



Micro/nano Fabrication

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cryocourse 2011

Why ?

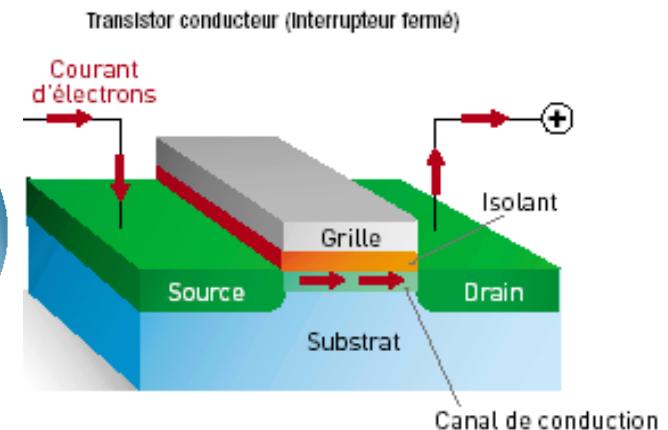
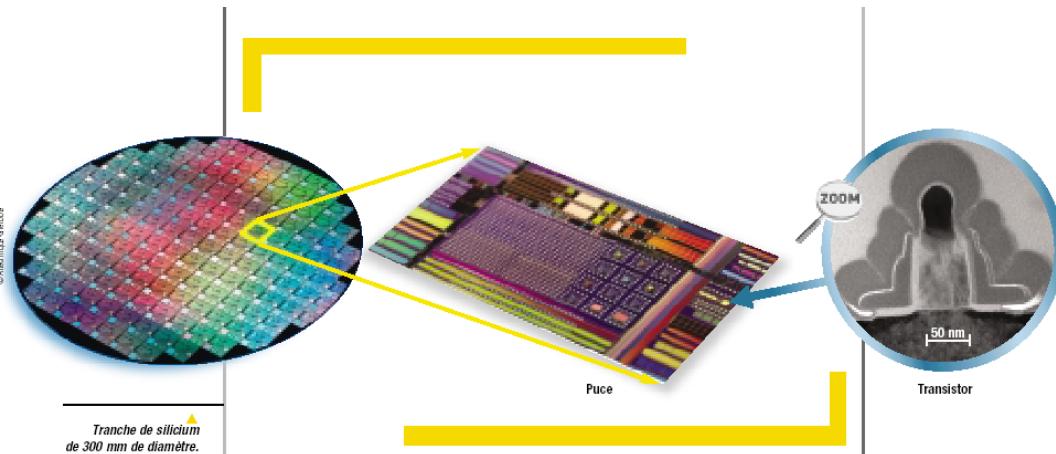
- Device miniaturization
 - smaller, faster and lighter electronic system
 - More informations on the same surface
 - Molecular electronic
- Biological applications
 - Labs on chip
 - In vivo
 - Gene sequencing
- Surface chemistry effects (great surface/volume ratio)
- Access to a new physic
 - Low dimension
 - Quantum effects

Access to nanoworld

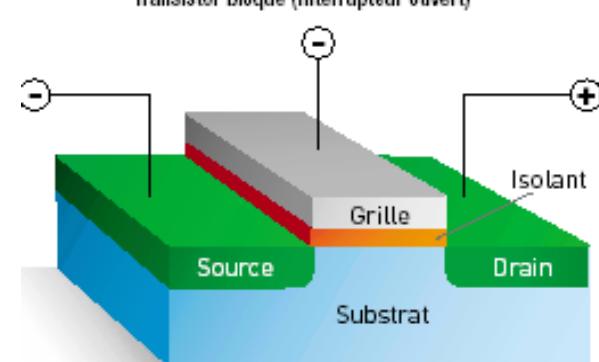
- Top-Down
 - Reduce the sizes from the « macroworld »
 - Lithography
- Bottom-up
 - Build nano-objects from individuals bricks
(atom, molecules)
 - autoorganisation

Top-down Microelectronics

© Alainna Géodé



From Silicon wafer to MOS Transistor



La fabrication d'une puce

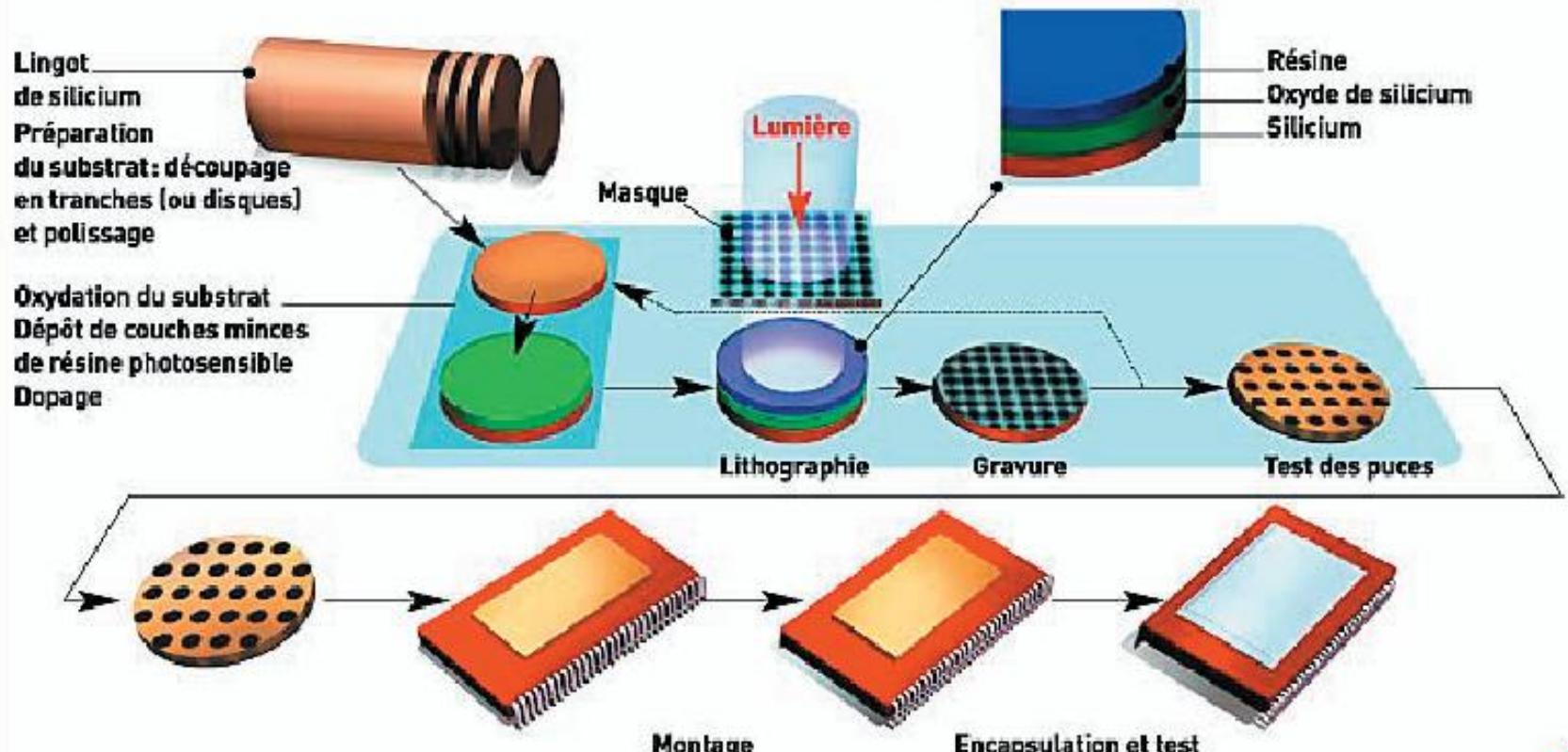


Fig.4 : Détails des étapes de réalisation des circuits intégrés, procédés Front-end et Back-end. Source CEA

Lithography

- Reproduce a pattern on a substrate
 - Through a resist
 - Optical lithography
 - Electronic lithography
 - Ion Beam lithography
 - Without resist
 - Focussed Ion Beam
 - Probe lithography

Lithography

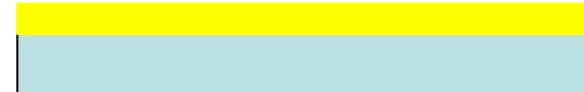
- Reproduce a pattern on a substrate
 - Mask Lithography
 - Optical lithography
 - Contact, projection
 - Nanoimprint
 - Maskless lithography
 - Scanning electron Beam lithography
 - Focussed Ion Beam Lithography
 - Zone-Plate-array Lithography
 - Probe Lithography

RESIST PROCESS

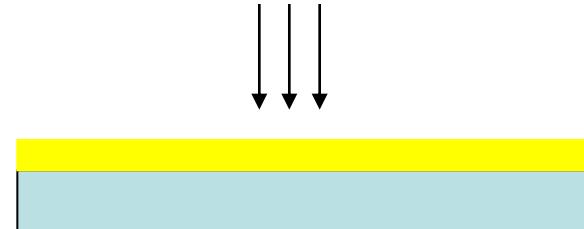
- 1/ Flat substrate



- 2/ Resist spinning

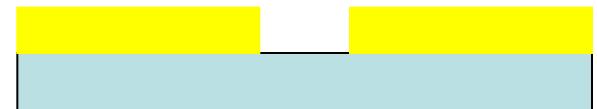


- 3/ Exposure

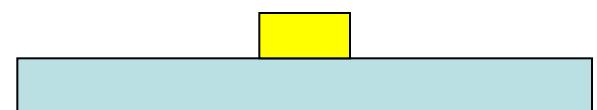


- 4/Developpement

- Positive resist



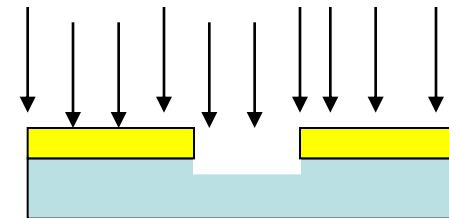
- Negative Resist



Transfert

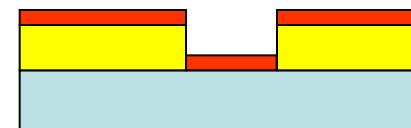
Etching

- Ion, chemically,...



- Lift-Off

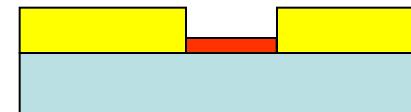
Déposition:
Metal,oxide



Dissolution
of the resist



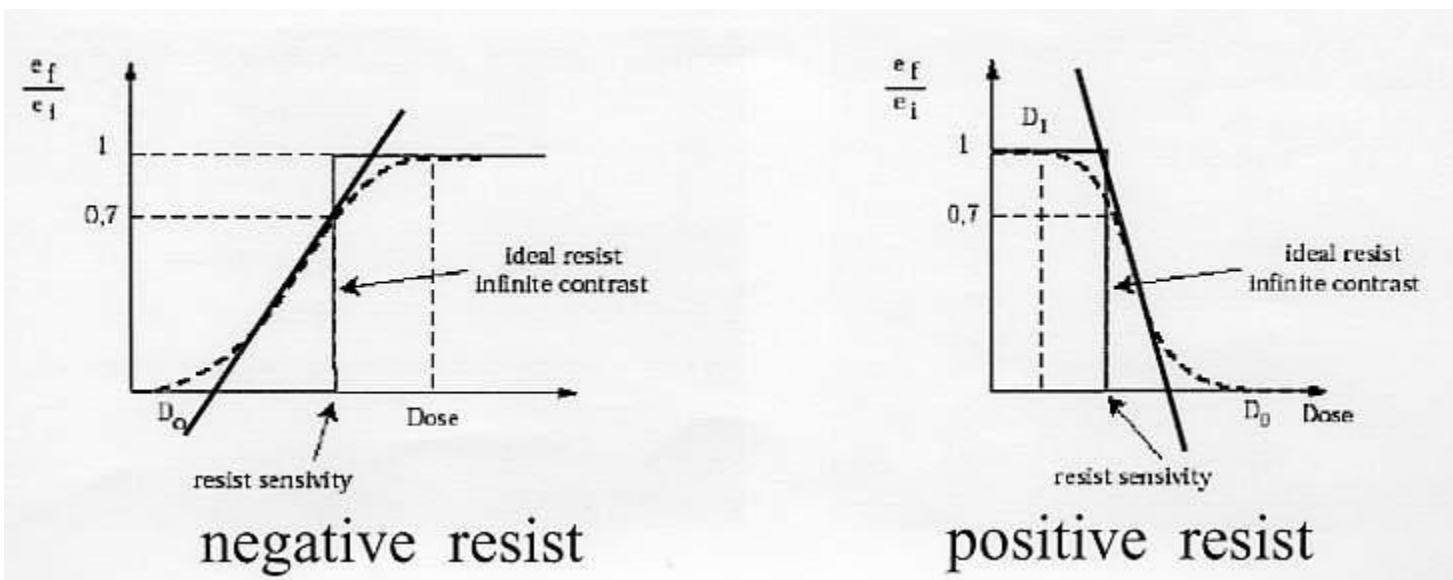
- Electrolytic growth



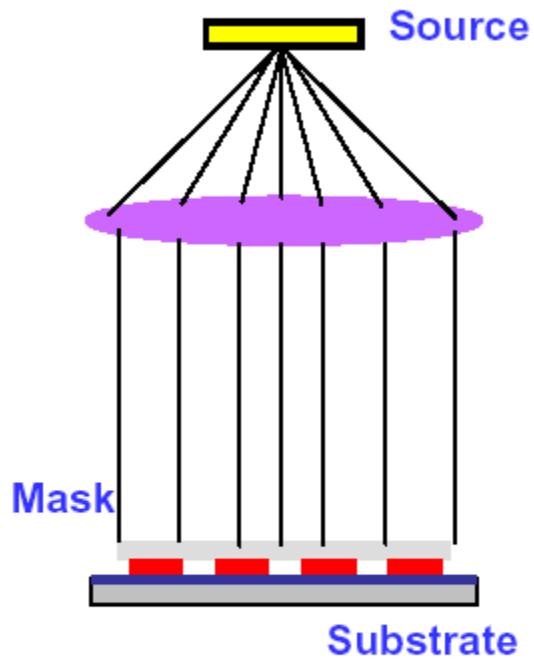
Resist

Dose= Incident Energy/Surface

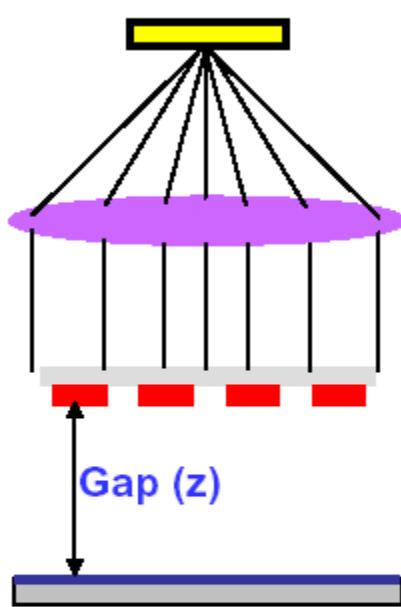
$T(D) = T_0 \gamma \ln(D/D_0)$ T : Photoresist remaining after development
D: Dose γ : contrast



