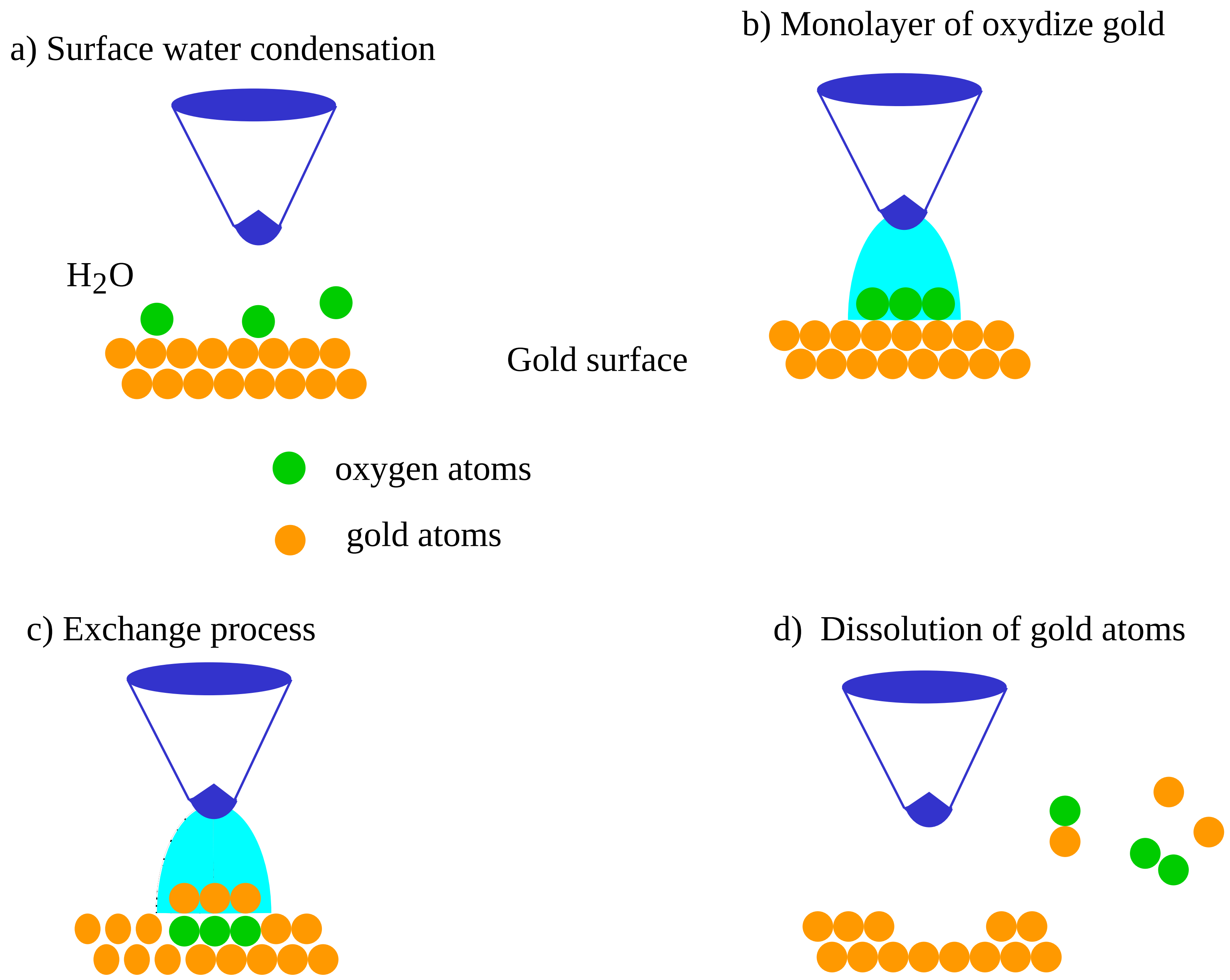
Near field lithography



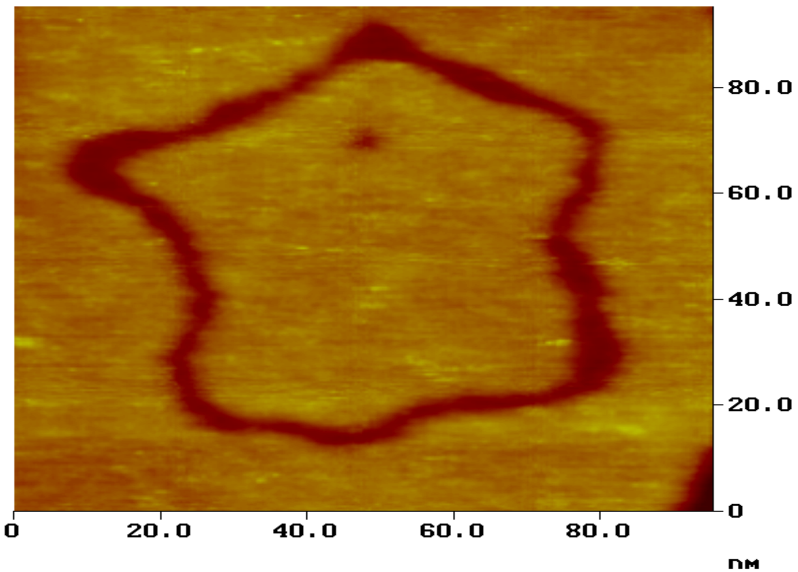
Donald Eigler et al. (IBM-almaden)

Xe / Cu

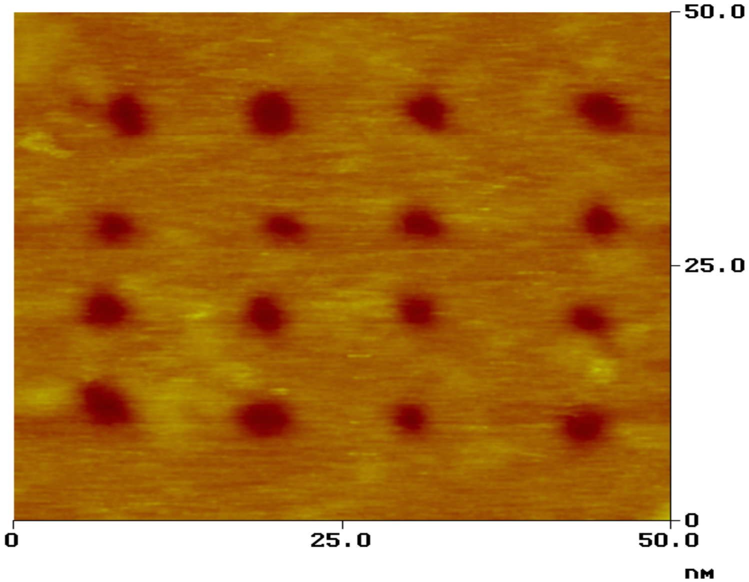
Near field lithography through local electrochemistry example of gold



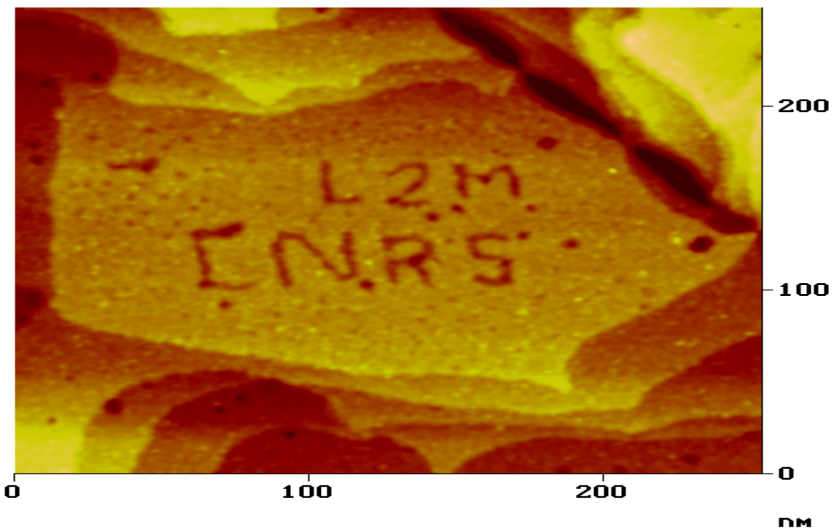
examples



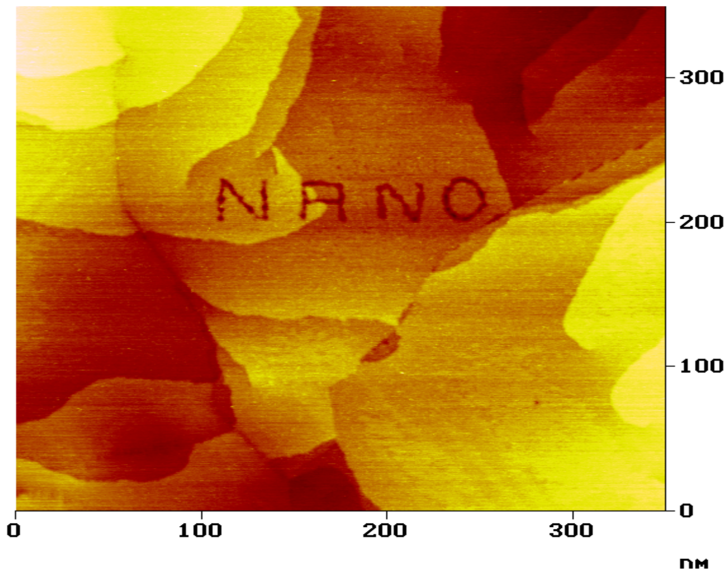
Carte de France (32,000 atomes d'or enleves) L2M
04081014.501