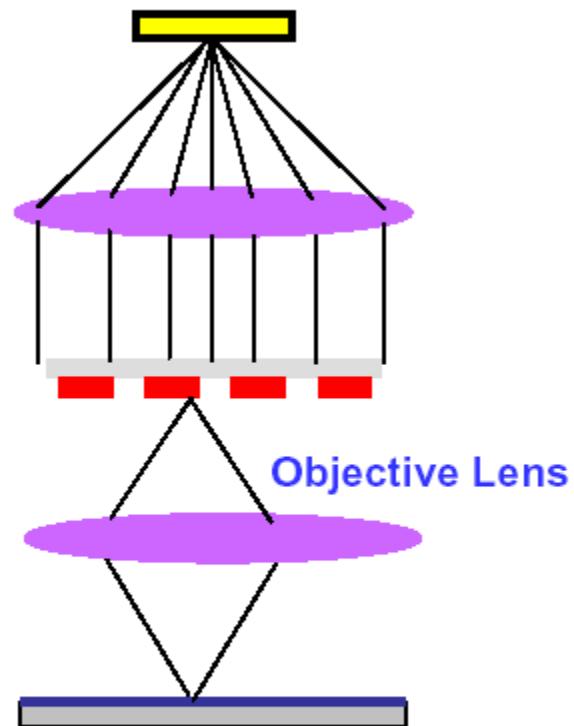
Contact



Proximity

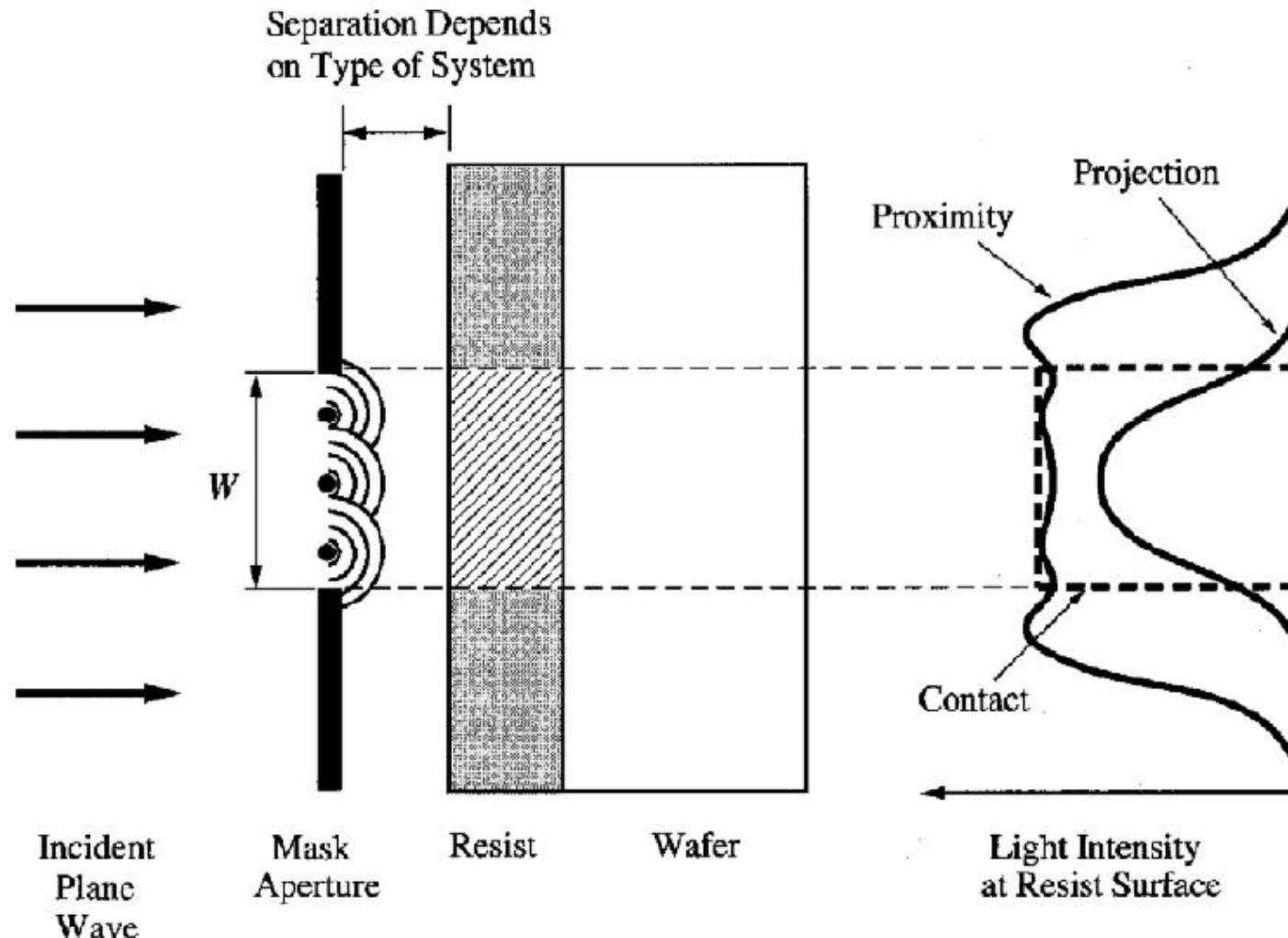


Projection



- Resolution controlled by λ and z
- Mask issues: 1x, damage
- Resolution affected by λ , NA
- Mask 4x, protected

Aerial Images formed by Contact Printing, Proximity Printing and Projection Printing

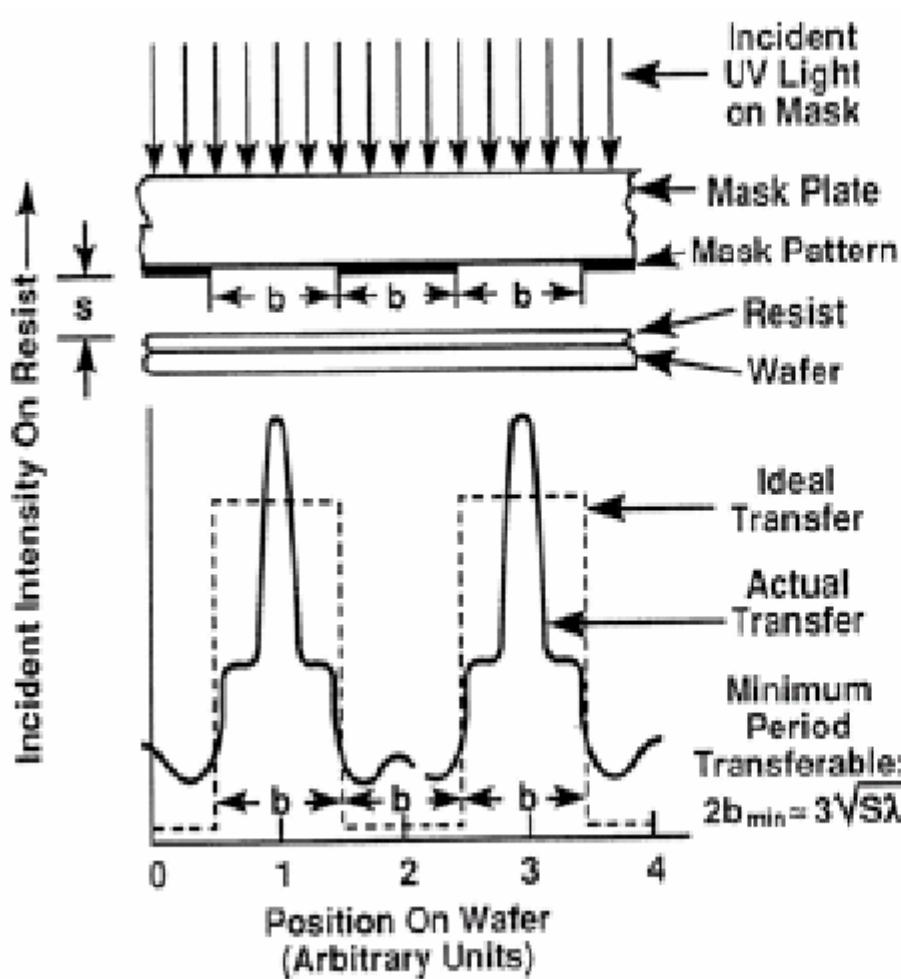


Professor Nathan Cheung, U.C. Berkeley

EE143

Lecture #11

CONTACT/PROXIMITY



- ✓ Light pass the mast should be square wave.
- ✓ It is never a square wave because diffraction.
- ✓ Photo-resist help to compensate for diffraction and give us a uniform pattern
- ✓ the Resolution limits

$$2b_{\min} = 3(\lambda s)^{1/2}$$

	$\lambda = 405nm$	$\lambda = 220nm$
$s = 1\mu m$	$0.68\mu m$	$0.50\mu m$
$s = 0.5\mu m$	$0.48\mu m$	$0.25\mu m$

Contact/Proximity

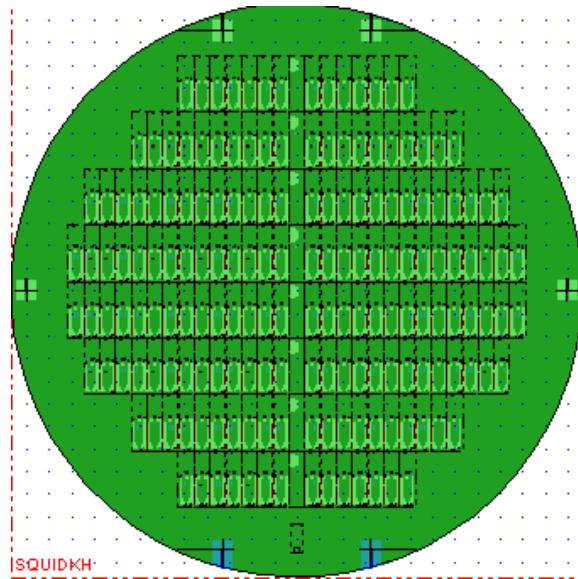
- + Simple/ Economical tools
popular in all RD labs
Parallel way 150 mm wafer



- Mask and Resist damages
Substrate flatness
Mask 1:1
Practical Resolution 0.5 micron



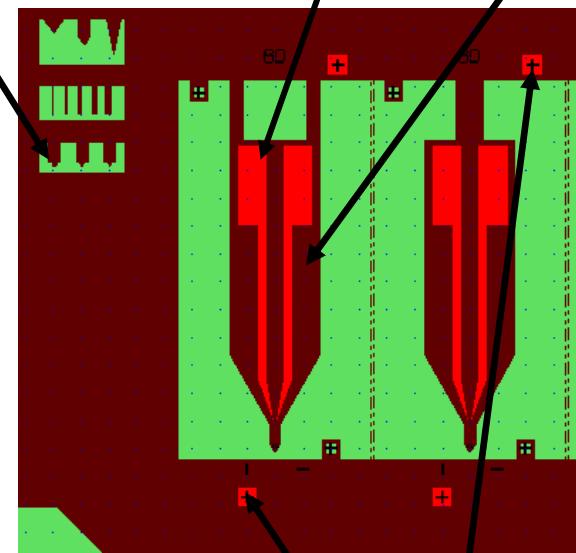
Mask Design



Test Device

Layer1

Layer 2



Multi-level design

Differents layers

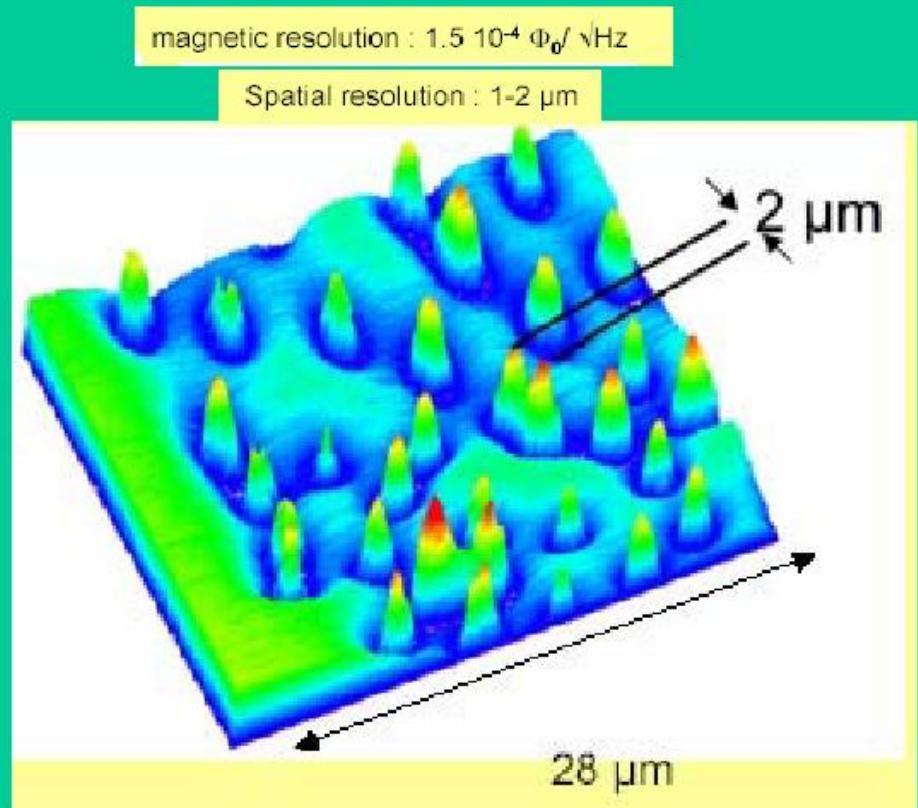
100 mm 1:1 mask

Cr/Glass UV Process

Cr/Quartz DUV Process

Cross alignement

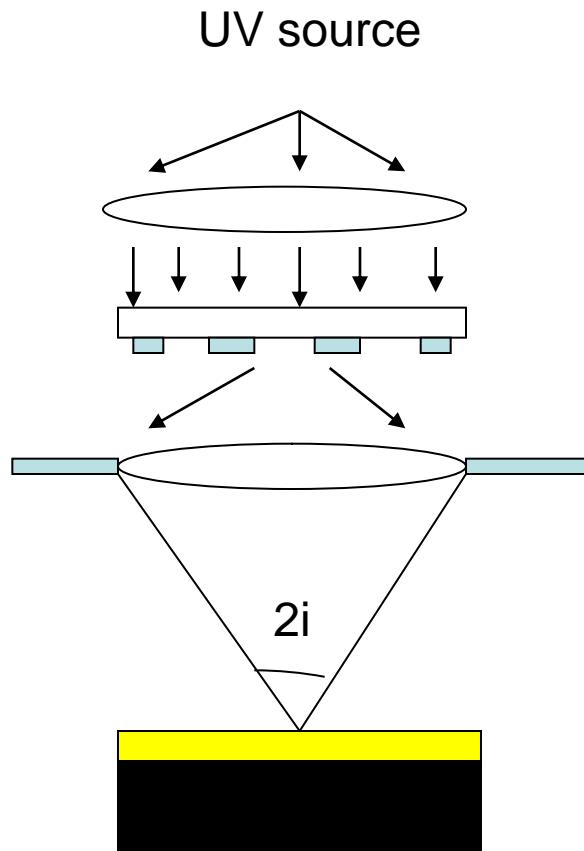
microSQUID on a tip



SEM picture of the μ SQUID

LPN
CRTBT Grenoble

Projection Lithography



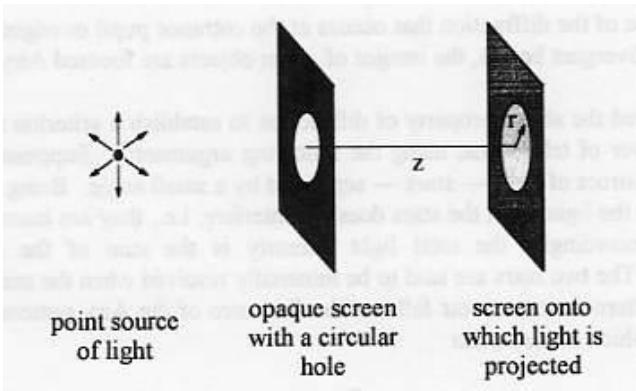
Resolution (diffraction)

$$R = k \lambda / N.A$$

- k : process parameter
Rayleigh criteria = 0.61
- λ : UV wavelength
- N.A Numerical Aperture
 $= n \sin i$

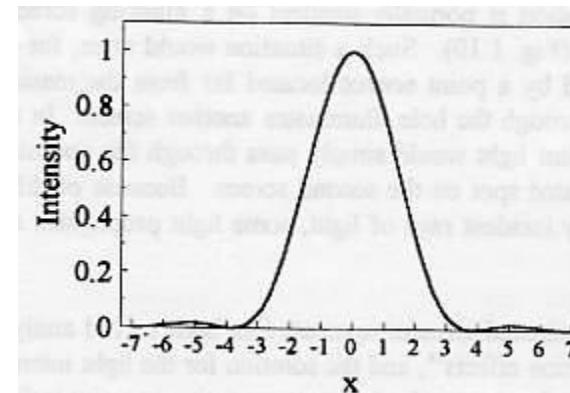
1:4 to 1:20

RAILEYGH CRITERIA



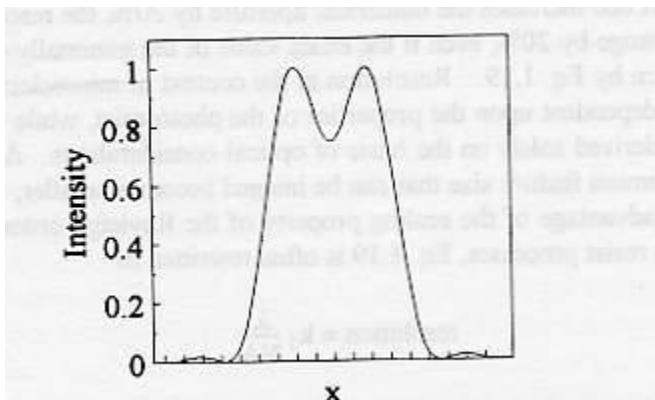
$$I(x) = I_0 \left(\frac{2J_1(x)}{x} \right)^2$$

$$x = kdr/2z$$
$$k = 2\pi/\lambda$$



A circular aperture illuminated by a point source

Light intensity distribution of one point source



Light intensity distribution of two sources

Two peaks are separated when

$$x/2\pi = 0.61$$

Or $d = 0.61\lambda/n\sin i$

« Raileigh resolution »

Lithography

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

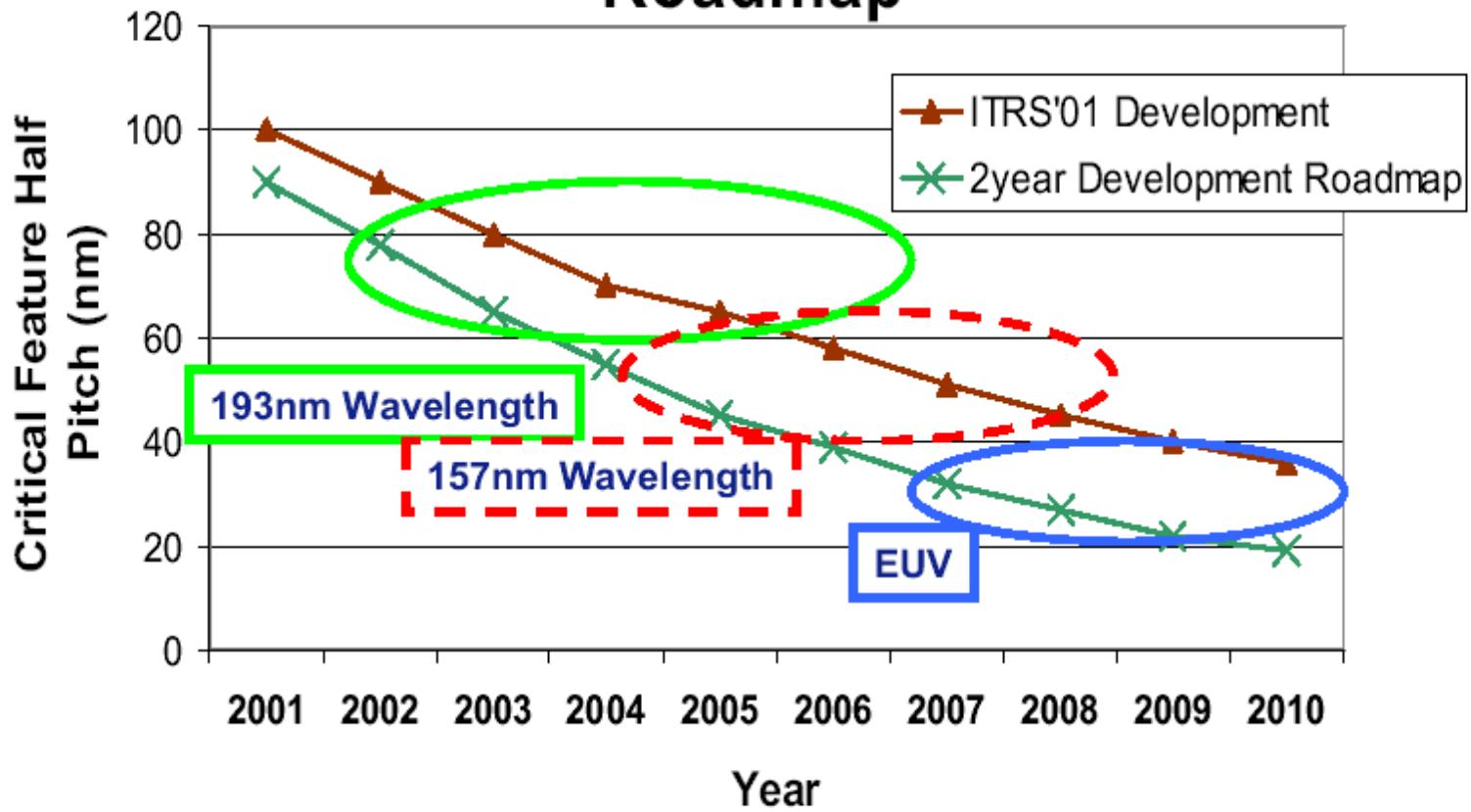
k: process parameter (resist, process dépendant)