Monolayer nanolithography on gold film L2M/CNRS
04271526.521



Nanowriting <17:44:18 Wed Oct 13 1993>
logol2m

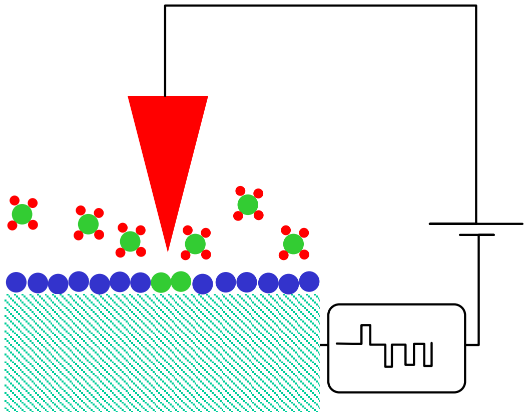


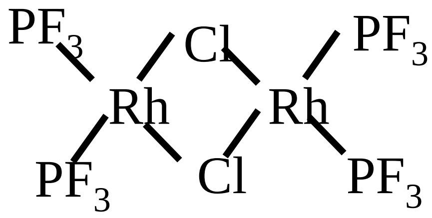
Near field scheme

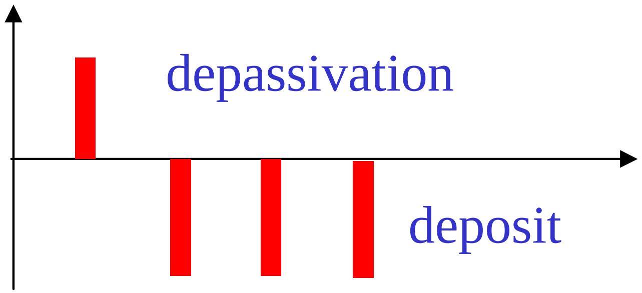
Electrical pulse
Mechanical pressure $\longrightarrow$ threshold

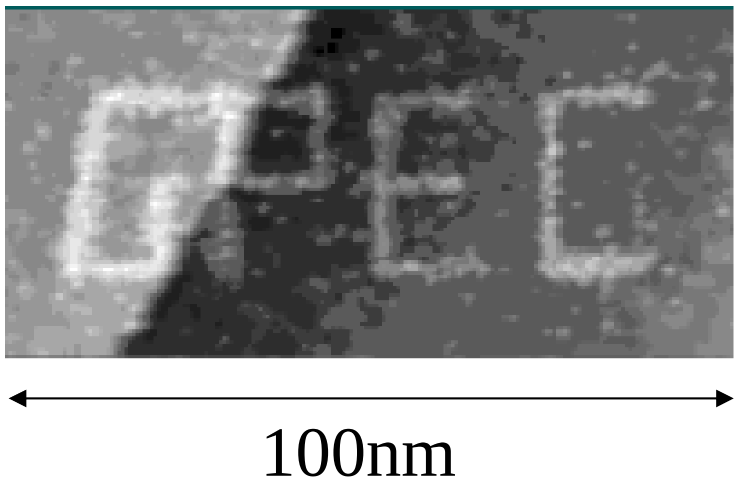
Below threshold $\longrightarrow$ Observation/alignment

Local CVD deposition







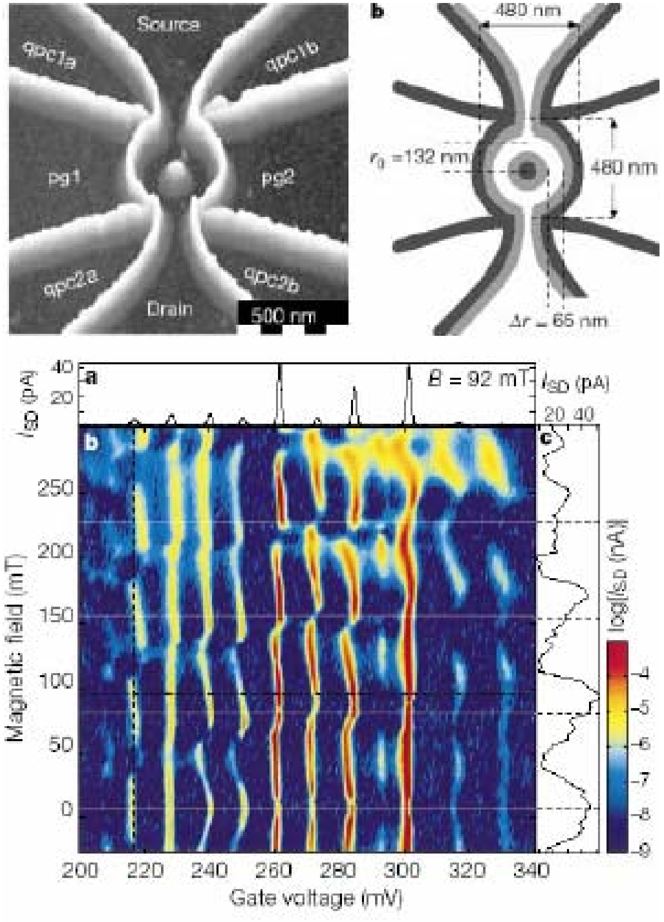


low pressure
one pulse → one atome

GPEC Marseille

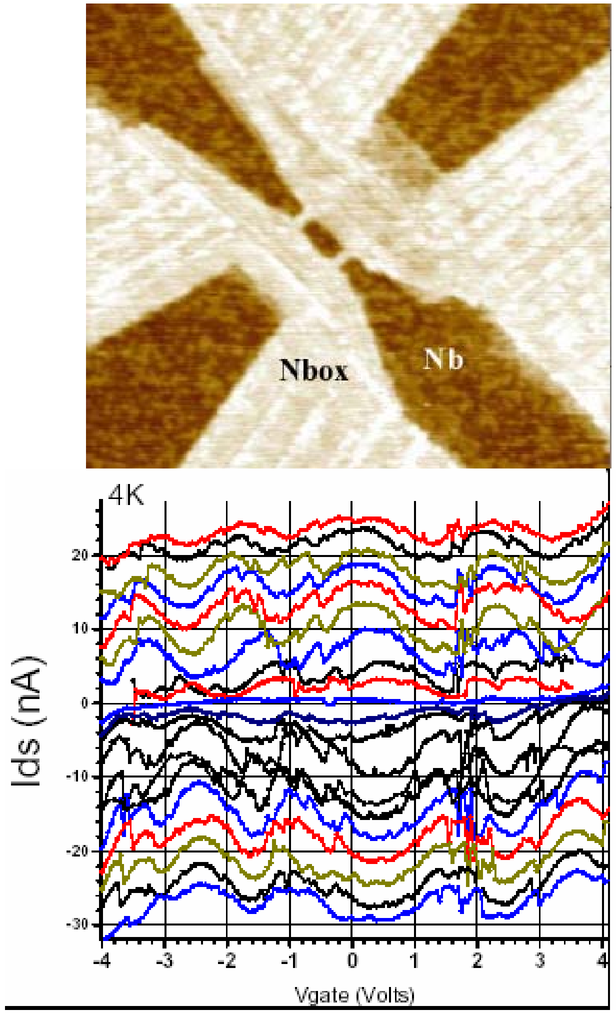
Example of useful structures

Anodization of GaAs



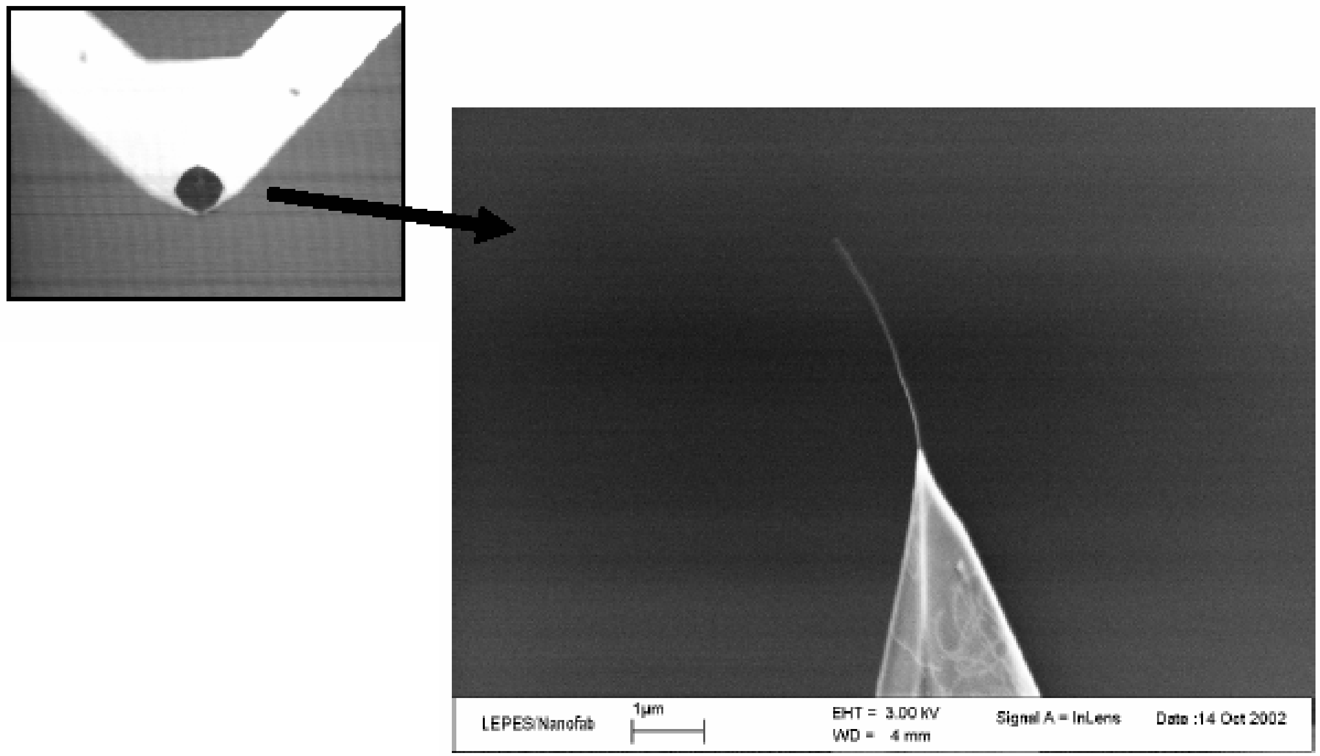
ETH Zürich

Anodization of Nb



CRTBT

Use carbon nanotube to improve the resolution

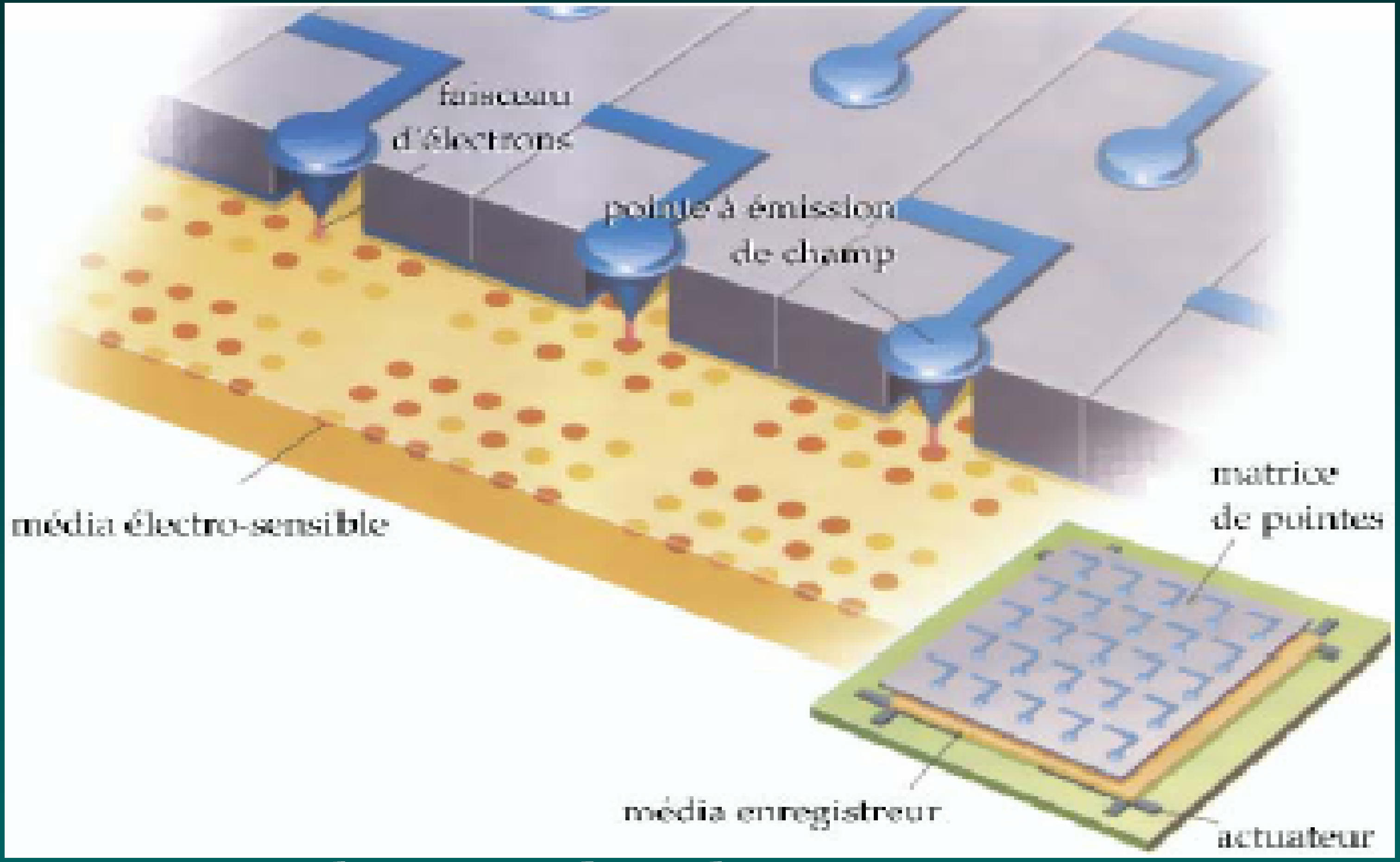


Pb vibrations needs short tube 0.2µm

LEPES Grenoble

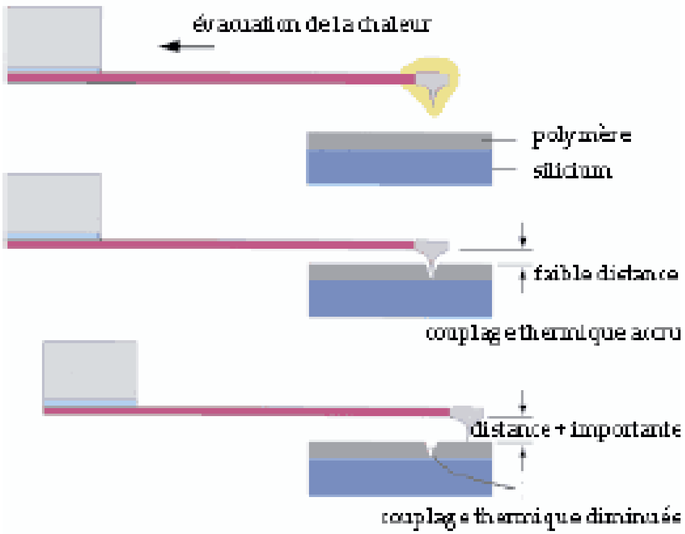
Slow process parallel set-up

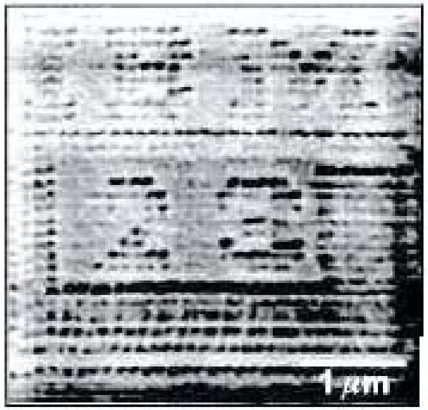
Actuated e-beam matrix

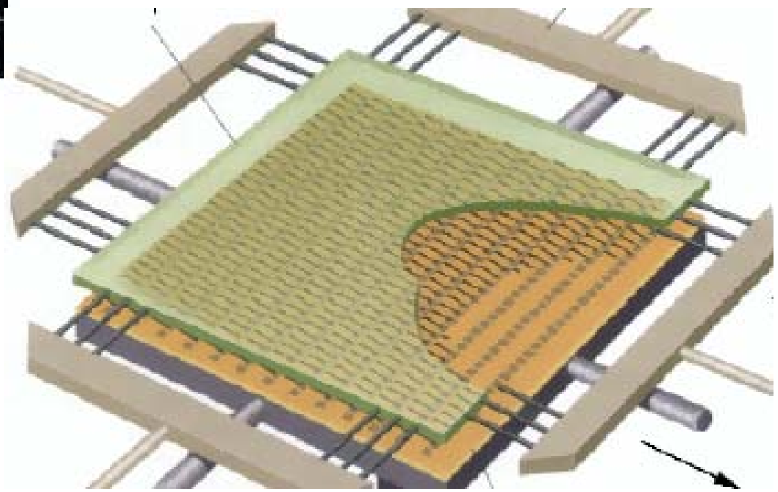


- Hewlett Packard
- Densité > 1.5 Terabit/ in ²
- Appl. Phys. Lett.vol.75, no.22; 29 Nov. 1999;

Thermal lithography

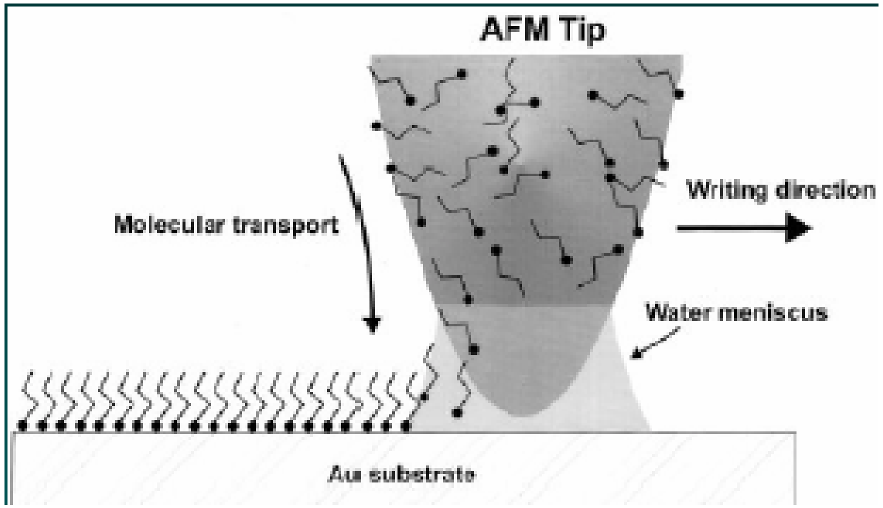


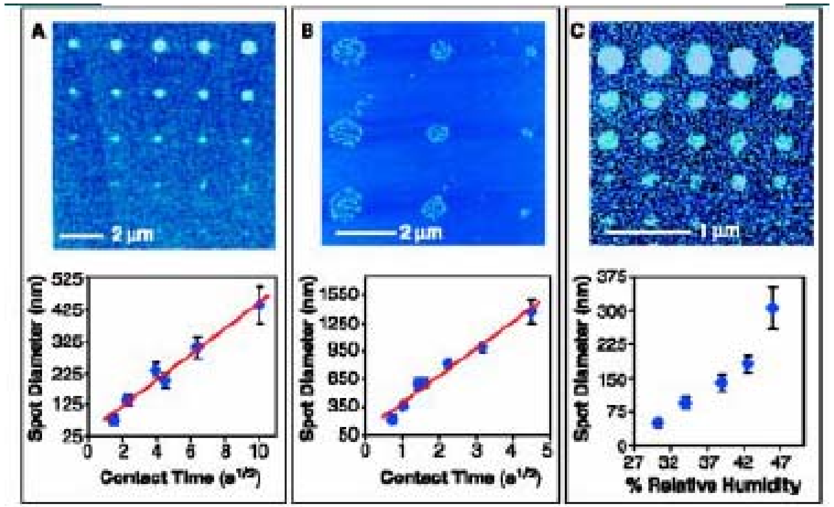




Milliped project IBM Zürich

Dip pen lithography

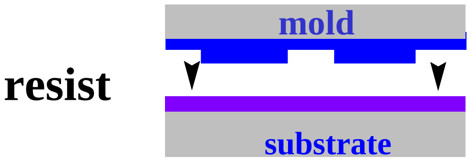




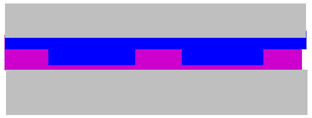
Application to DNA Chip resolution =40nm
Northwestern Univ