Improve R: **-Decrease Wavelength**

-Increase N.A

-Reduce k

2001 Semiconductor Industry Roadmap



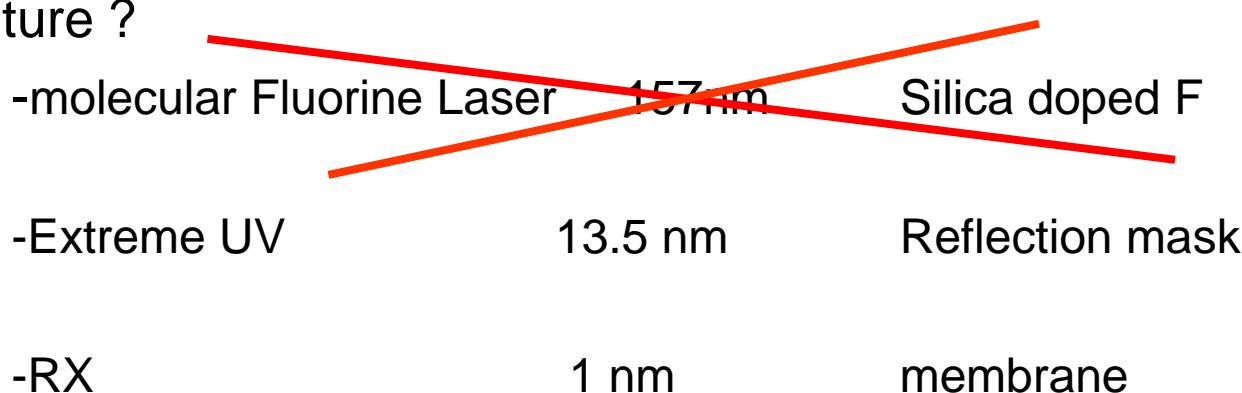
Brewer Science ARC Symposium, Albany, Oct 28, 2004



Wavelength

- 1980
 - Hg discharge lamp: G line 436nm glass UV 1.2 μm
 - Hg discharge lamp: I line 365 nm glass UV 0.5 μm
- 1990
 - Hg discharge lamp 250 nm Quartz DUV 0.3 μm
 - Laser KrF 250 nm Quartz DUV 0.3 μm
- 2000
 - Laser KrF 250 nm Quartz .13 μm
- 2003-2005
 - Laser ArF 193 nm .65

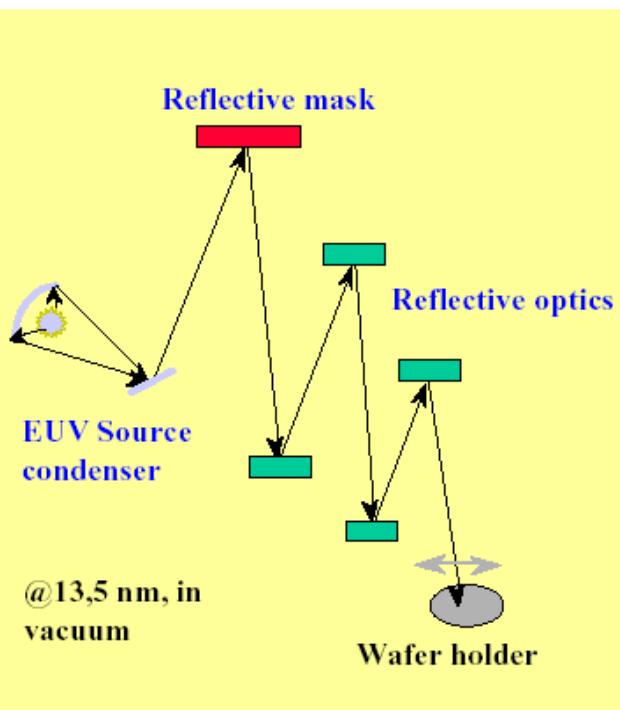
Future ?



Extreme UV



EUV Lithography: technological breakthrough



Everything absorb EUV light

✗ Vacuum

✗ Reflective masks and optics

Sources: based on plasma (Xe,Sn,In) emitting in EUV (13.5 nm)

✗ Laser Produce Plasma (LPP)

✗ Discharge Produce Plasma (DPP)

Specifications very tight

✗ ML mirrors: 70% reflectivity

✗ Masks: defects < 10^{-3} defects/cm²

✗ optics: < 0.1 nm roughness

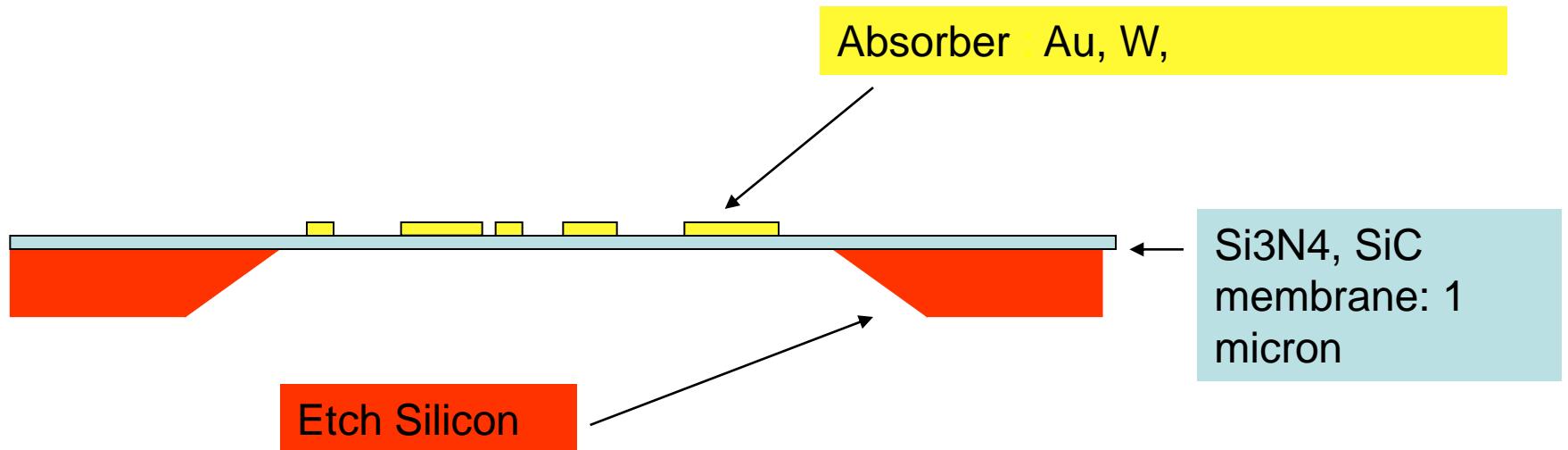
✗ sources: 120 W, no debris



X-Ray Lithography

X Ray Mask

- Stresses Control of membrane and absorber
- Mask 1:1



Lithography

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

k: process parameter (resist, process dépendant)

Improve R: -Decrease Wavelengh

-Increase N.A

-Reduce k

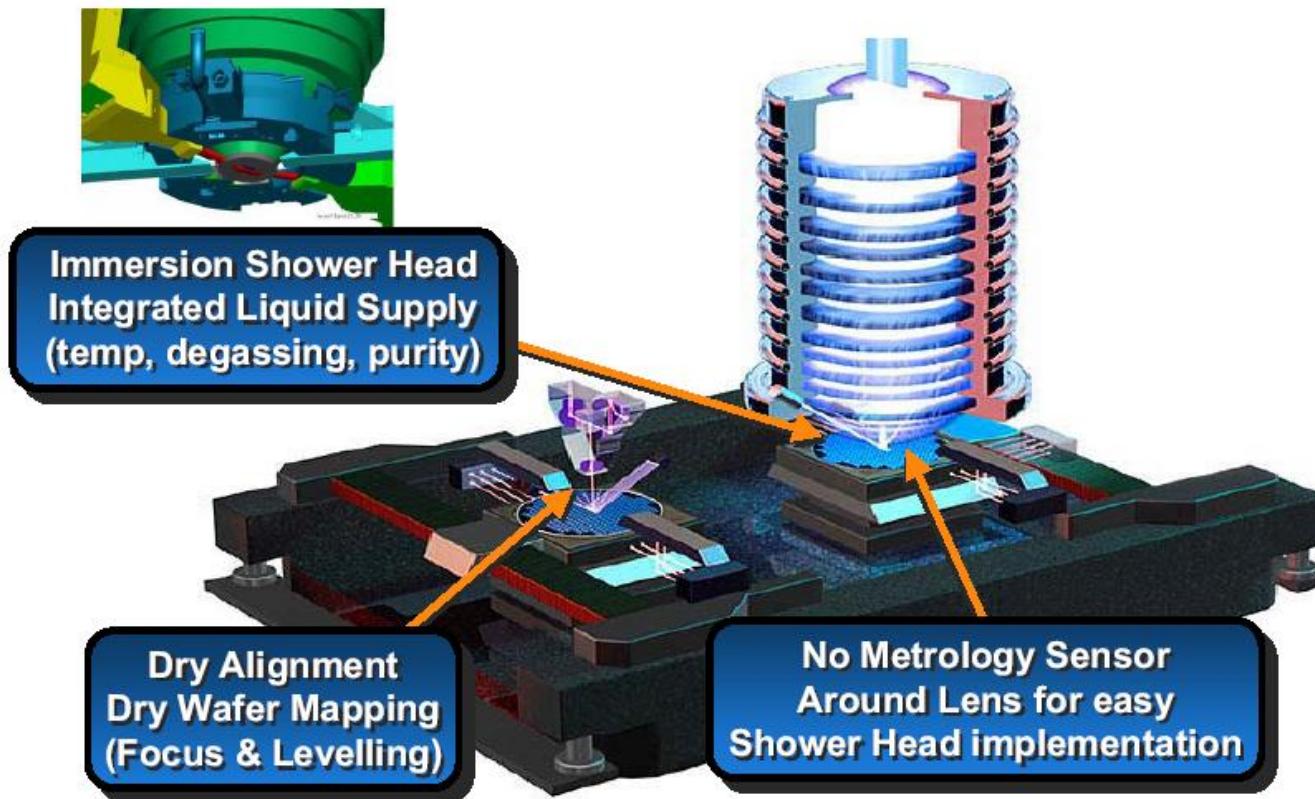
Increase N.A

$$N.A = n \sin i$$

- Increase i
 - From 0.5 in 1990 to 0.8 in 2004
 - Limitations: aberrations, size of image
- Increase n
 - Replacing air by a transparent liquid

Immersion

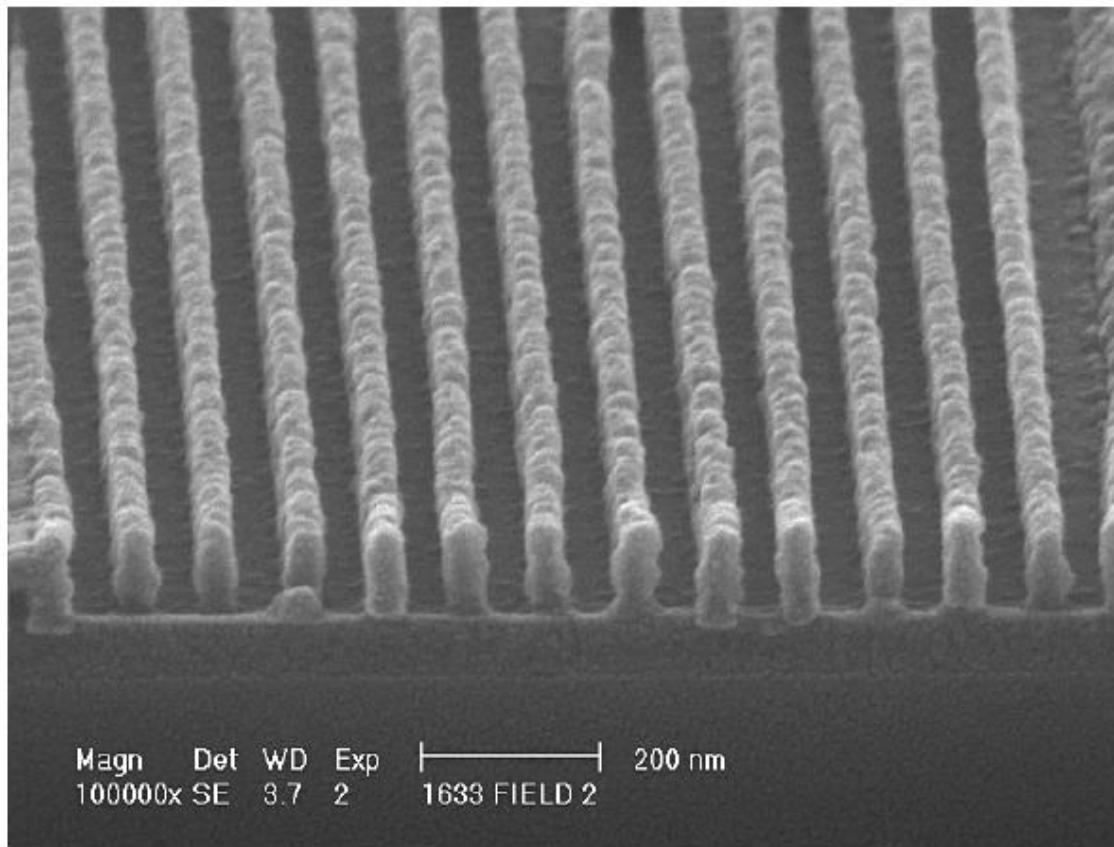
Dual Stage Advantage : Measure Dry - Expose Wet



Brewer Science ARC Symposium, Albany, Oct 28, 2004



45nm Node Imagery at 193nm Wavelength



Brewer Science ARC Symposium, Albany, Oct 28, 2004



Lithography

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

k: process parameter (resist, process dépendant)

Improve R: -Decrease Wavelengh

-Increase N.A

-Reduce k

Reduce k : optical engineering

- From 0.8 (1980) to 0.4

Masks

- OPC (Optical Proximity correction)
- PSM (Phase Shifting Masks)

Illumination

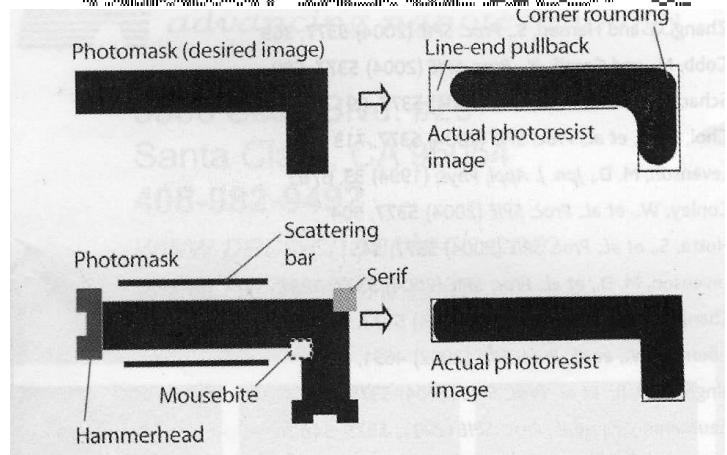
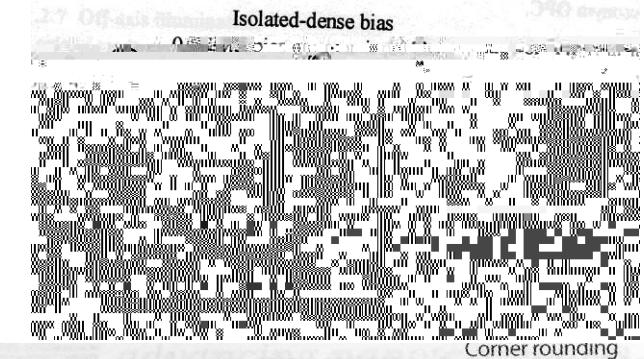
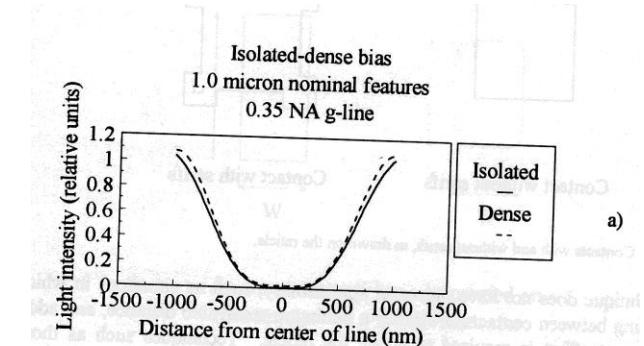
- Off-Axis illumination