Nano-imprint

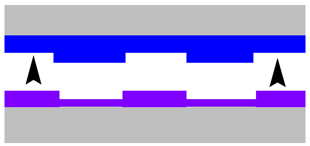
1.temp +pressure 50Bars



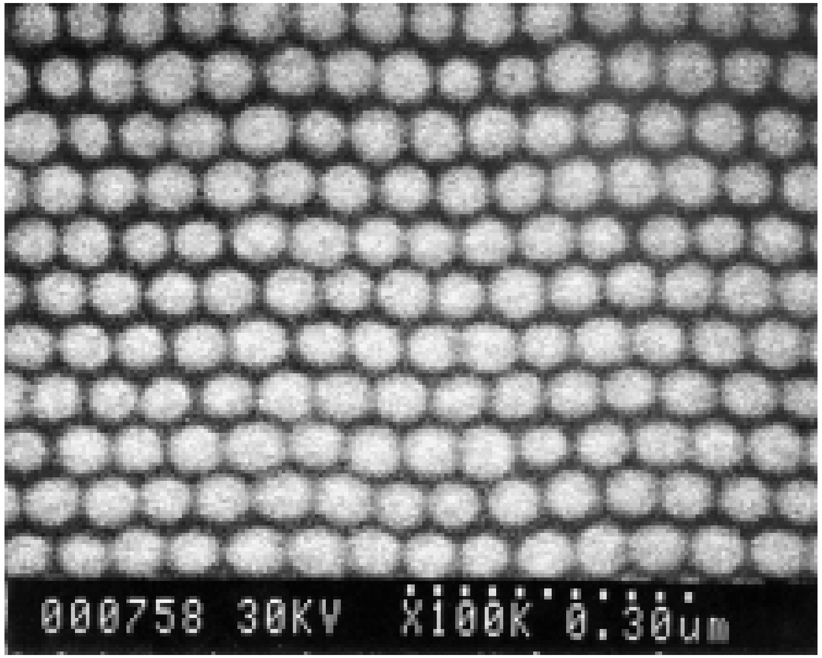
2. cooling



3. Remove mold (tricky!)

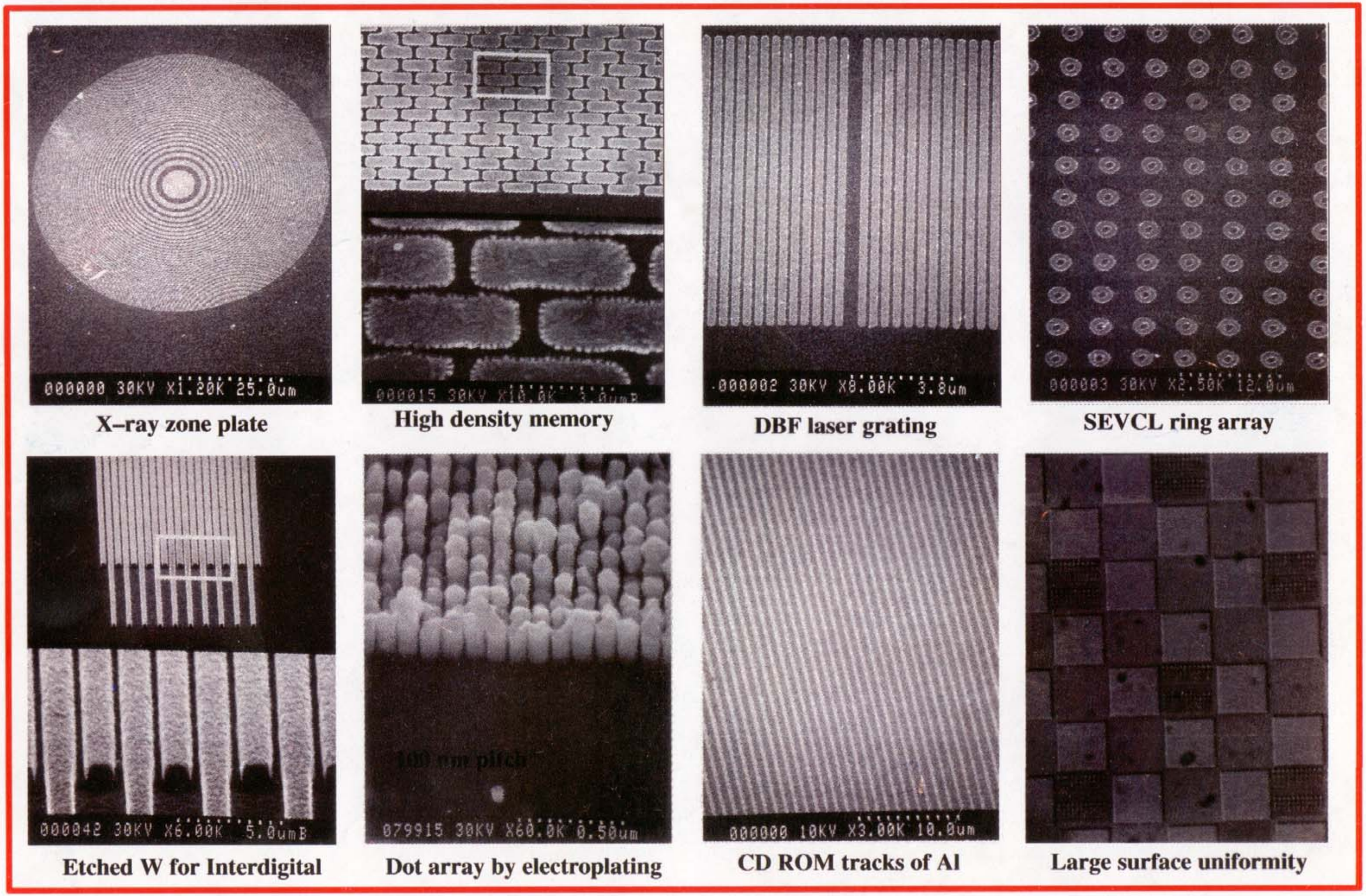


4. Etch of residual resist

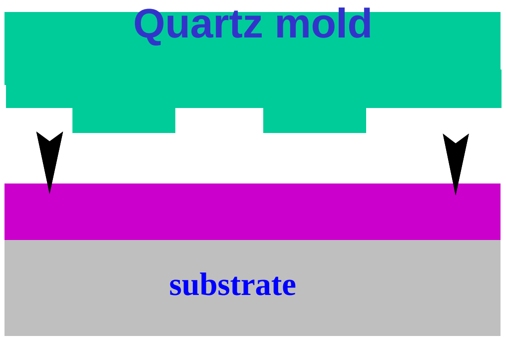


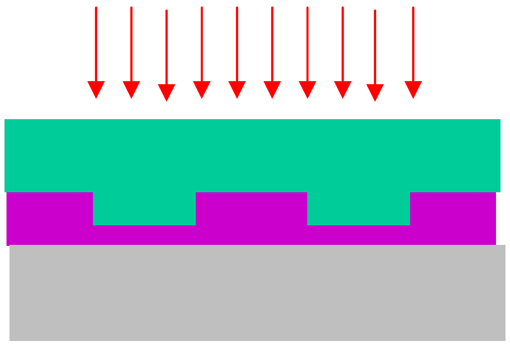
Slow process, Need mask at 1/1 scale i.e. e-beam lithography
Resolution demonstrated down to 10nm. Very chip!

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





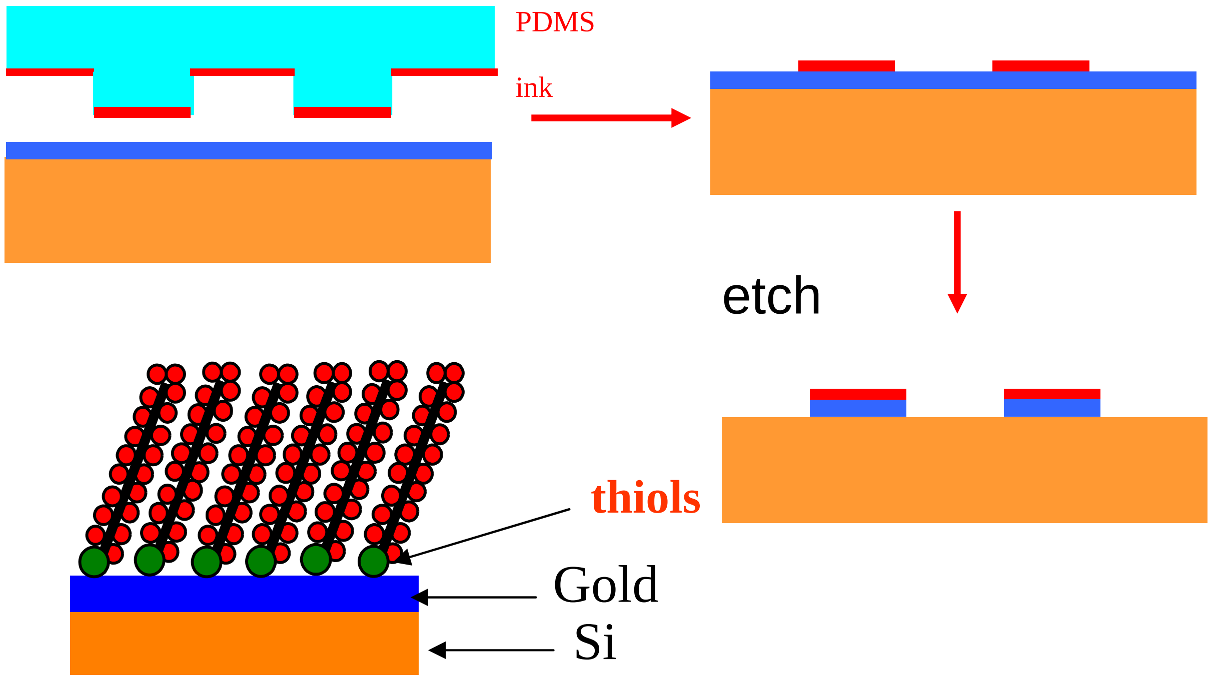
UV hardening of the resist

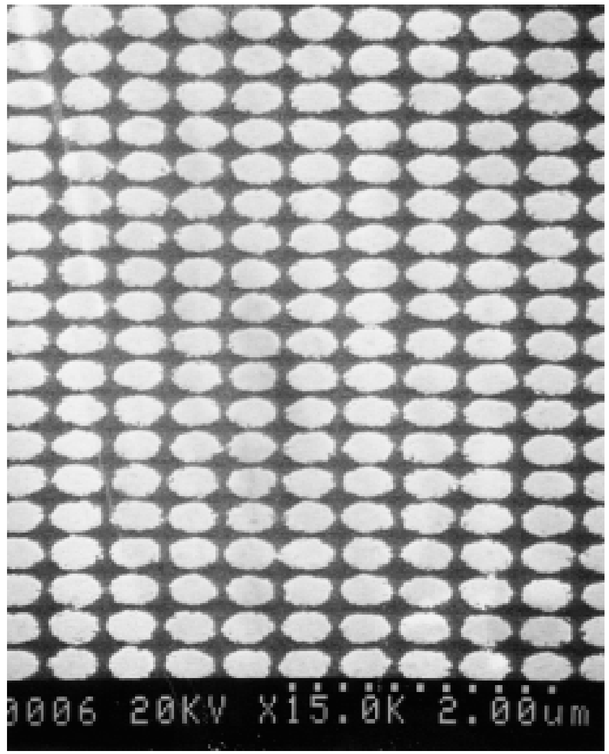
Much faster , still problem for alignment, commercial systems now