Process

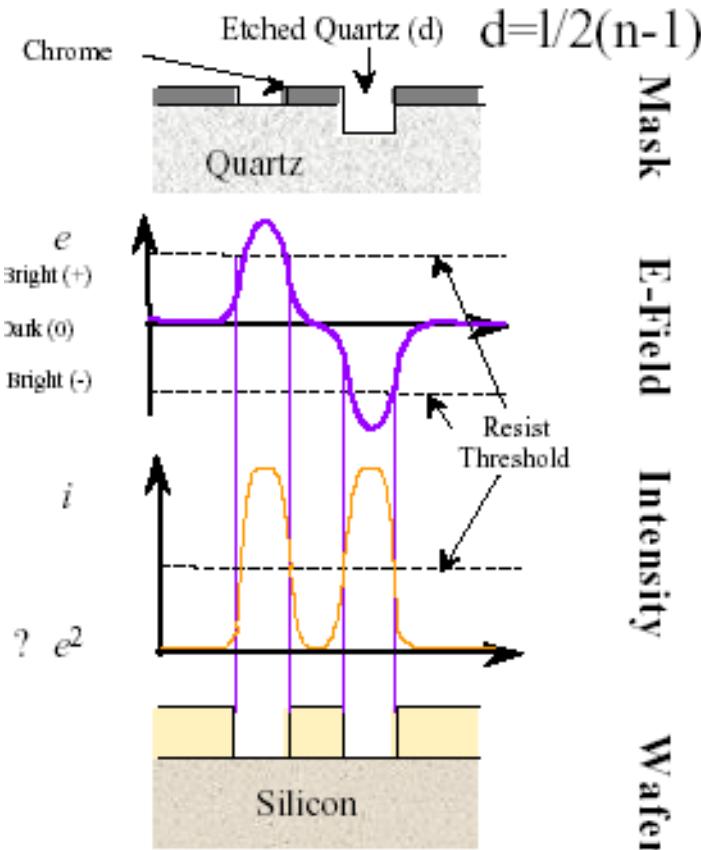
- Double exposition

OPC

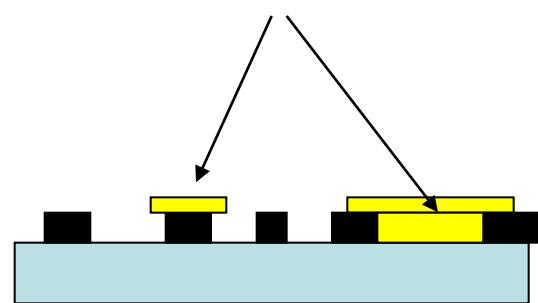
- Subwavelength lithography
- Diffraction
 - Proximity effects
 - Dense lines/ isolated line
 - Distortion
- Calculation inverse diffraction
- Correction of mask



Phase Shifting Masks



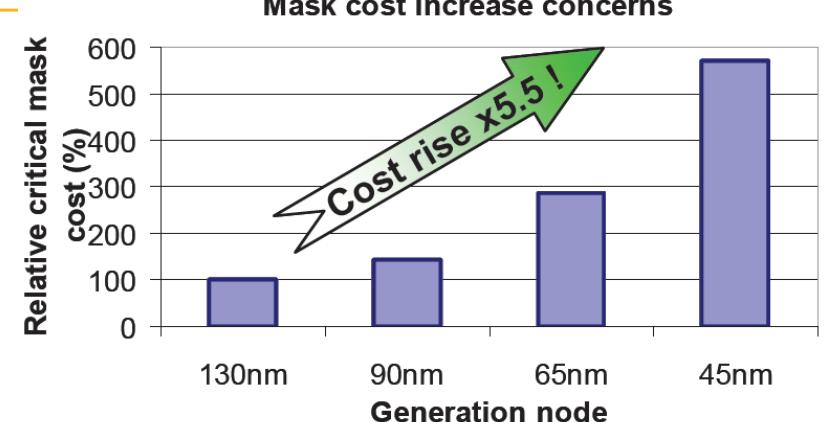
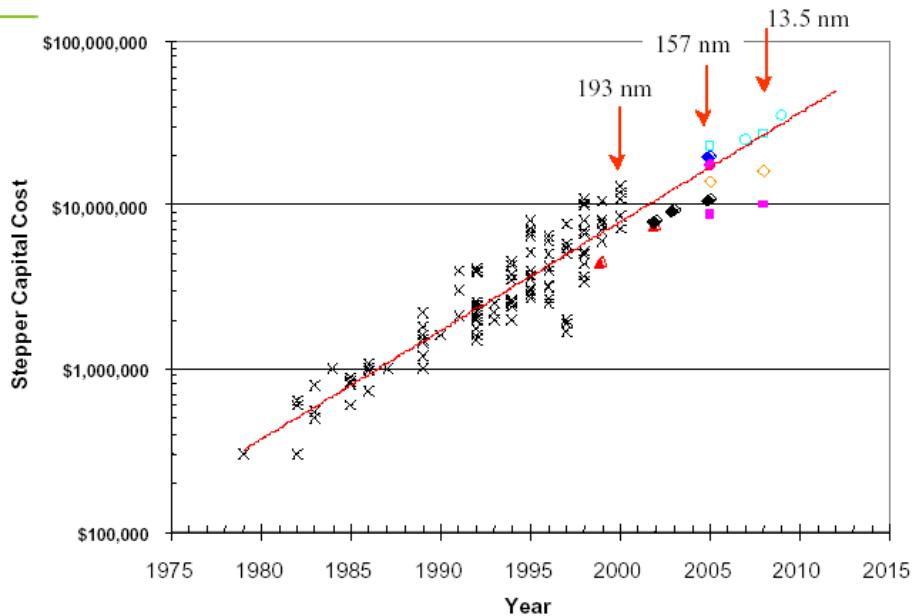
Phase Shifters



Résolution improvements: Increase of costs !!!



ISMT Exposure Tool Cost Projections

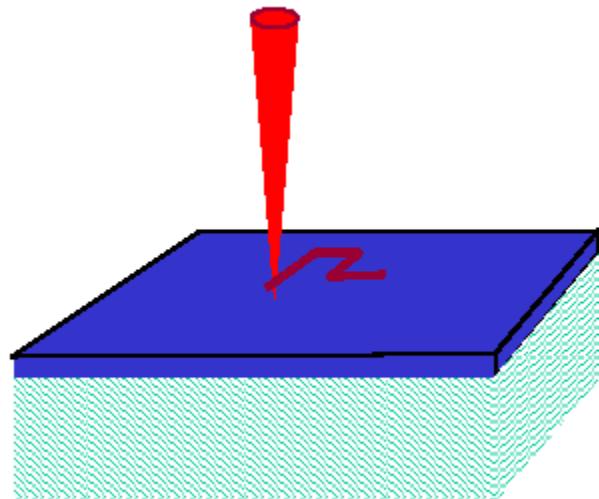


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S. Tedesco - litho 2006

Electron and Ion Lithography

Electron Beam Lithography



- Direct writing: no Physical masks
- Small spots (3-10 nm)
 - SEM
- Very small wavelength: no diffraction limitation
- Resolution: depends on resist, spot sizes
- Sequential: low throughput

EBL

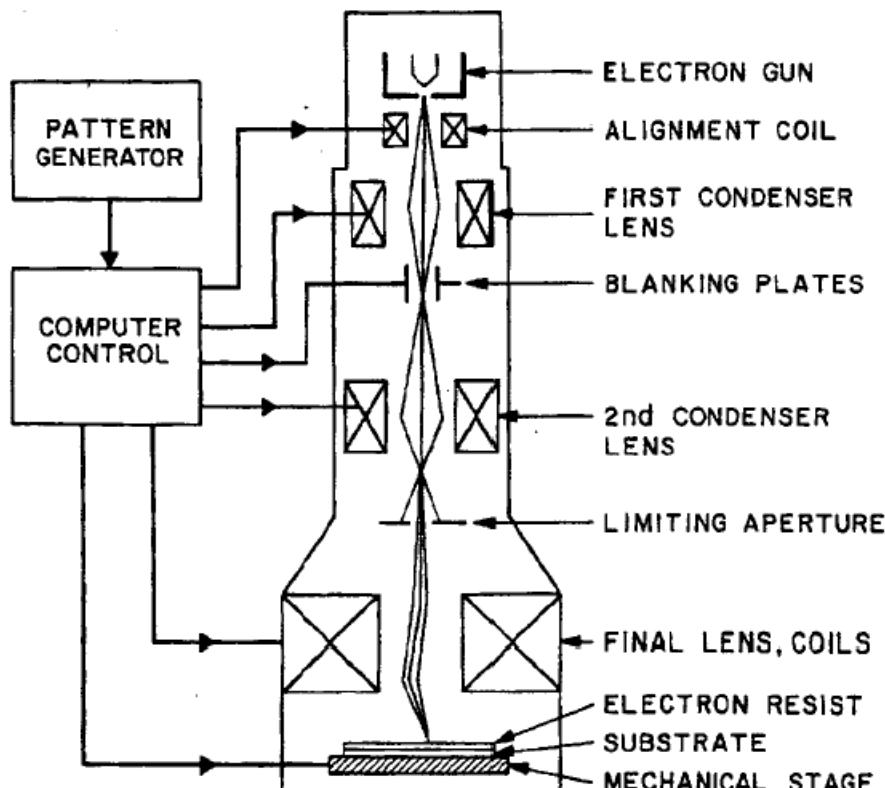


Fig. 13 Schematic of an electron beam machine.¹²

$$\lambda = \frac{12.3}{\sqrt{V}} \text{ Angstroms} \quad \text{for } V \text{ in Volts}$$

*Example: 30 kV e-beam
=> $\lambda = 0.07$ Angstroms*

NA = 0.002 – 0.005

Resolution < 1 nm

But beam current needs
to be 10's of mA for a
throughput of more
than 10 wafers an hour.

E.B.L: Gaussian scan

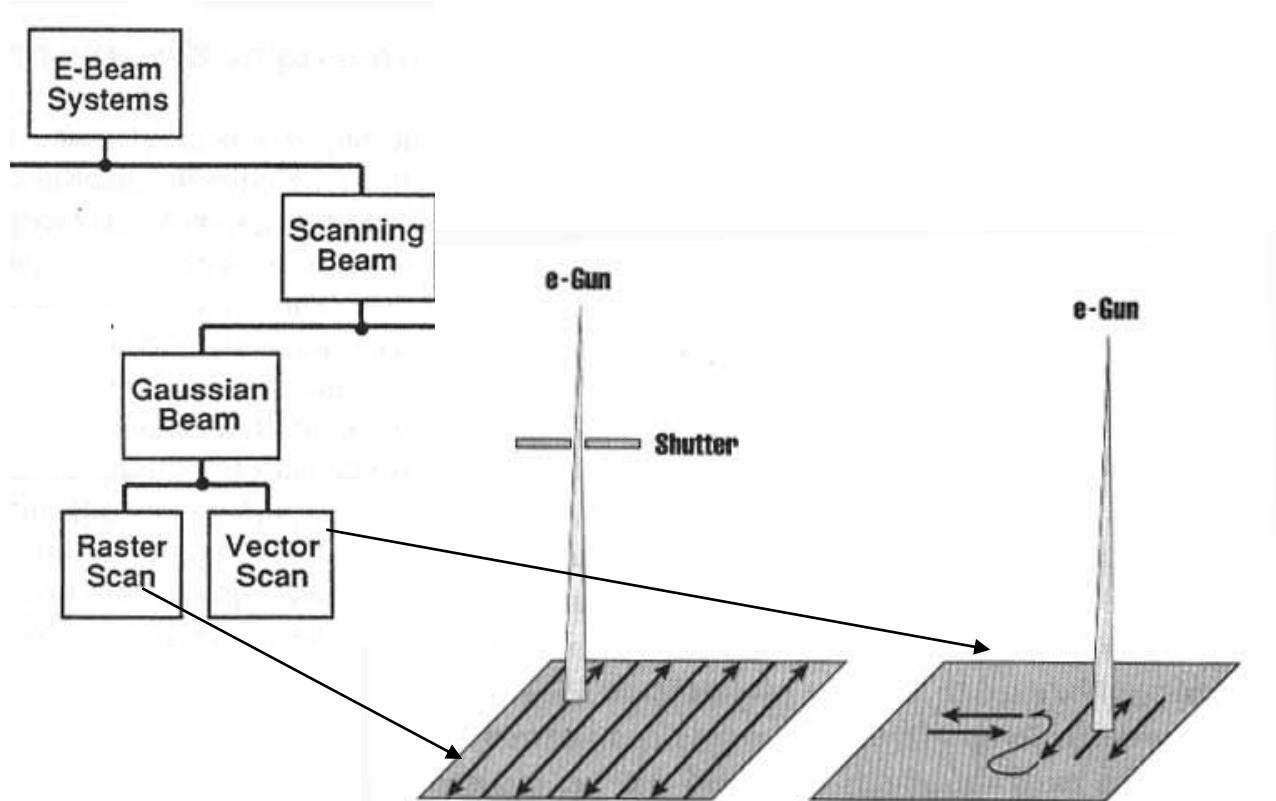
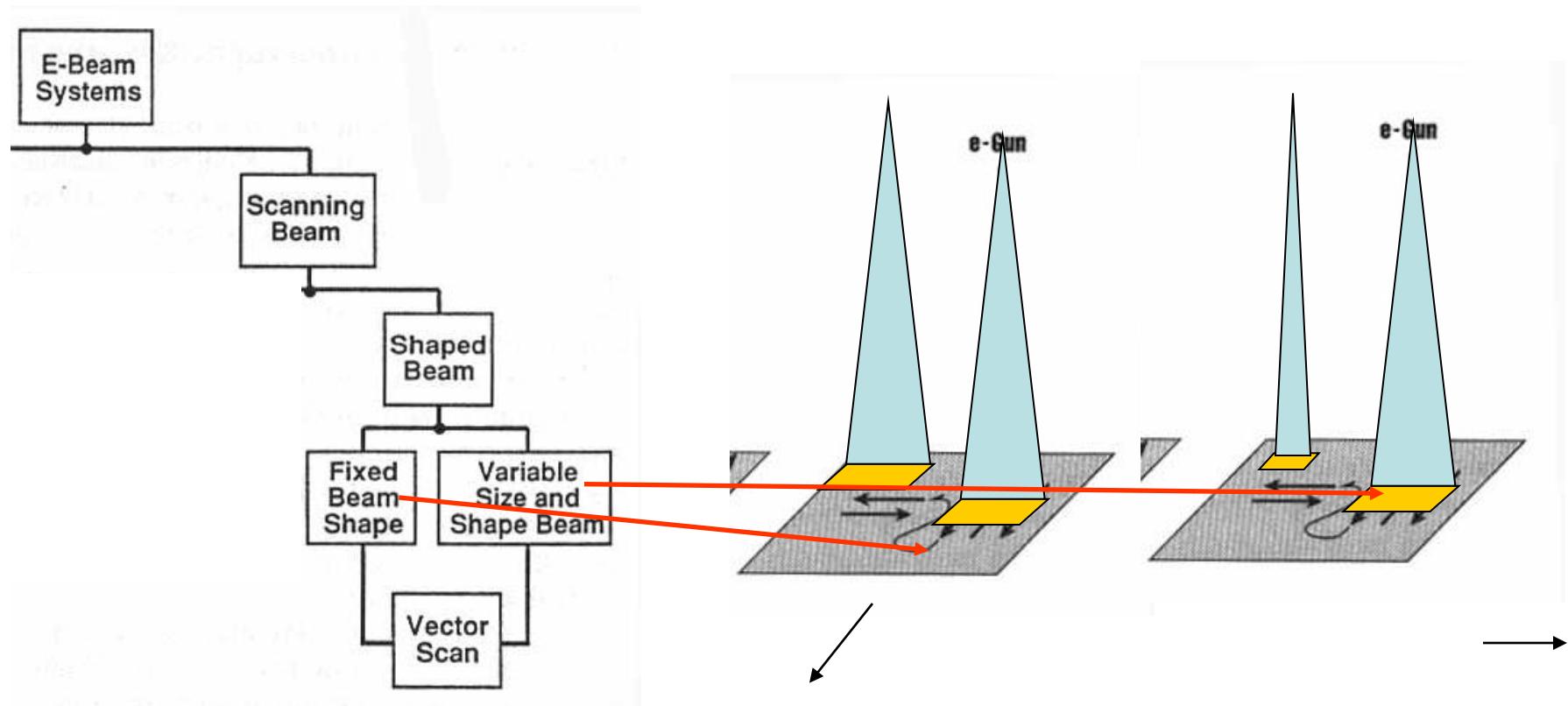


Figure 9-9 A comparison of scanning methodologies; raster scan (left) and vector scan (right).