Nano-stamp

- Use of molecular adhesion

- Example : thiol group on gold





P = 400 nm

Conclusion on lithography techniques

Technique		Resolution	Use	Remarks
Optical lithography	contact	0.25µm	Labs and R&D	Economical
	proximity	2µm	Labs and R&D	Economical but weak resolution
	projection	80nm	Industrial	Expensive but with constant progress
EUV		<50nm	Industrial	May be the next tehnique for 2005
Electron lithography		1nm	Labs andR&D Fabrication of optical masks	Technique without mask best resolution
Lithographie ionique		8nm	Labs and R&D	Better for etchig than lithography (diagnostic)
Near field lithography		Atom 10nm	Labs	Economical, very slow specific
Nanoimprint		10nm	Labs and industry?	Economical, fast Alignment problems mask 1 :1

Transfert techniques

- Wet etching
- Ion Beam Etching
- Reactive Ion Etching
- Reactive Ion Beam Etching
- Dense plasma

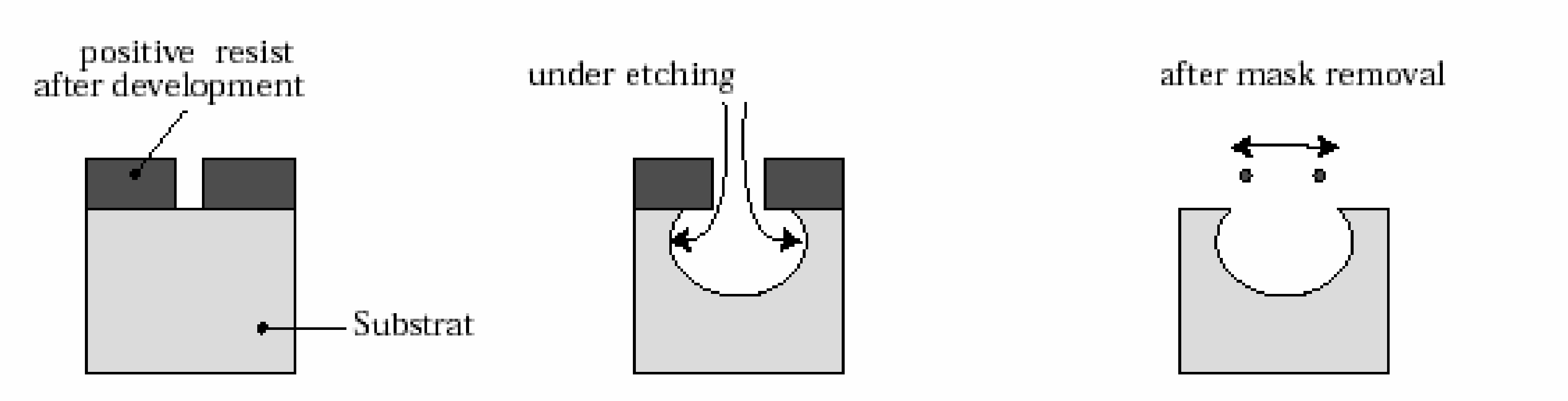
Wet etching

isotrope wet etching

•Simple

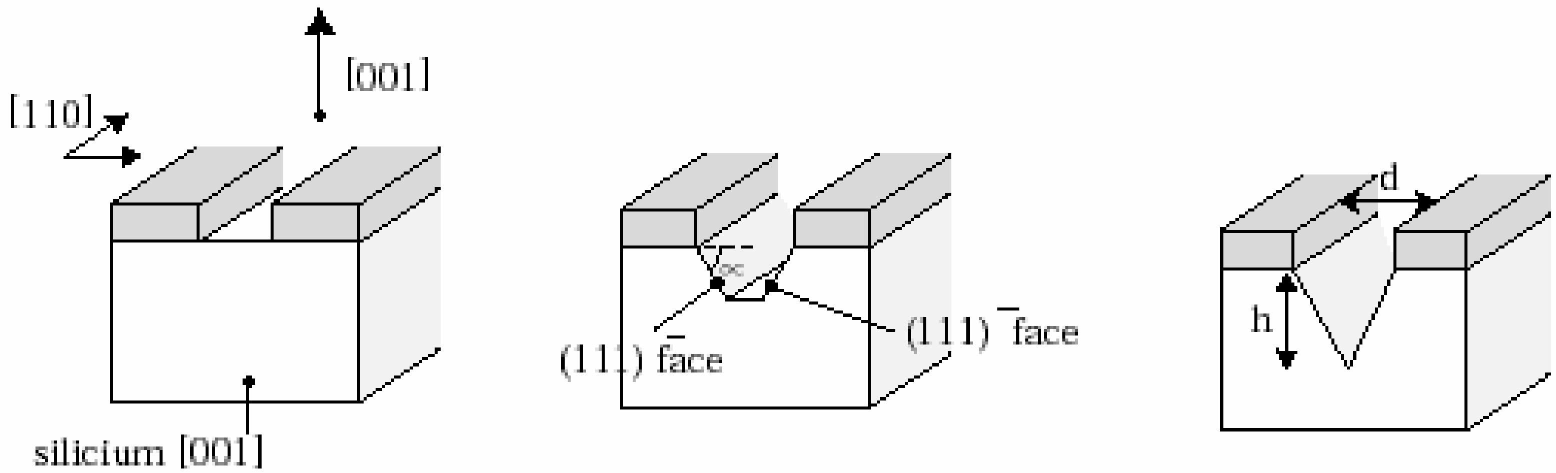
•Fast

•Do not respect the design rule



You may think to use under etching to reduce thee size. Difficult to control because of surface state:
strong etching (not sensitive to surface state) too fast
Weak etching slow but too sensitive to surface state

Anisotropic wet etching



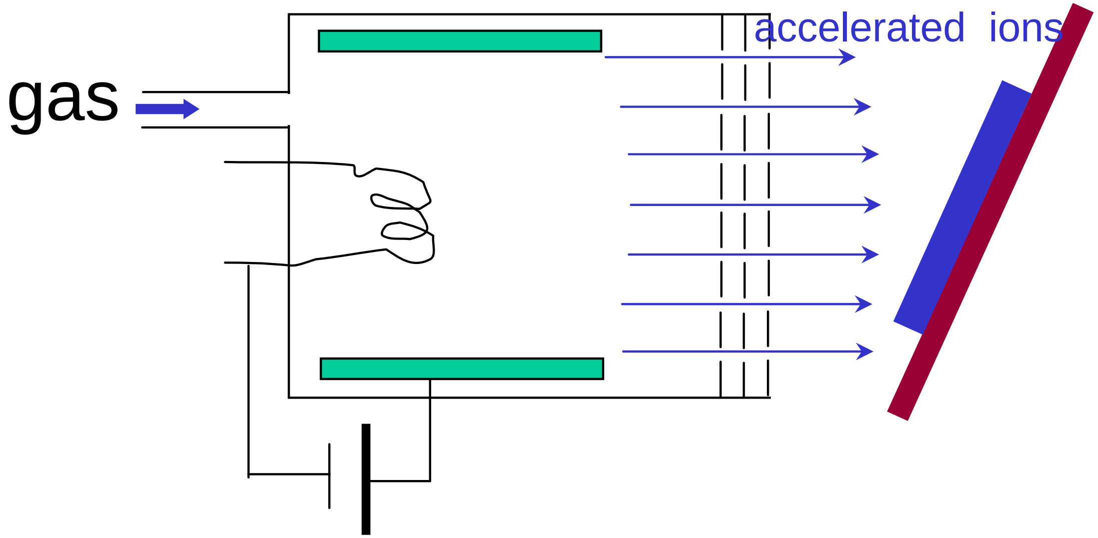
Use anisotropic etch rate with crystal face
Still some under-etch
Use to produce nice features over-growth in V-groves
Can be mixted with stop layer