EBL: Shaped beam scan



Déplacement continu

Thierry FOURNIER CNRS/Institut Néel-Septembre 2011

E-Beam

$$\text{Dose } \mu\text{C/cm}^2 = I \times \text{Dwt} / \text{ASS}^2$$

I : electric courant measured with a faraday cup

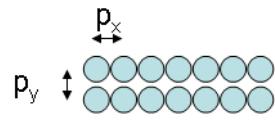
ASS: Area Step Size: distance between exposure spots

minimum ASS: writing field / 65536

Dwt: Area Dwelltime: waiting period of the beam in each writing spot

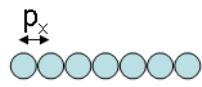
minimum Dwt with Elphy plus: $0.375 \mu\text{s} = 1 / 2.66\text{MHz}$

Surfacic



$$D = \frac{I_x t}{P_x P_y} \quad (\text{C/cm}^2)$$

Linear



$$D = \frac{I_x t}{P_x} \quad (\text{C/cm})$$

E-Beam Lithography

Resists: electrons modify locally the solubility of a thin layer

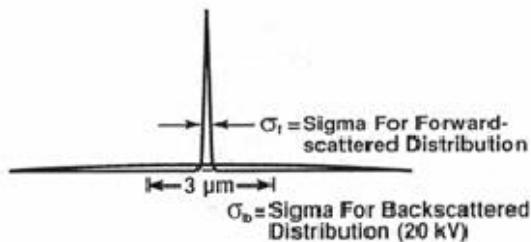
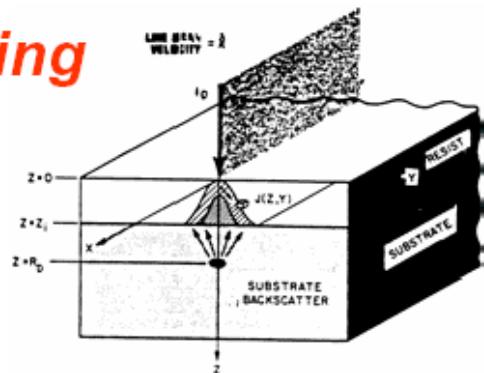
Positive resist: The resist is rendered more soluble

- PMMA (polymethylmethacrylate)
- Photo resists (UV or DUV resists)
- ...

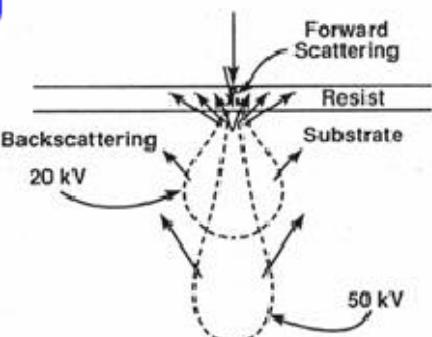
Negative resist: The resist is rendered less soluble

- Shipley SAL, calixarene
- Photo resists (SU8, UV or DUV resists)
- Inorganic (AlF₃, FOX, ...)

Scattering

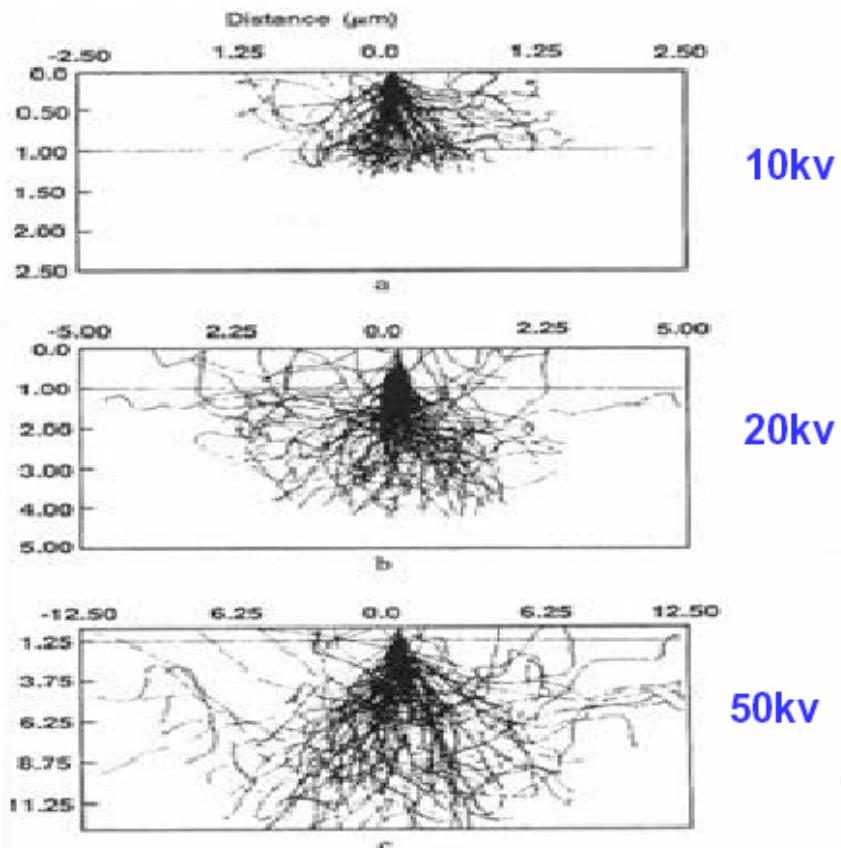


Forward Scattering



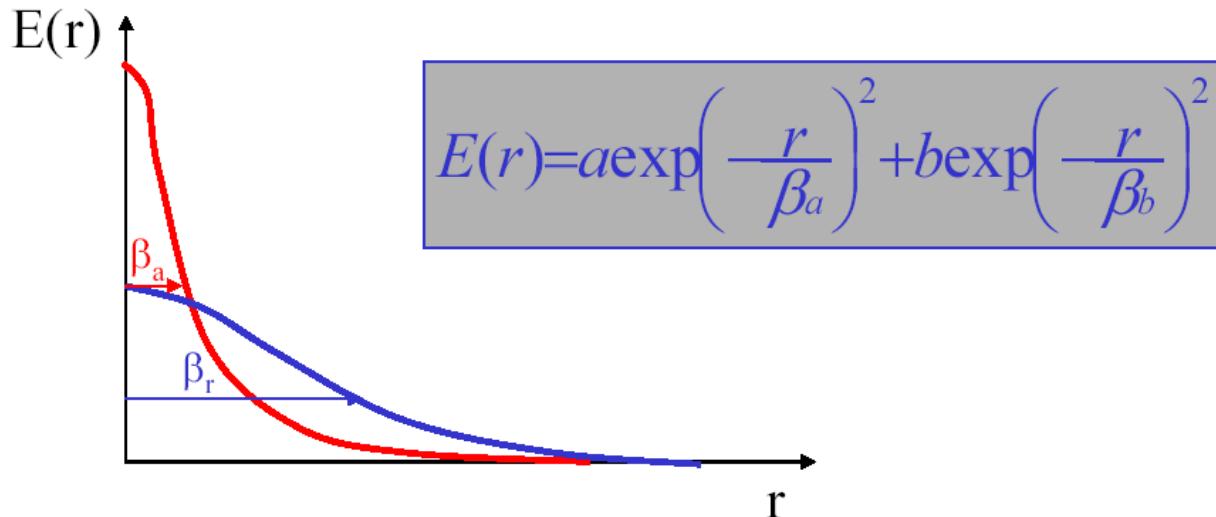
Backward Scattering

Monte-carlo simulation for scattering



✓ Resolution depends less on spot size, and more on scattering.

Double Gaussian model



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

Substrate: Si

β_a forward scattering:

Essentially depends on the resist and the voltage

β_r backscattering:

Depends on the voltage and the substrate

E-Beam Lithography solutions

- **-Industrial e-Beam Lithography System** (Leica, Jeol, Crestec, Hitachi, Raith,...)
- -High cost (from 1 M€ to 10 M€...)
- -Very High resolution, High writing speed, High voltage
- -Large sample (up to 300 mm)
- -interferometric stage



Leica VB6

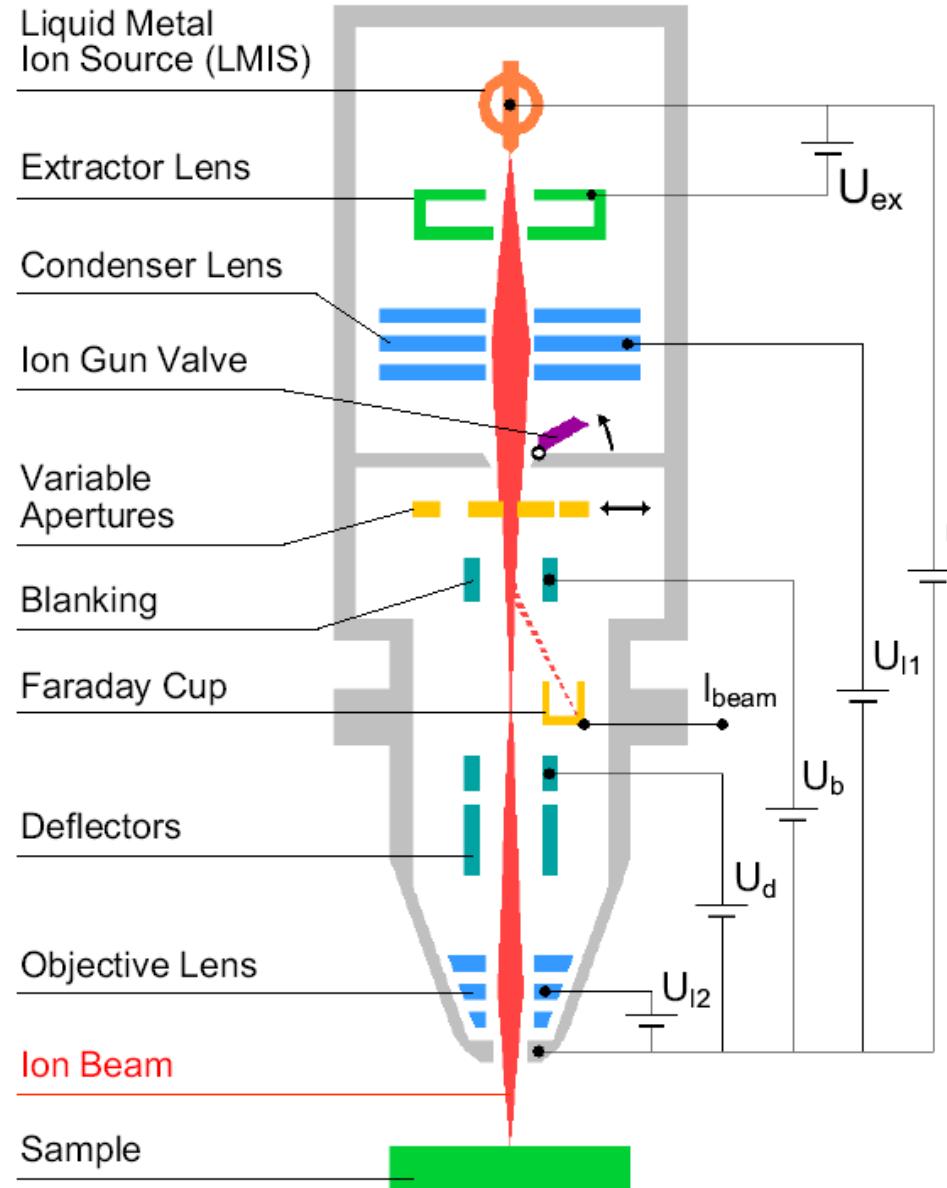
E-Beam Lithography solutions

- **-SEM conversion** : industrial SEM (Carl Zeiss, Jeol, FEI, Hitachi..) + software (Home made, Raith, Nabity..)
- -Low cost (from 0.2 M€ to 0.5 M€)
- -High Resolution, Low writing speed, Low voltage
- -small sample, versatile



SEM Leo 1530 + Raith Elphy
+ FIB Orsay Physics
Nanofab- CNRS Grenoble

Focused Ion Beam



Some figures

		FIB	SEM
		Ga+	e-
Particle	Size	0.2 nm	'petit'
	mass	$1.2 \cdot 10^{-25}$ kg	$9.1 \cdot 10^{-31}$ kg
	Velocity 30 kV	$2.8 \cdot 10^5$ m/s	$1.0 \cdot 10^8$ m/s
	Velocity à 2 kV	$7.3 \cdot 10^4$ m/s	$2.6 \cdot 10^7$ m/s
	Moment 30kV	$3.4 \cdot 10^{-20}$ kg.m/s	$9.1 \cdot 10^{-23}$ kg.m/s
	Moment 2 kV	$8.8 \cdot 10^{-21}$ kg.m/s	$2.4 \cdot 10^{-23}$ kg.m/s
Beam	Size	Quelques nm	1 nm
	Energy	2 - 30kv	0.5 - 30 kV
	Courant	pA à 20 nA	pA à 20 nA
Depth length	Polymer 30 kV	60 nm	12000 nm
	Polymer 2 kV	12 nm	100 nm
	Iron 30 kV	20 nm	1800 nm
	Iron 2 kV	4 nm	25 nm

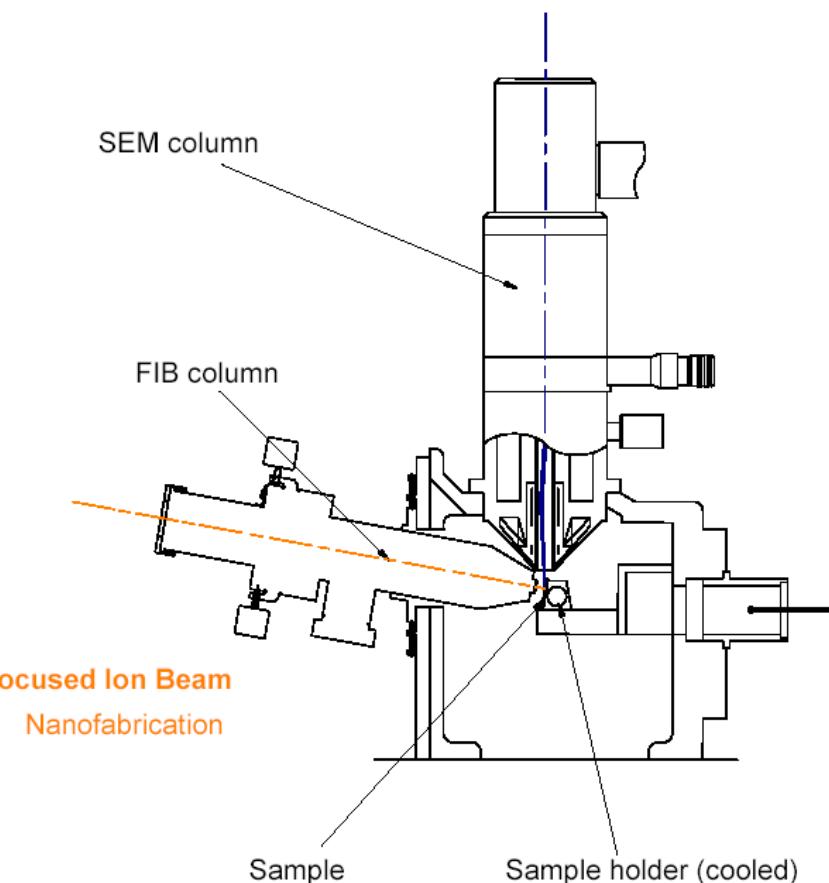
FIB

- Ionic and electronic emission
 - Image
- Direct writing
 - Lithography without resist
 - 3D Etching
- Ionic implantation
- Chemical
 - Local etching or deposition

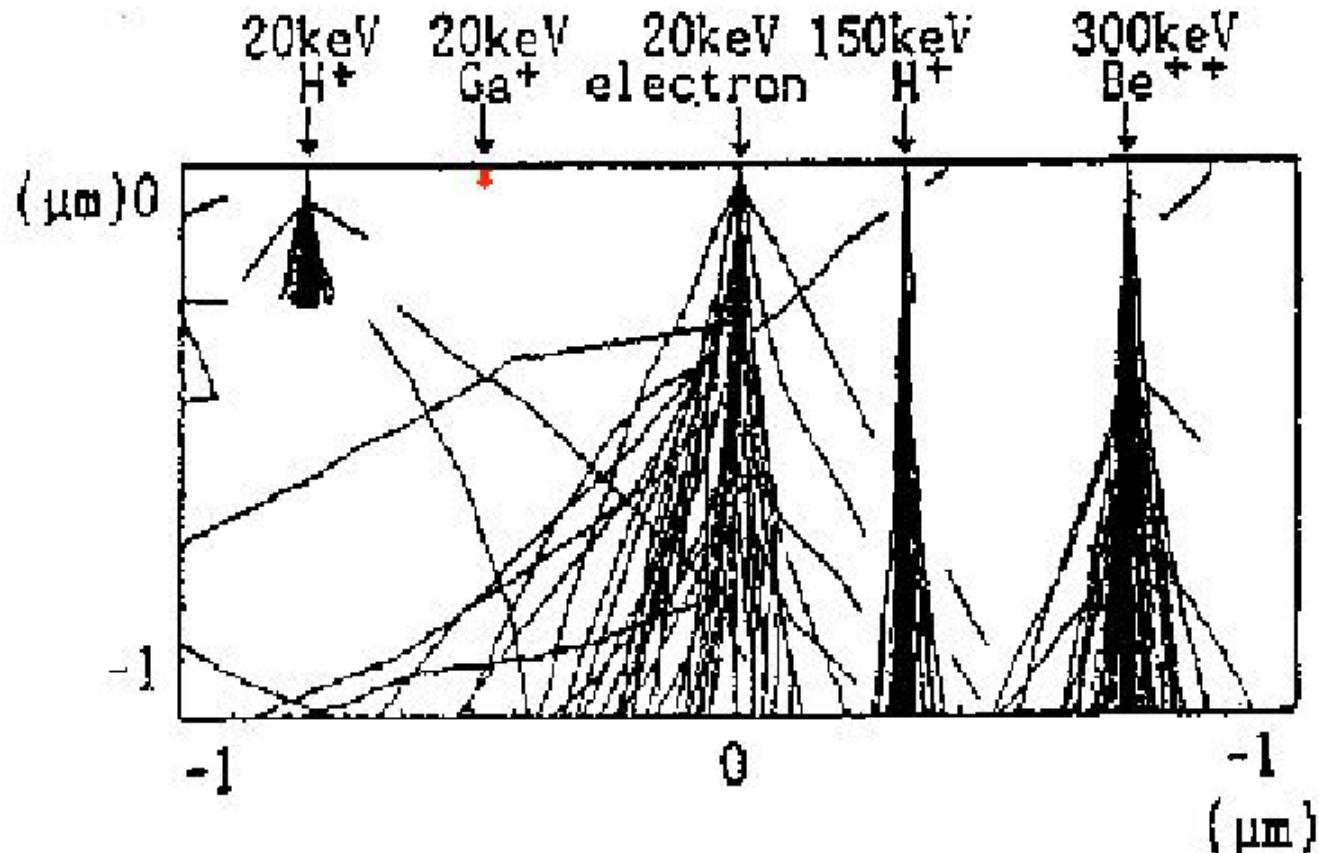
Dual Beam SEM/FIB

Scanning Electron Microscope

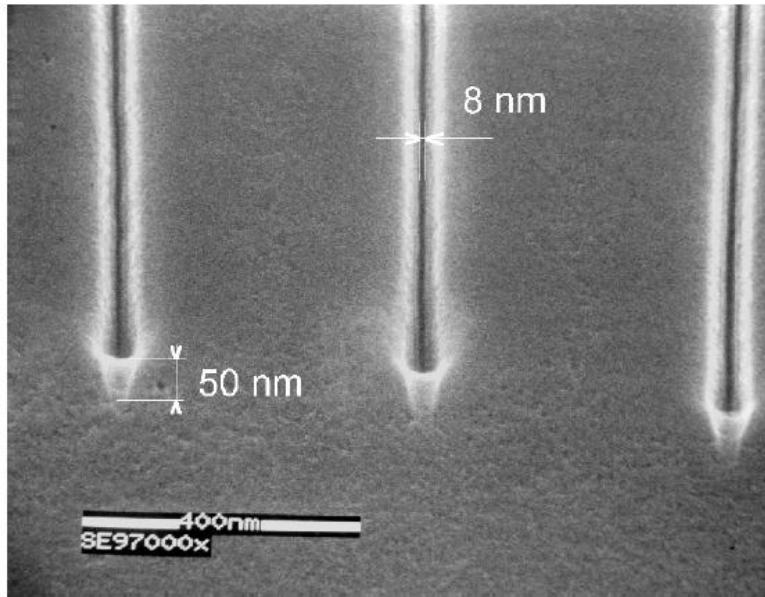
- Non destructive observation
- Positionning accuracy



Ion Trajectories

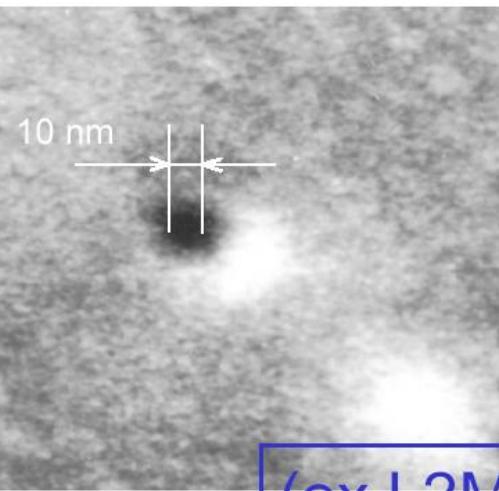
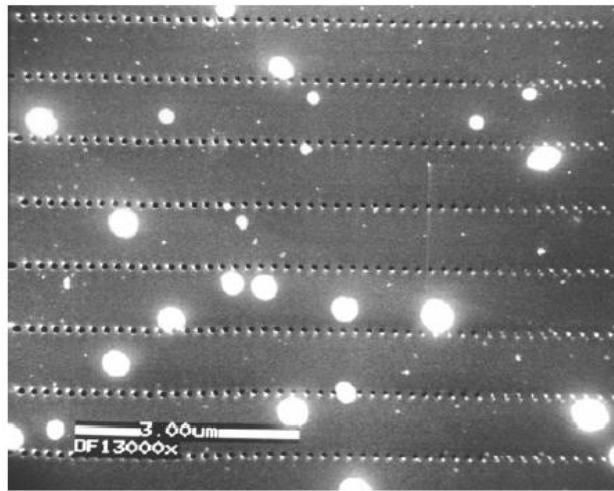


LPN Marcoussis



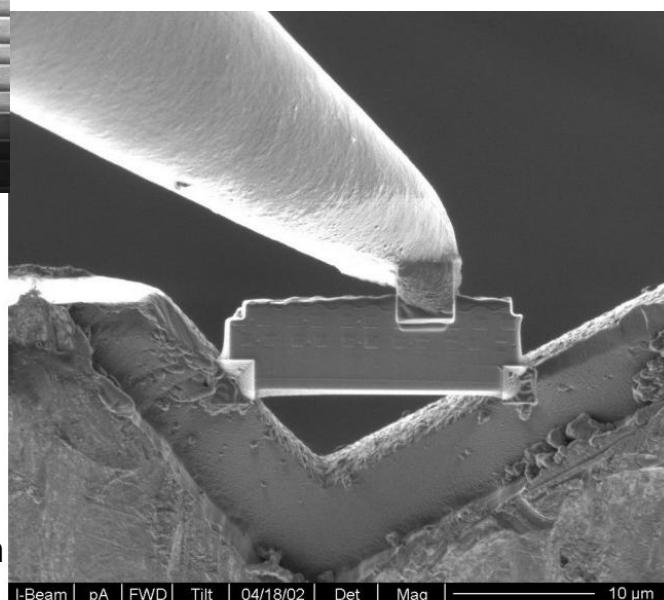
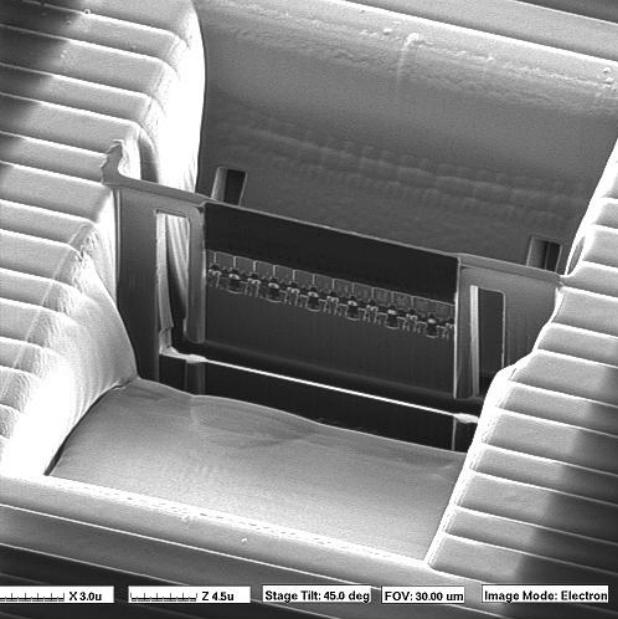
30kV Gallium ions

Holes in a Si_3N_4 membrane



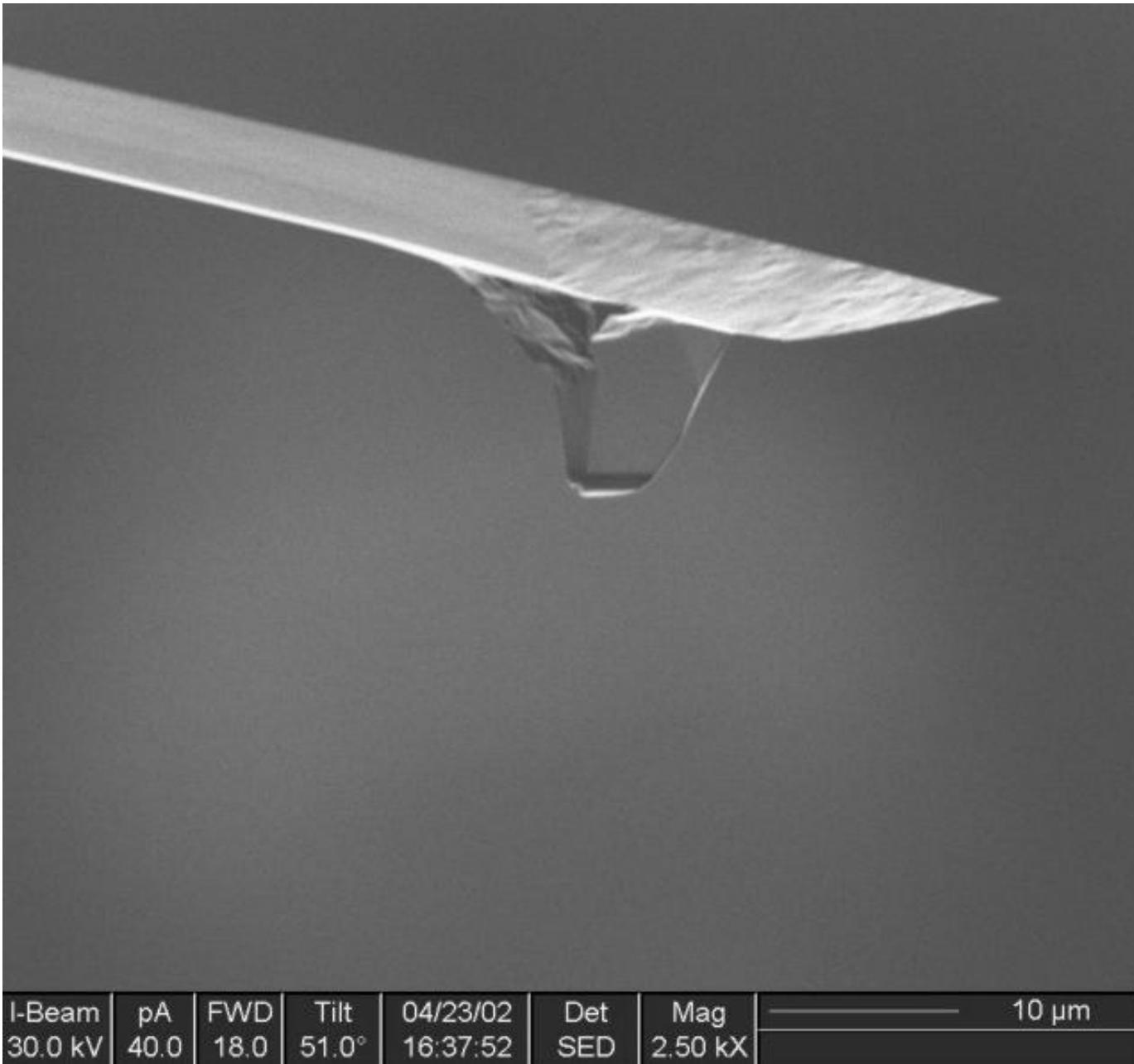
Ex 12Mv 1 PI

LPN Marcoussis



Thierry FOURNIER CNRS/Institut Néel-Septem

I-Beam 30.0 kV	pA 110	FWD 18.0	Tilt 0.0°	Date 04/18/02	Detector SED	Magnification 6.50 kX	10 μm
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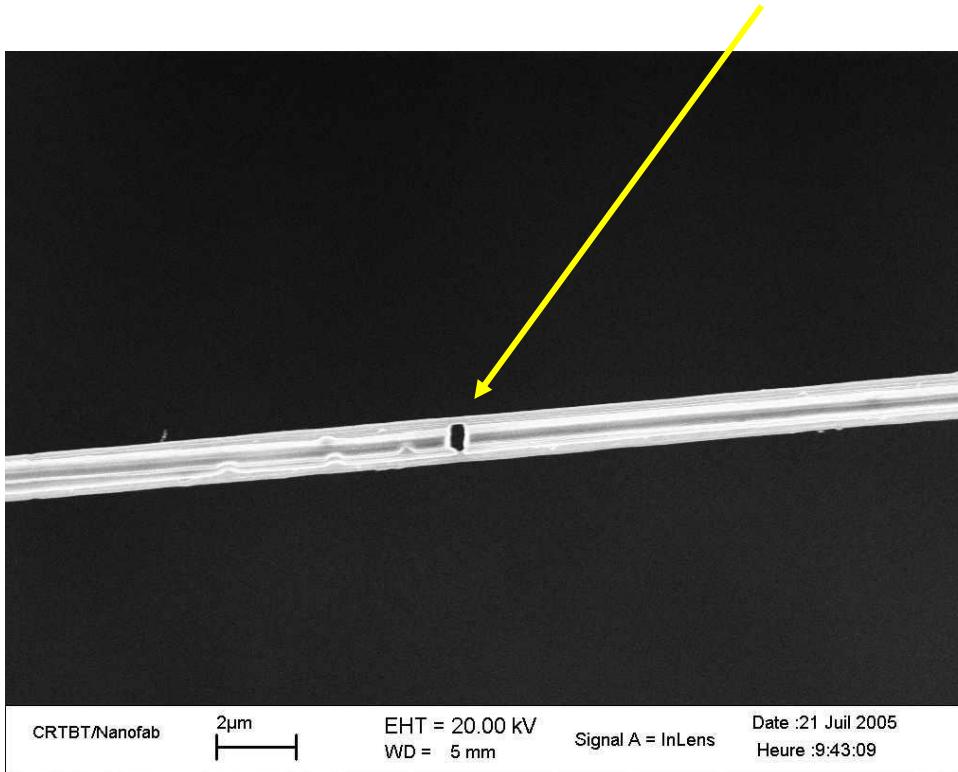


I-Beam	pA	FWD	Tilt	04/23/02	Det	Mag		10 µm
30.0 kV	40.0	18.0	51.0°	16:37:52	SED	2.50 kX		

3D Etching

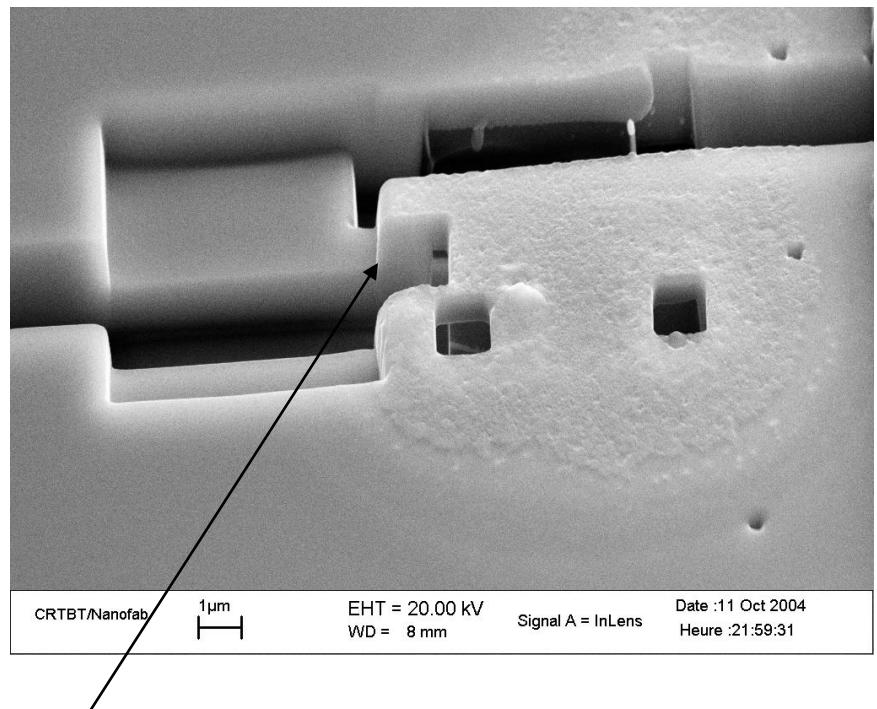
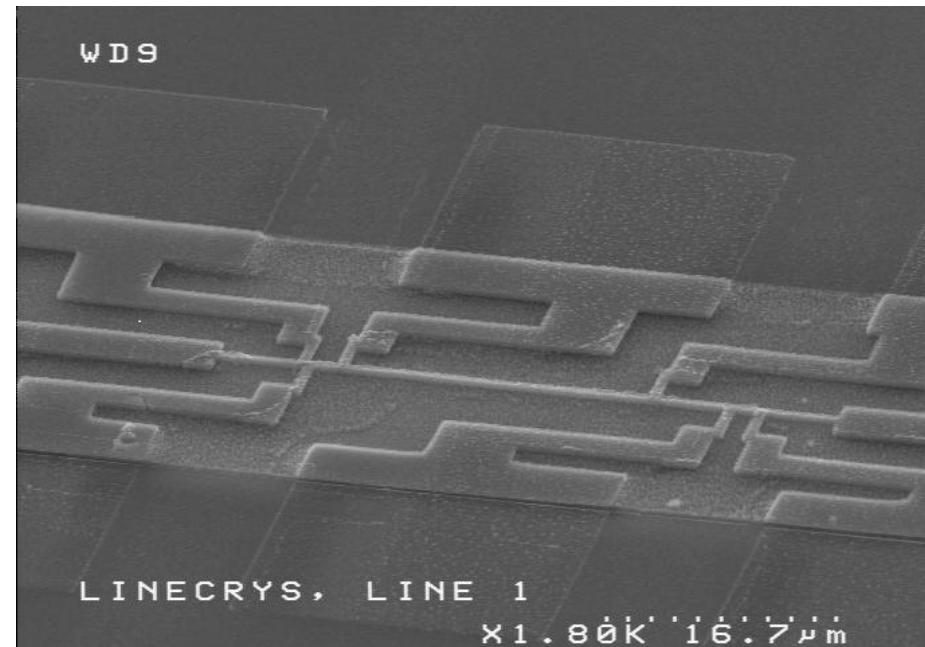
Lithography/Etching of non planar object.