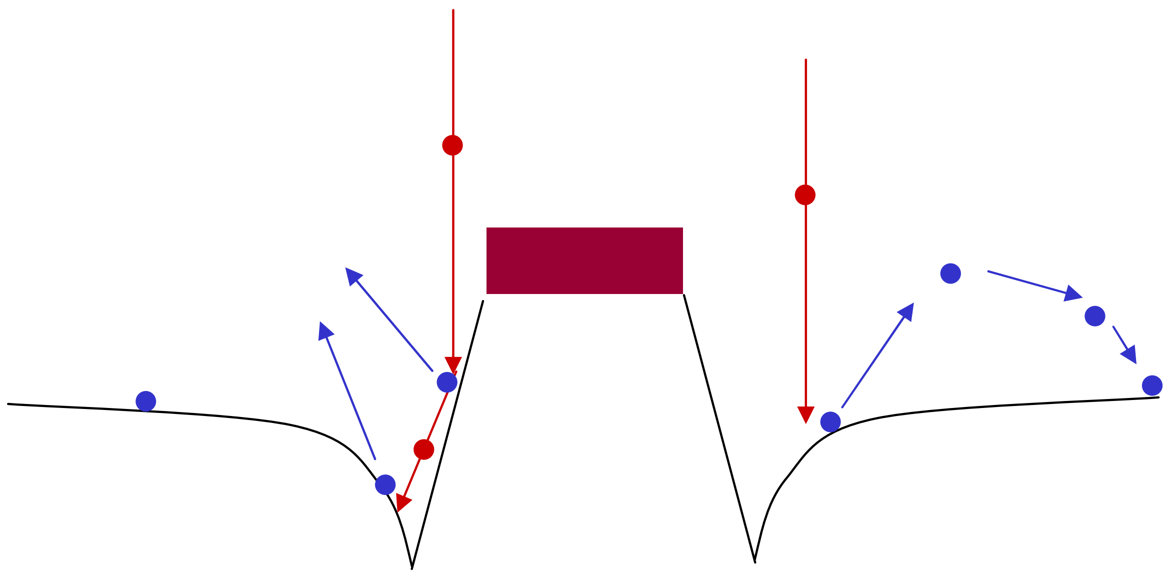
Ion Beam Etching
IBE

- Use the impact of impining ions.
- Purely physical
- Sputtering rate T

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

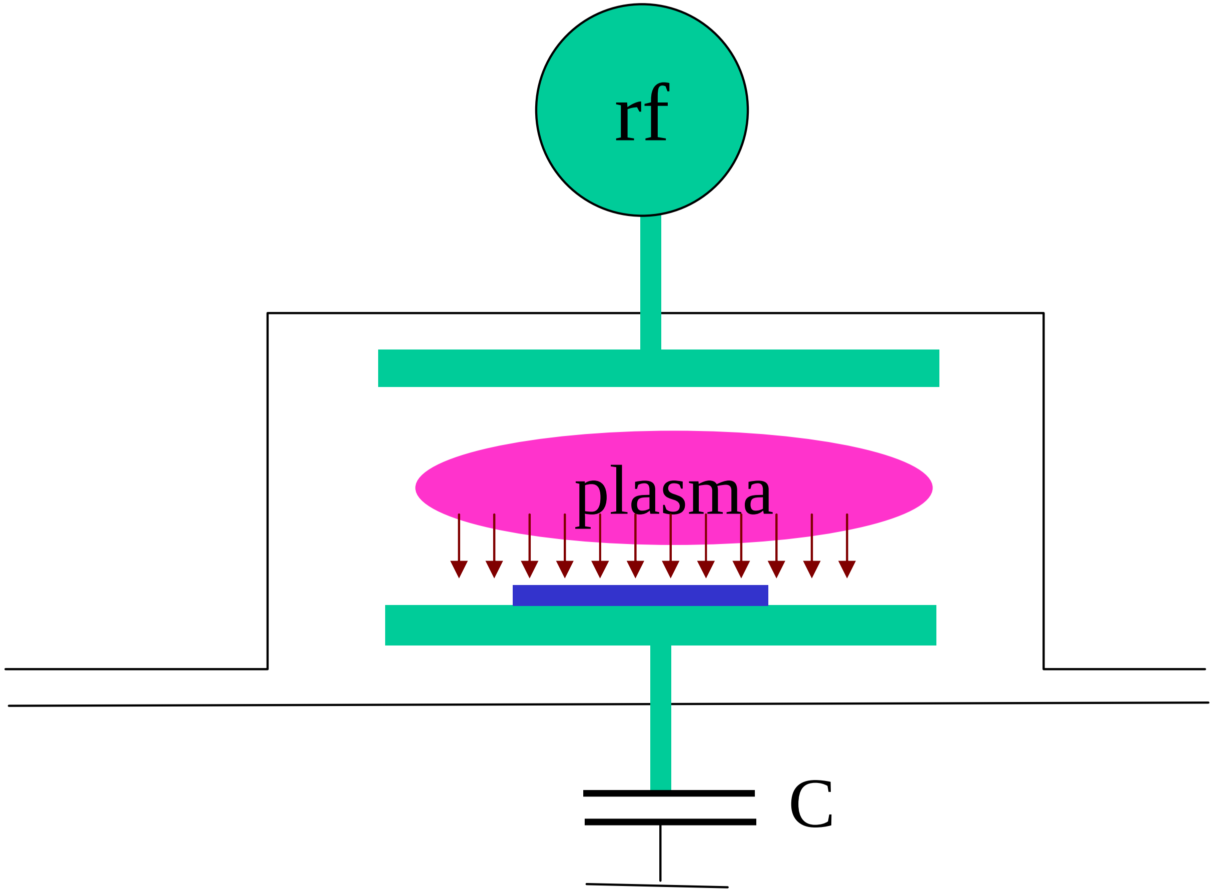
U binding energy of material
Z atomic number of mateerial
E ion energy x coeff (angle)





- Quite slow
- No selectivity
- Re-deposition
- Trenching
- damage

Reactive ion etching: RIE

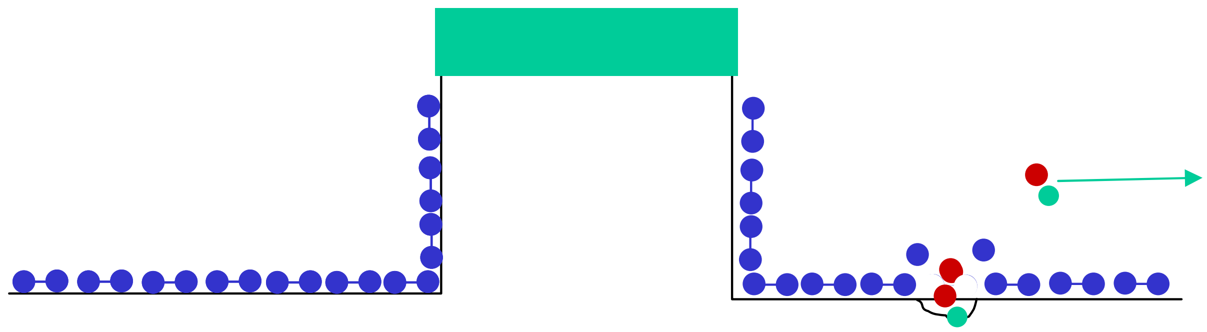


Autopolarisation few100V

Chemically active ions

Anisotropy achievement

●-● passivation gas

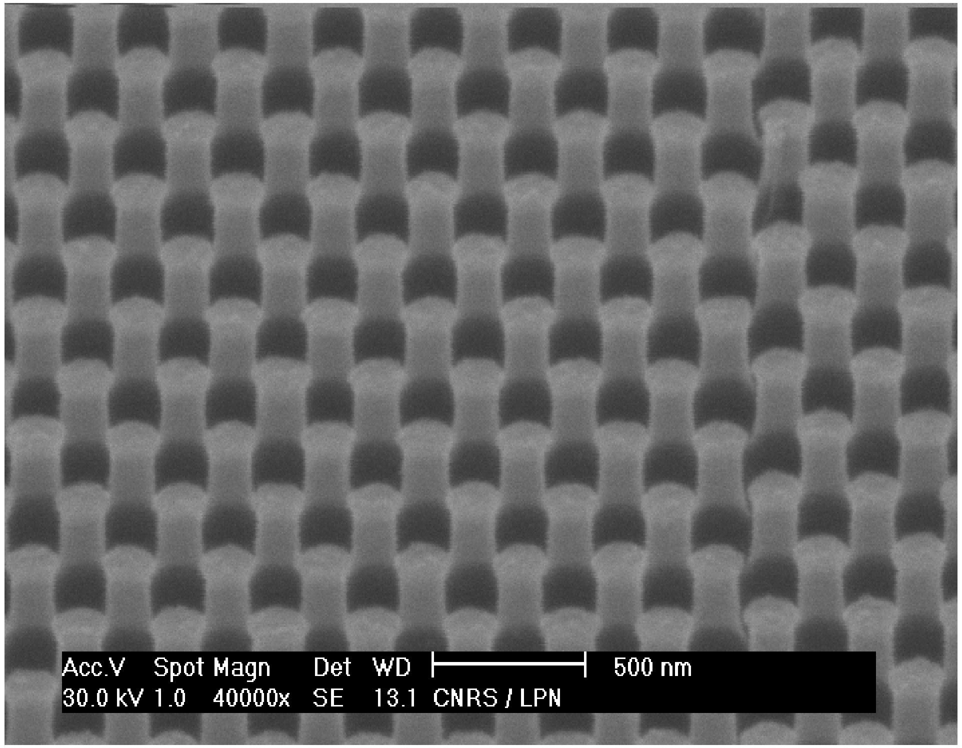


Avantages of RIE

- Fast proceess
- Selectivity
- Anisotropy
- No redeposition
- Use of passivation layer

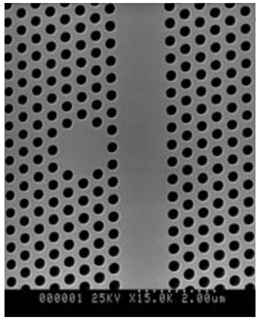
problems of RIE

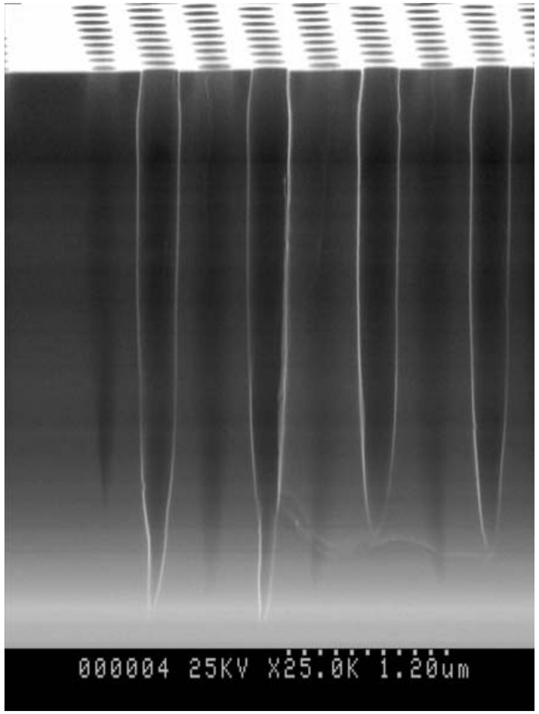
- Sensitive to pollution
- Energy and pressure are linked



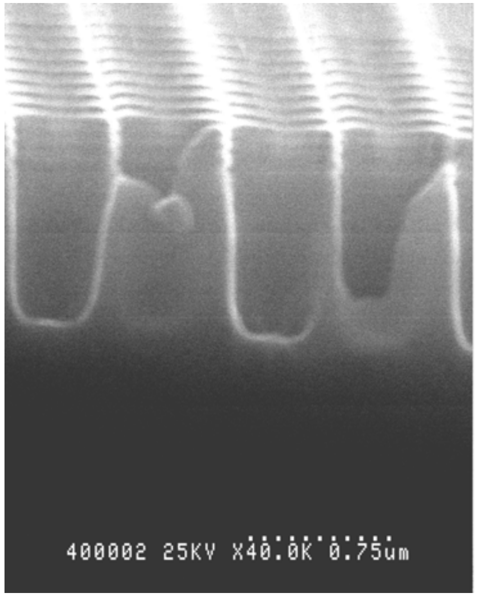
Reactive Ion Beam Ething:RIBE

- Same as IBE but with chemically active ions
- Allows to separate the physical/chemical action
- Impressive aspect ratio