Hole on a superconducting Wire

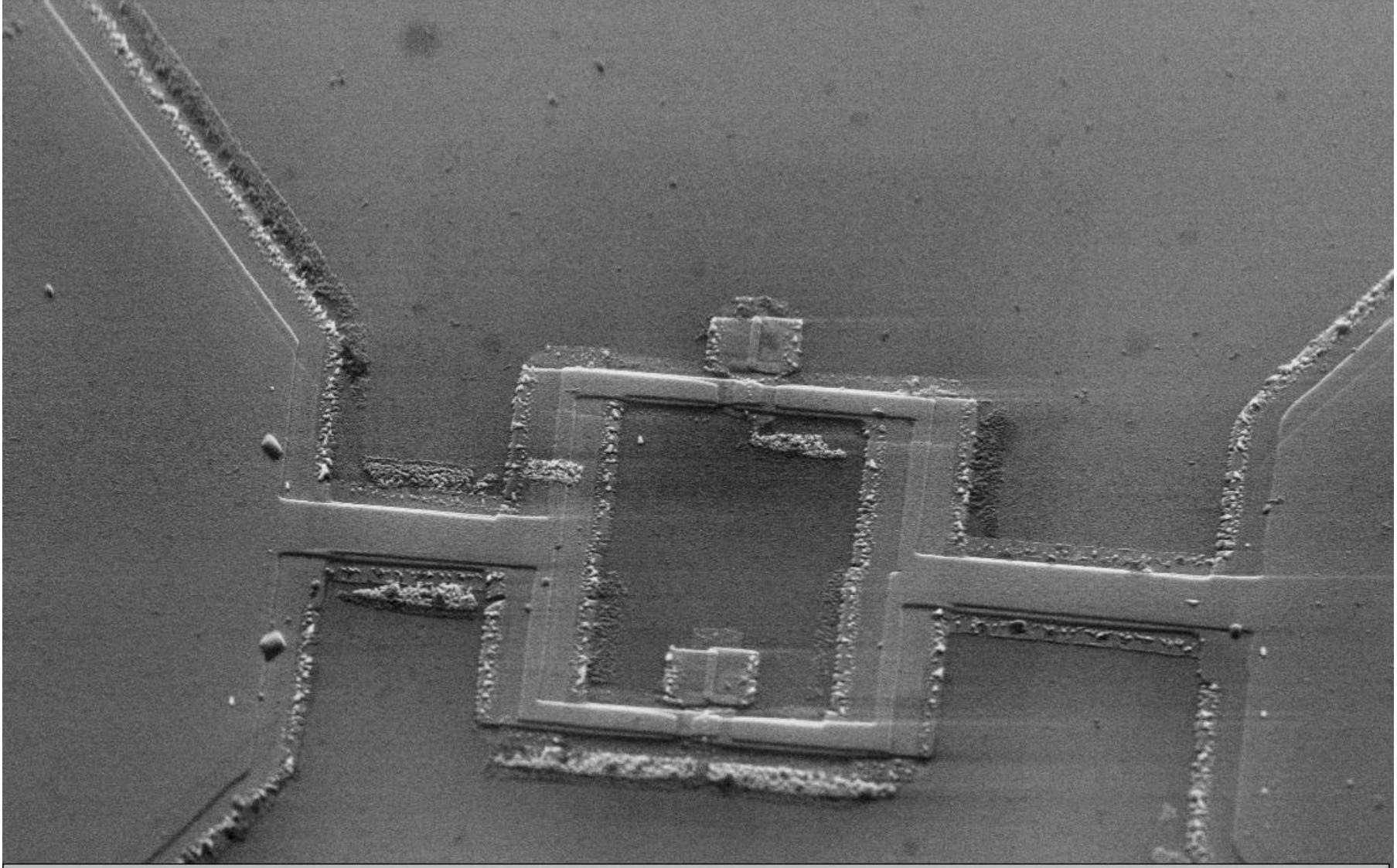


Patterning of non planar objects

Charged Density Wave Crystals : NbSe_3 , NbSe_2 , TaSe_2



Etching of junctions 1x1x0.2 microns

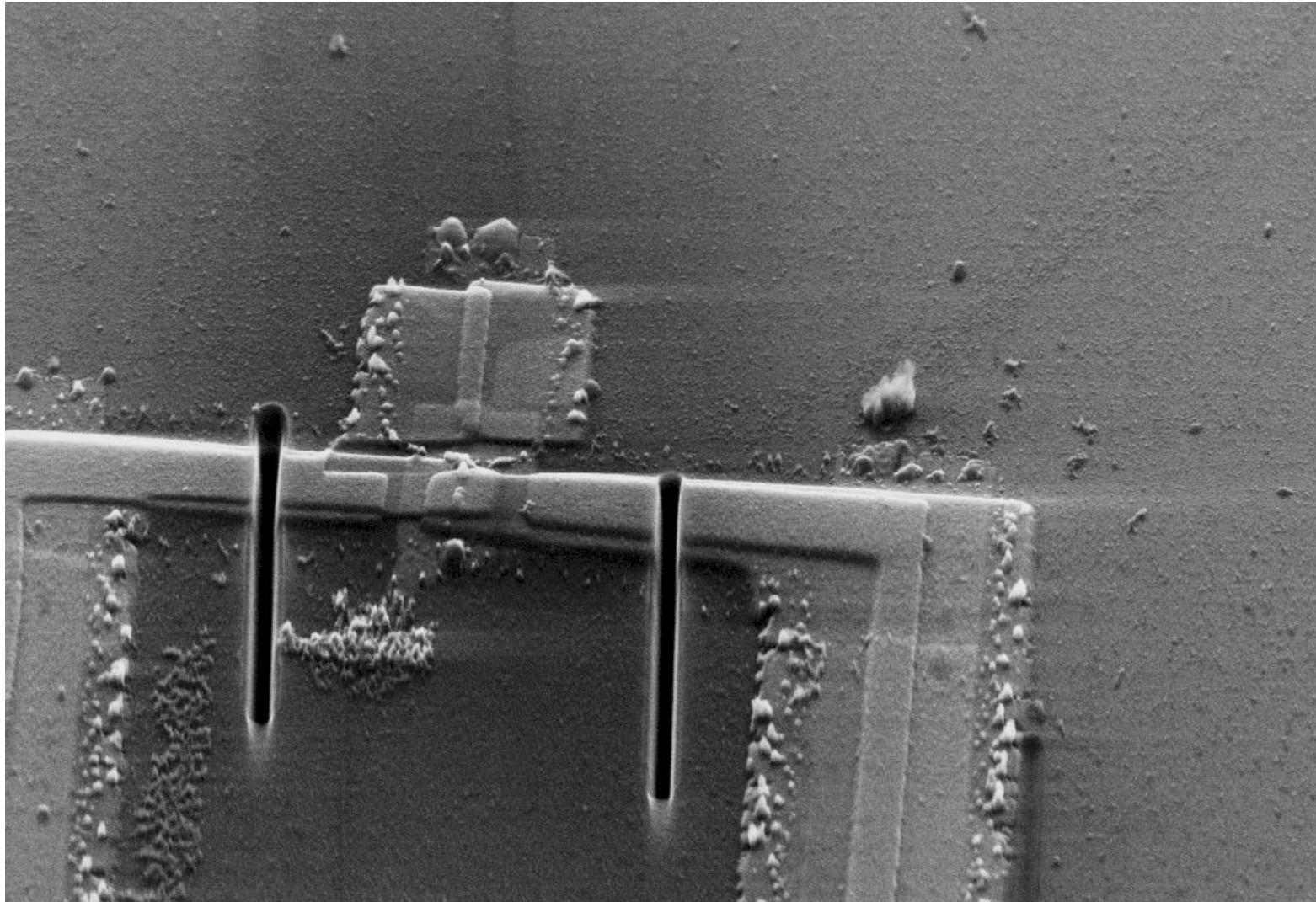


Nanofab/CRTBT
Date : 12 Sep 2002

EHT = 20.00 kV WD = 8 mm Signal A = SE2

2 μ m

Squid Pi CRTBT-CNRS



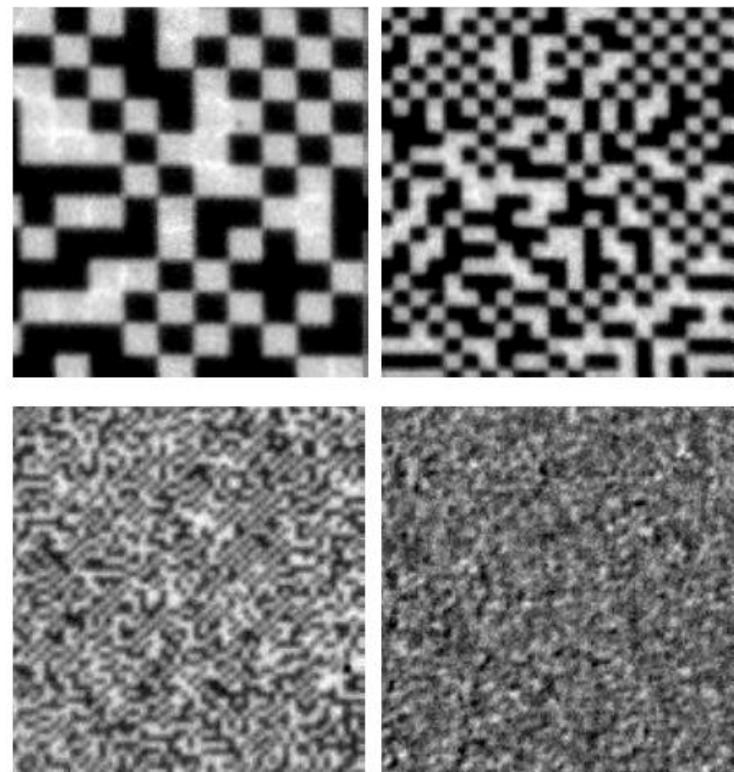
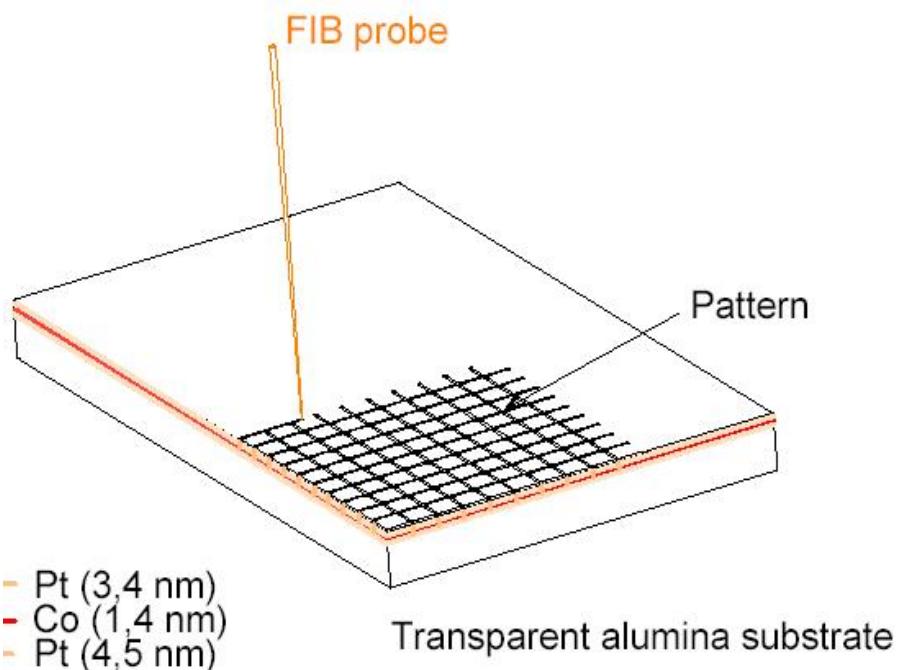
Nanofab/CRTBT
Date :12 Sep 2002

EHT = 20.00 kV WD = 8 mm Signal A = SE2

1 μm

Squid Pi CRTBT-CNRS

Local FIB induced mixing. Thin magnetic films patterning

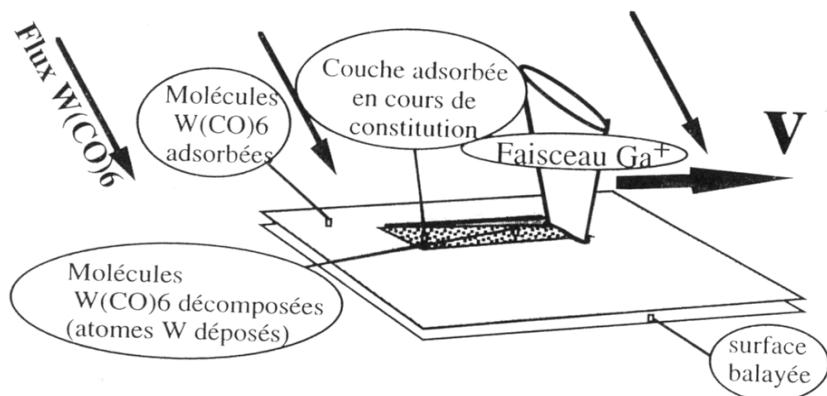
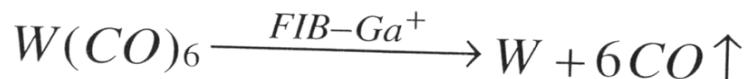
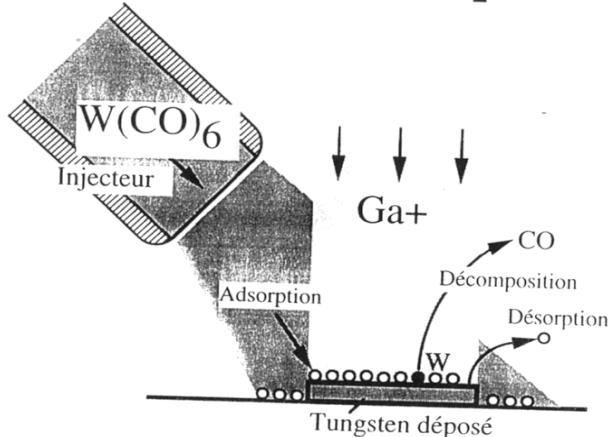


Magneto-optical image of magnetic domains defined between irradiated *lines* (Ga⁺ ions, 30 keV, 5×10^{15} ions/cm²).

⇒ Arrays of stable magnetic dots 1500 nm, 750 nm, 300 nm, 50 nm

LPN Marcoussis

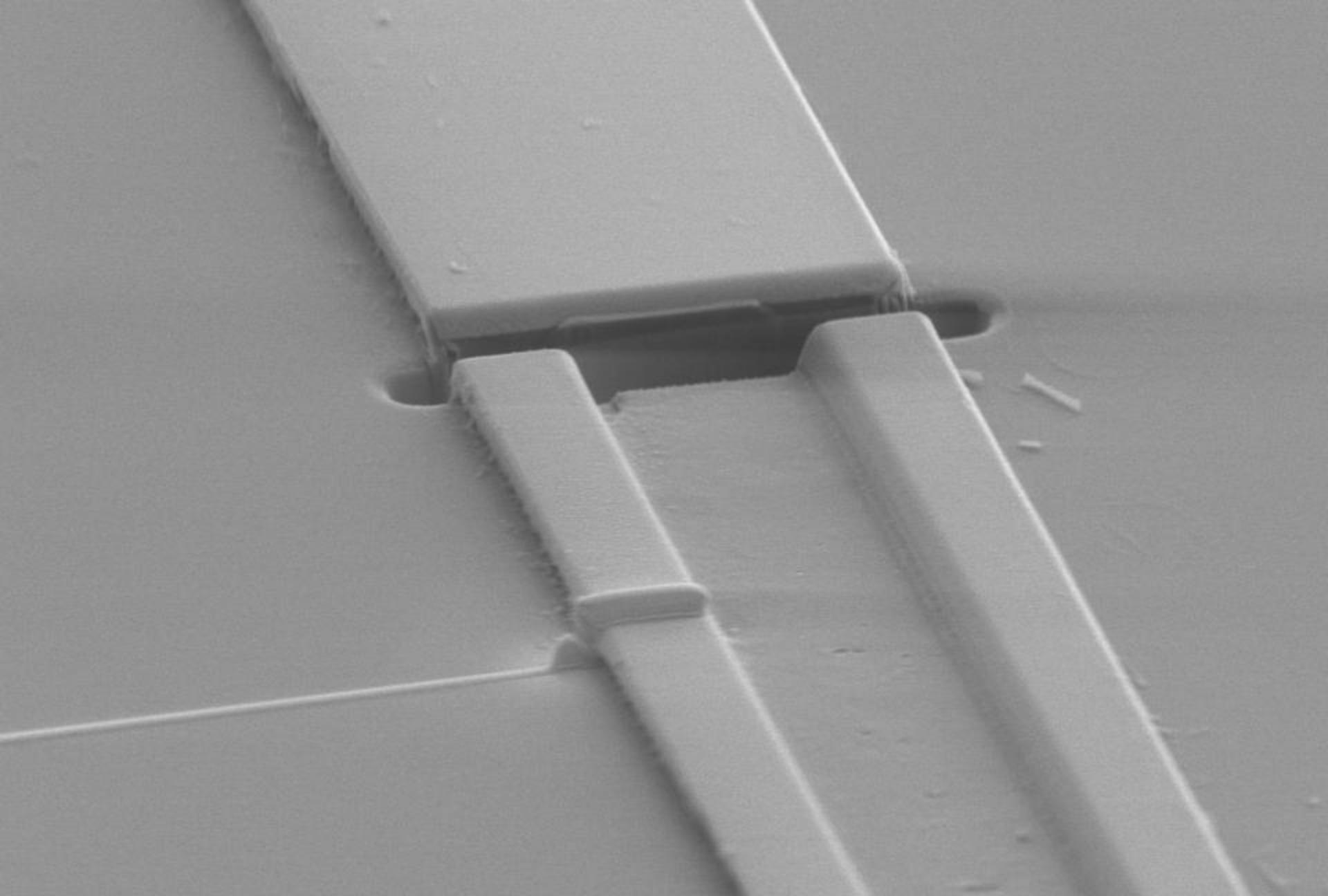
Dépot de tungstène assisté par ions Ga⁺



Dépot de W dans un rectangle par balayage ligne et trame d'un faisceau fin de Ga⁺