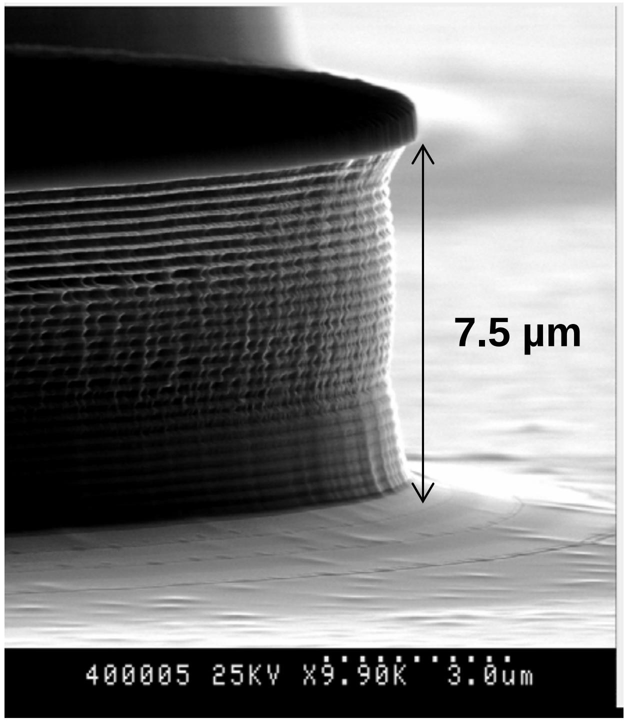




Examples RIE



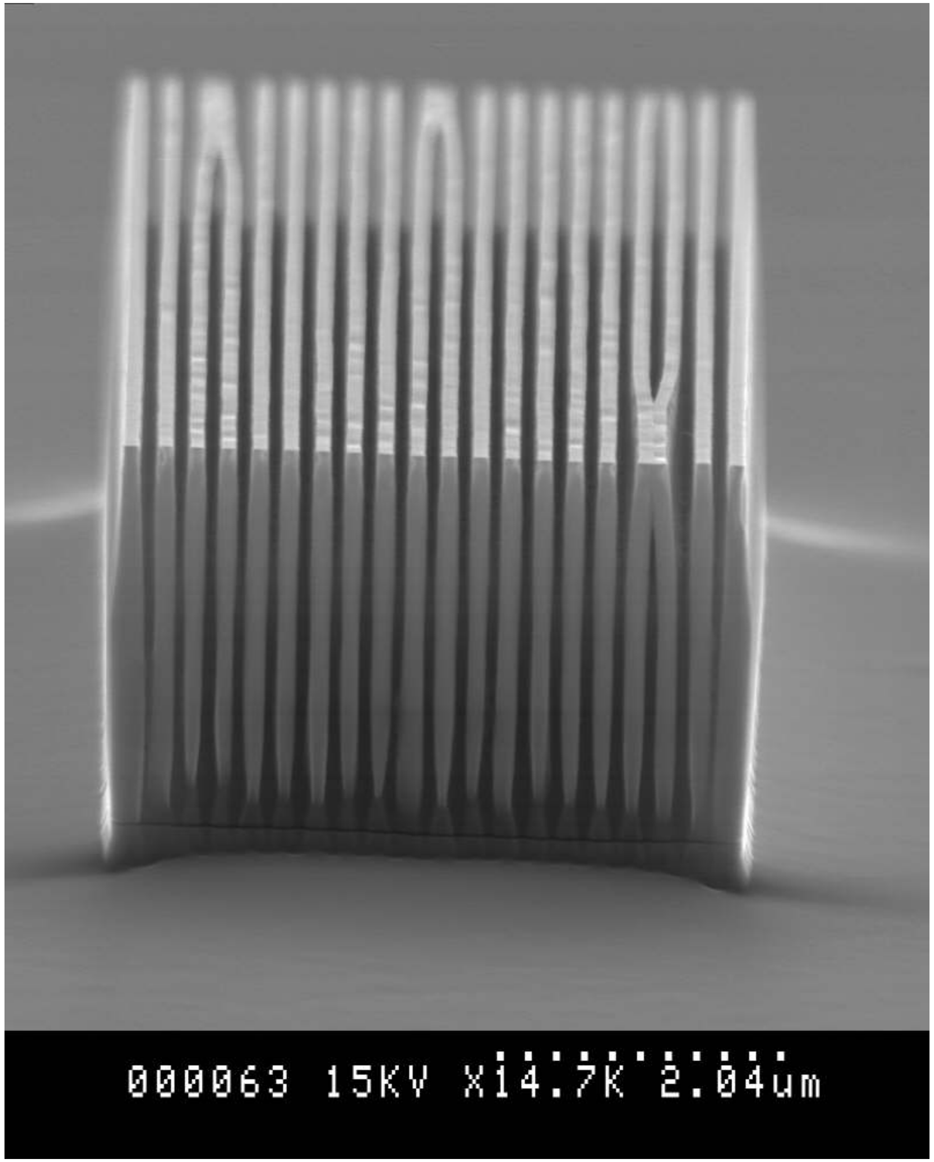
Depth limited to 1.2mm
For 0.4mm diameter holes



1,94µmby 6,25µm

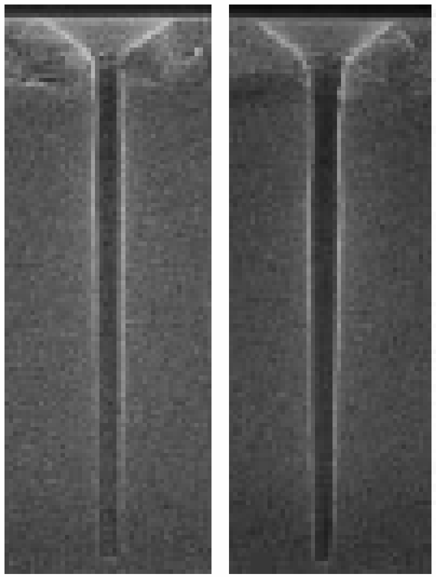
AlAs/GaAs miropillar

Example RIBE



Electron Cyclotron Resonance and Inductive Coupled Plasma

High density plasma (fast) with low energy (damage)
Independant control of energy/density



0.1-µm HARC

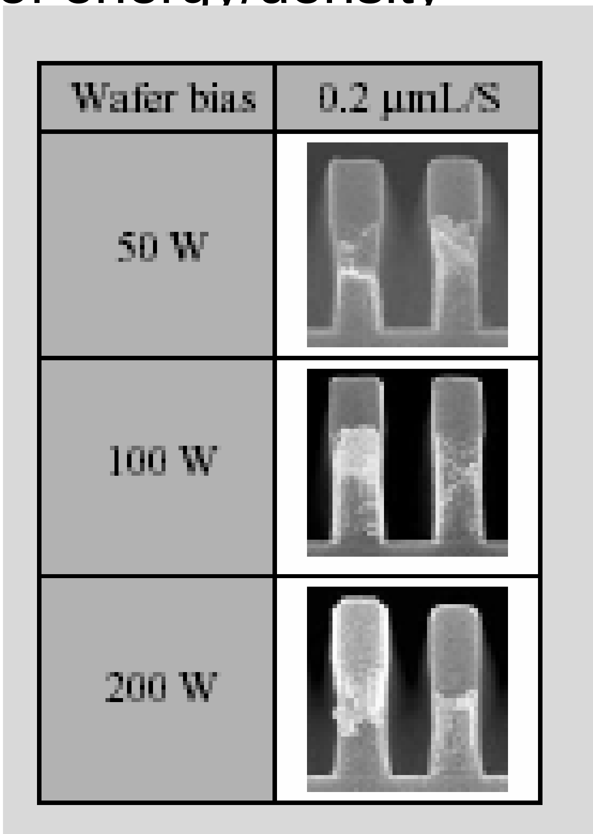


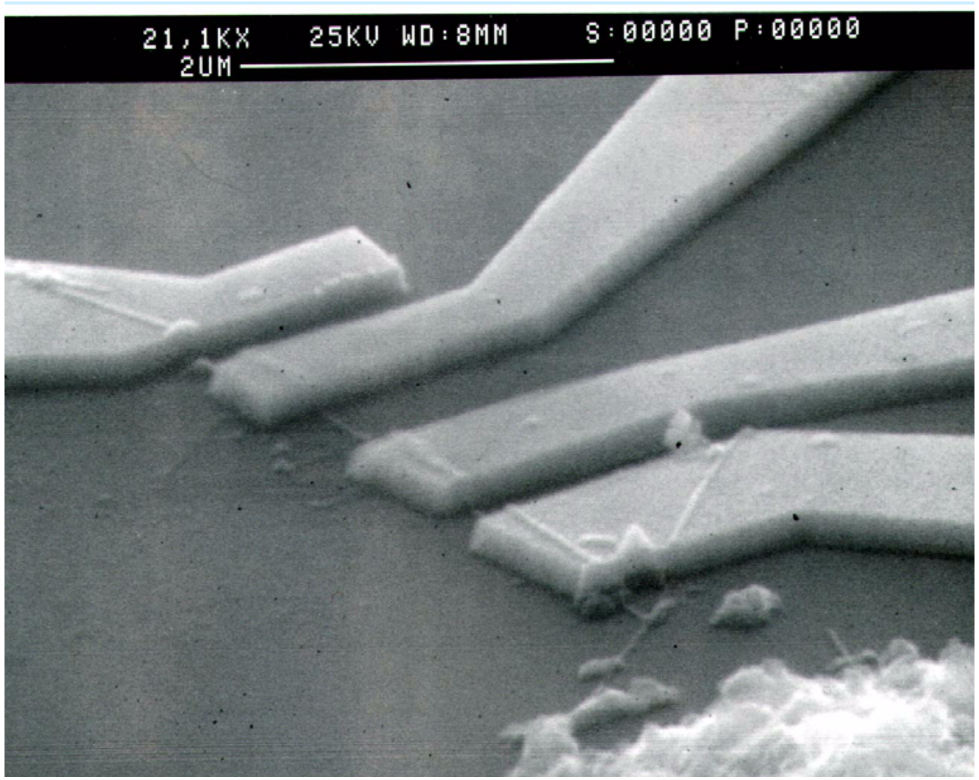
Fig. 7—Examples of Organic Film Etching
By independently controlling the ion energy, excellent mask shoulder selectivity and non residue etching are obtained.

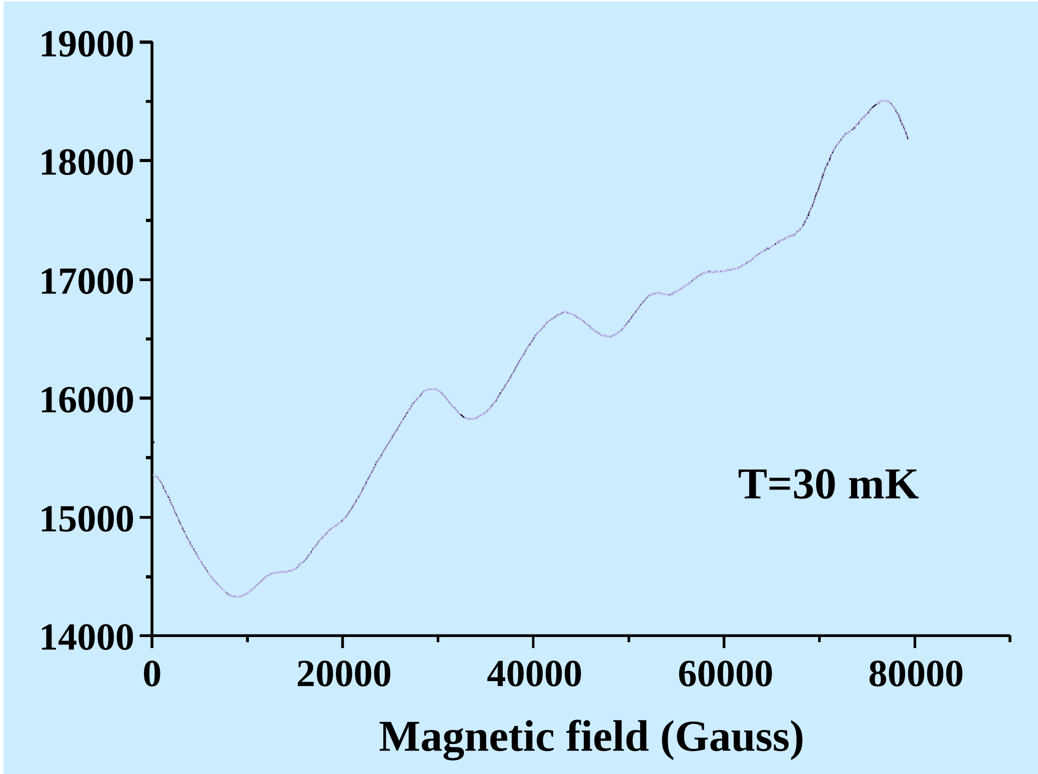
Top down and bottom up?

Both techniques tend to the same dimension

Future of nanotechnology will be certainly a mixing of these techniques
Addressing of individual macromolecules
Structuration of substrat

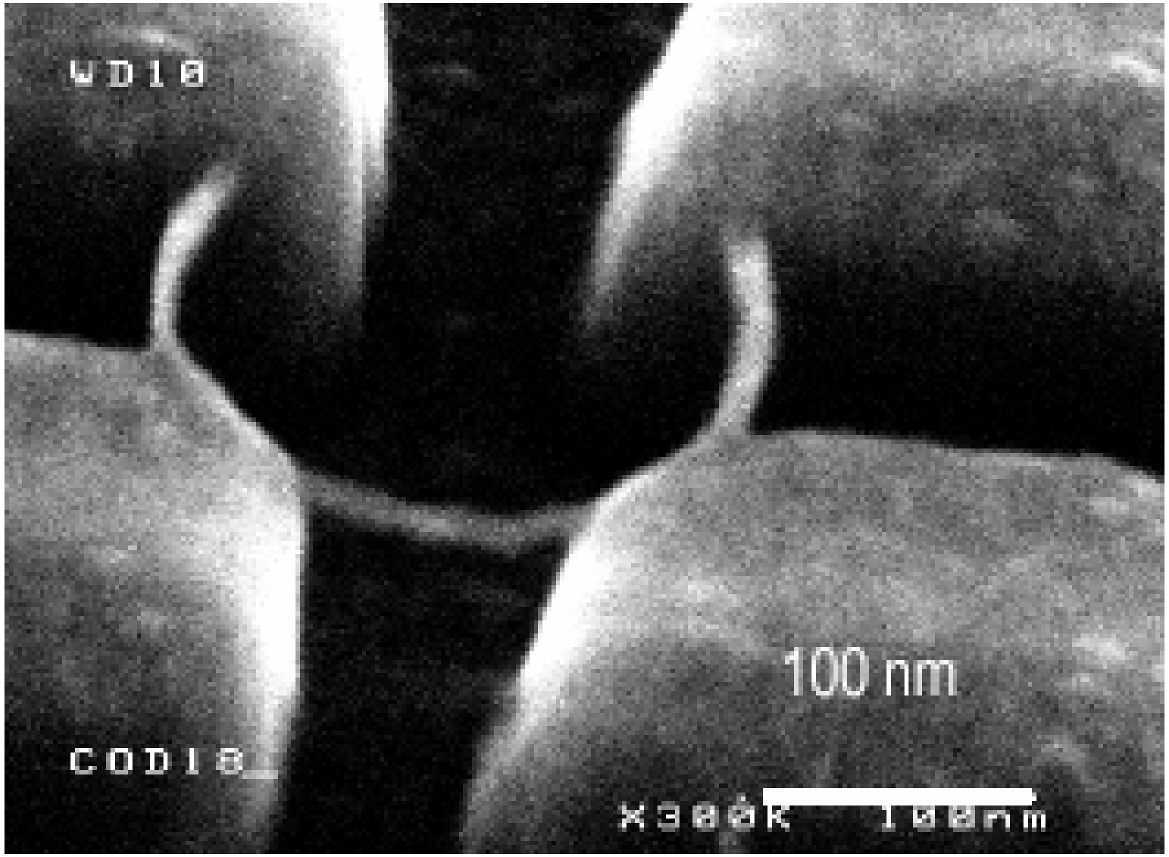
Carbone nanotube and e-beam lithography





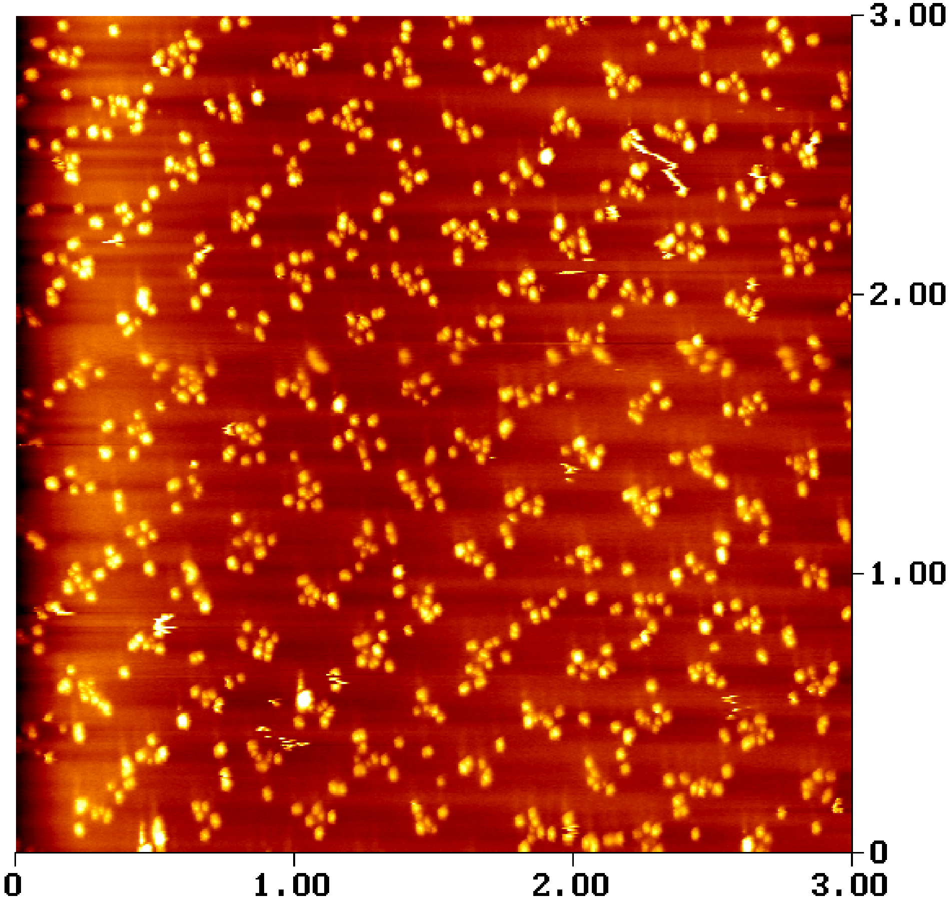
LPN-Marcoussis

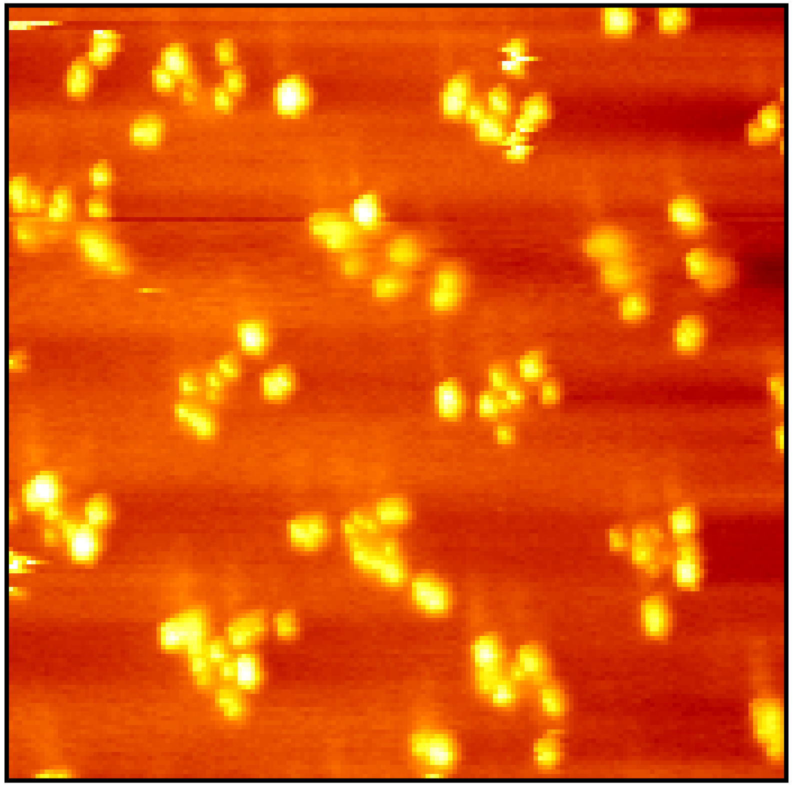
CVD growth of Carbone Nanotube on structured catalyst



LEPES Grenoble

Cluster deposition on structurated substrat





FIB structurated substart and gold cluster deposition
(coll. DMP Lyon - LPN)