$$\text{Temps d'exposition sous le faisceau} = \frac{K}{V}$$

- Introduction of gas
 - Deposition
 - Etching



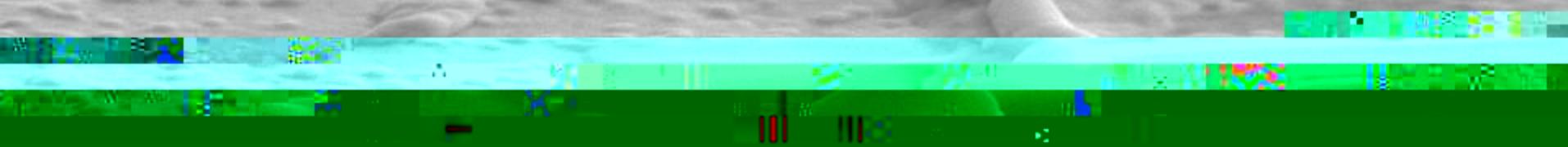
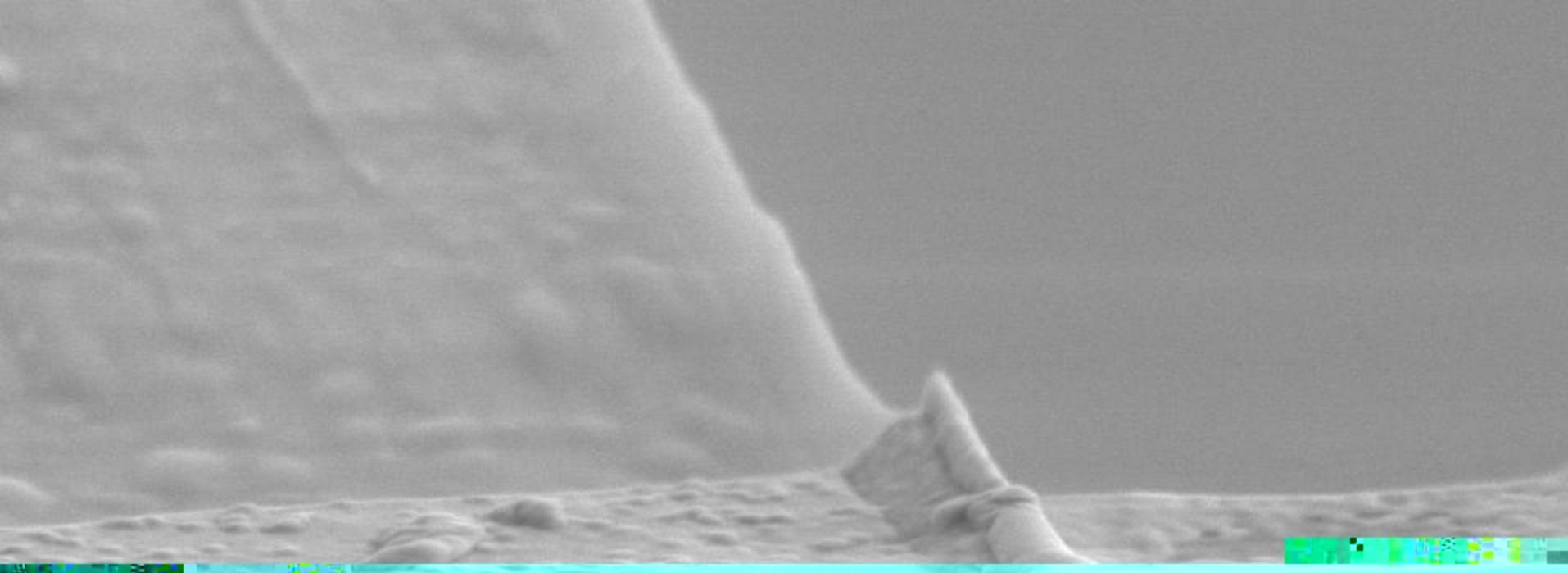
Mag = 5.58 K X

2μm*

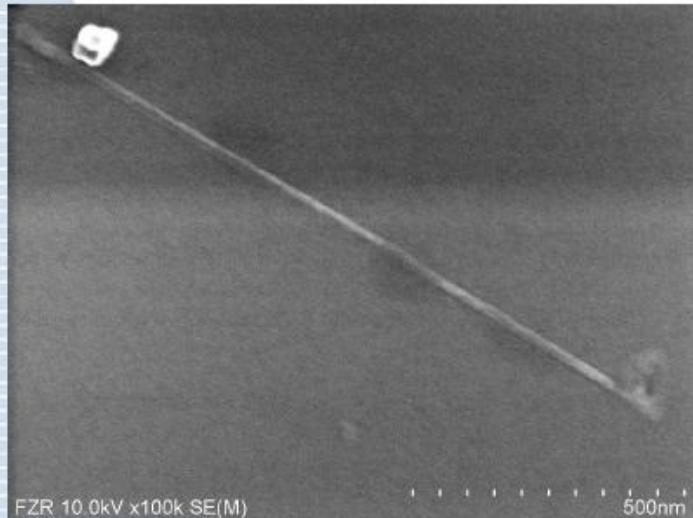
EHT = 5.00 kV
WD = 7 mm

Signal A = SE2
Photo No. = 346

Date :17 Oct 2000
Time :15:32

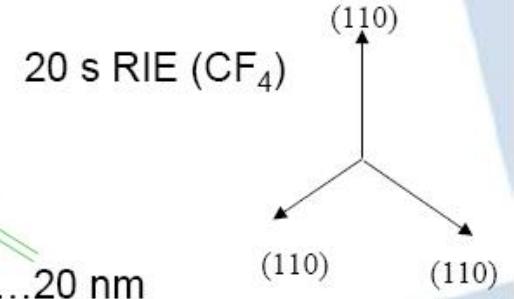


Direct FIB written CoSi₂ nano-wire



FIB-implantation Co⁺⁺
60 keV, 2.4e16 cm⁻²
Si <111>

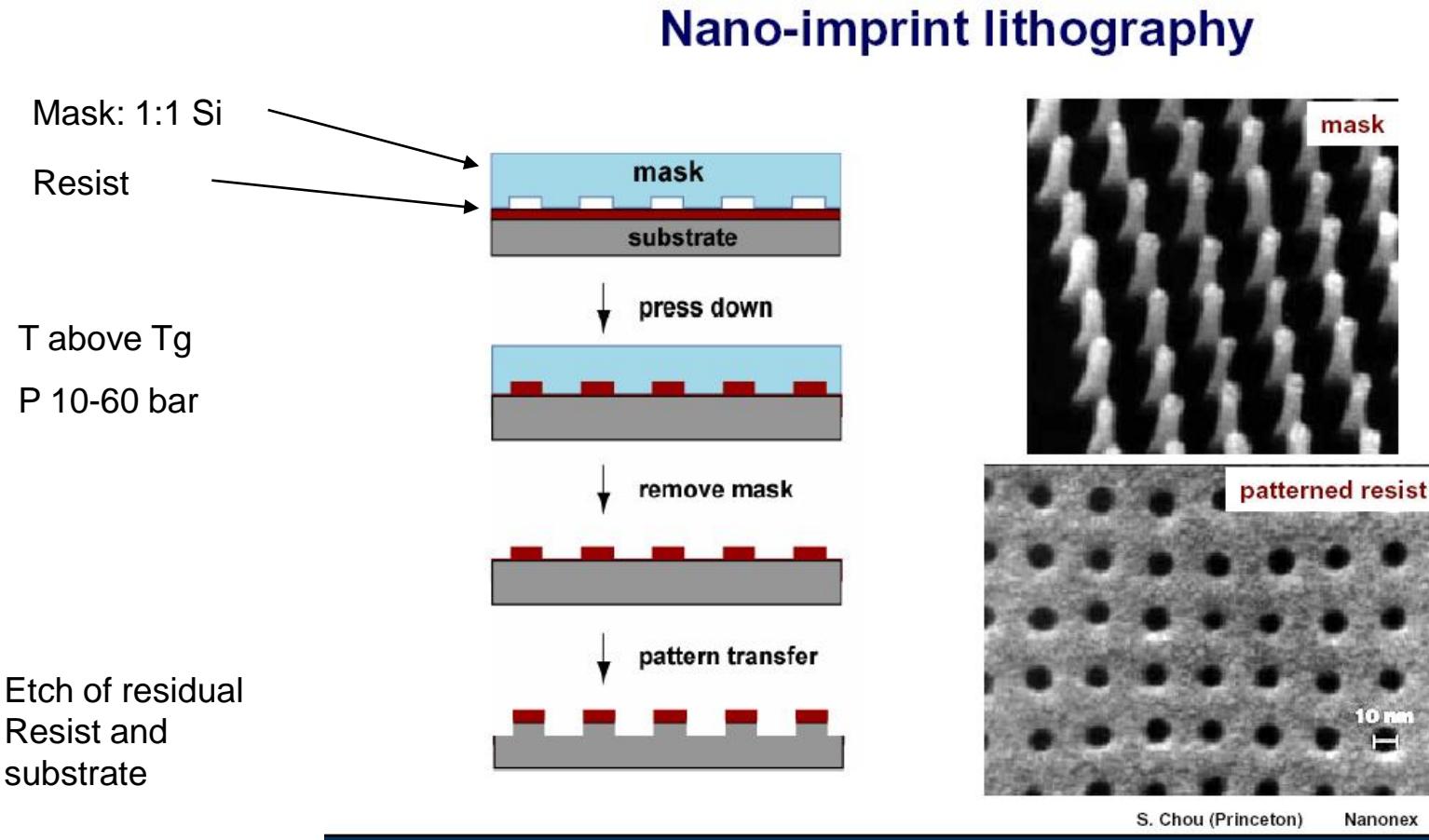
Annealed
600°C 60 min + 1000°C 30 min, N₂



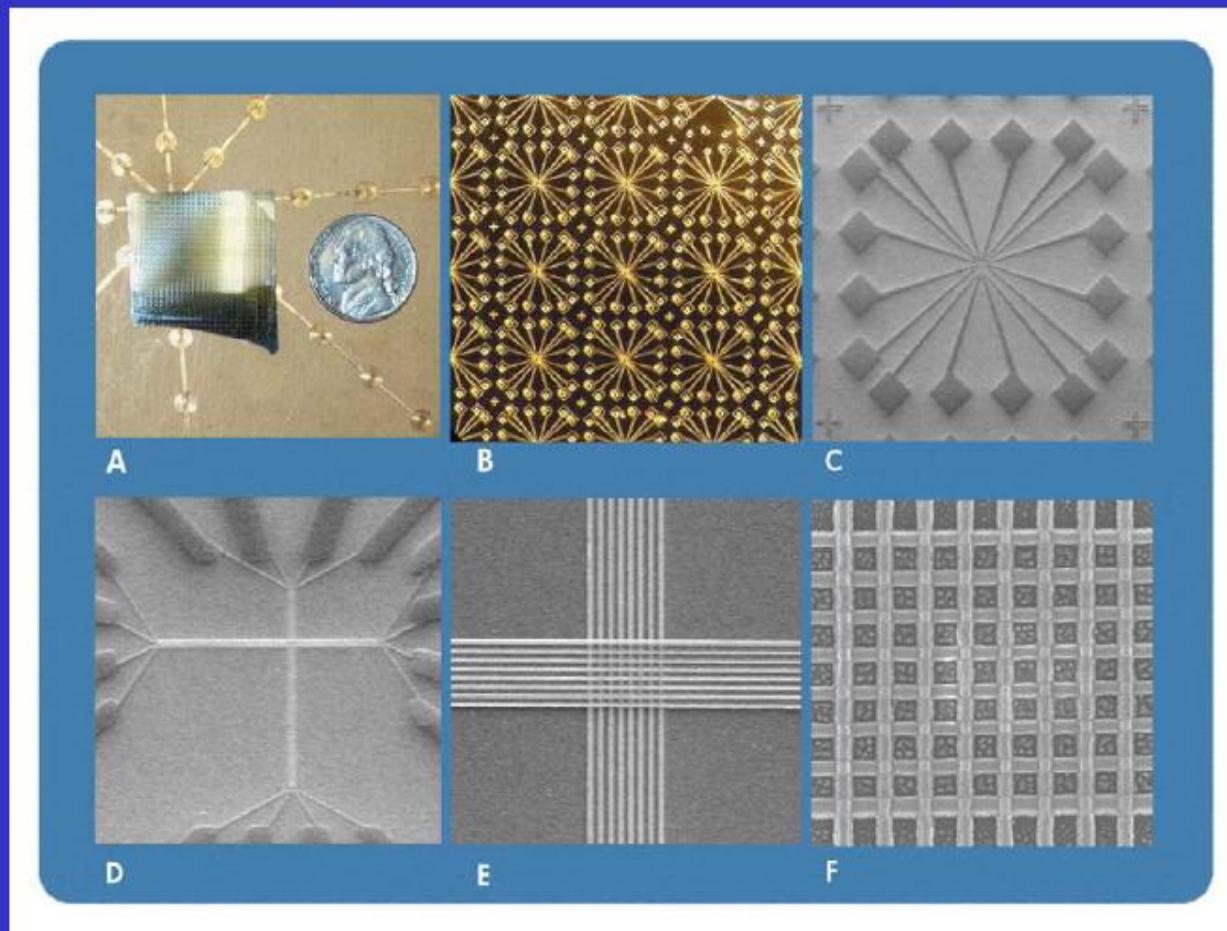
2-4 Emerging solutions

A-Nanoimprint

Nano-Imprint Lithography



Nanoimprint : exemples d'applications



électronique moléculaire
mémoires ultra haute densité
6.4 Gbits/cm²
(Hewlett Packard)

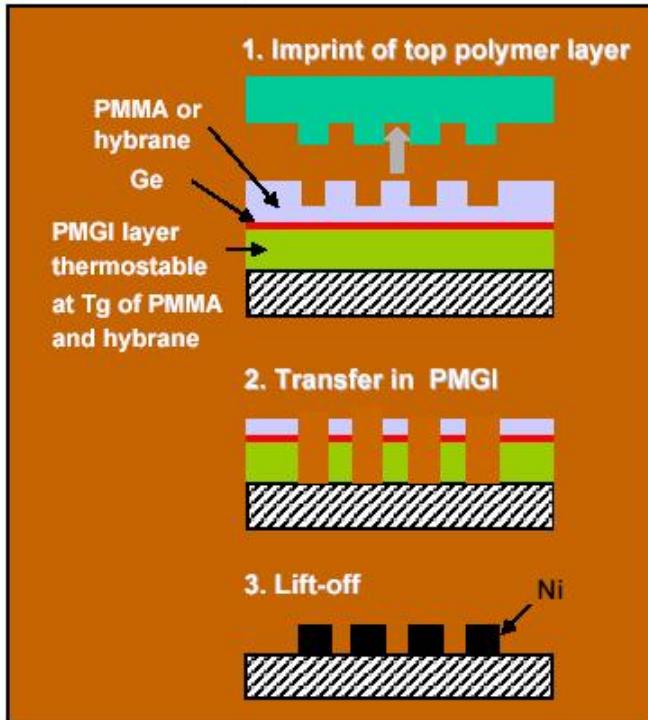
Avantages : simplicité, haute résolution, faible coût, grandes surfaces

Inconvénients : alignement, T°, P, durée

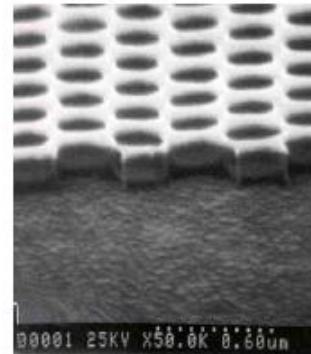
Trilayer Nanoimprint Lithography

tri-layer technique for improved aspect ratio

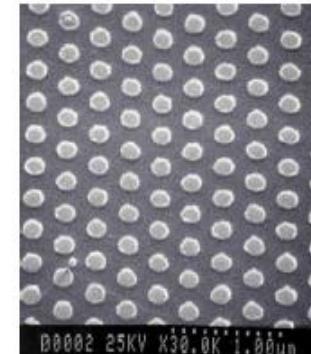
- better CD control
- non-planar surfaces



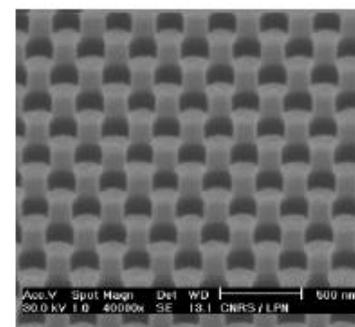
Y.Chen et al. Eur. Phys. J. Appl. Phys. 12,223 (2000)



Array of nanoholes
in hybrane layer
(80 nm)



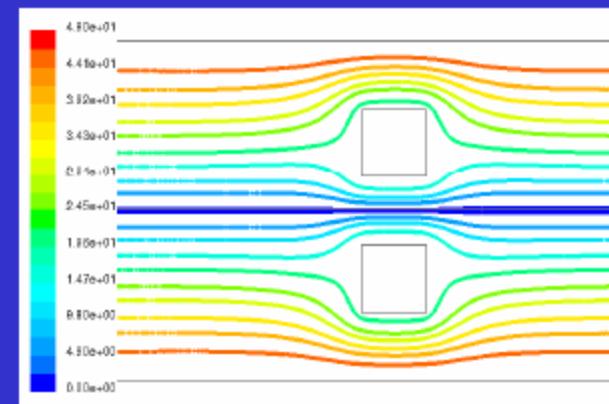
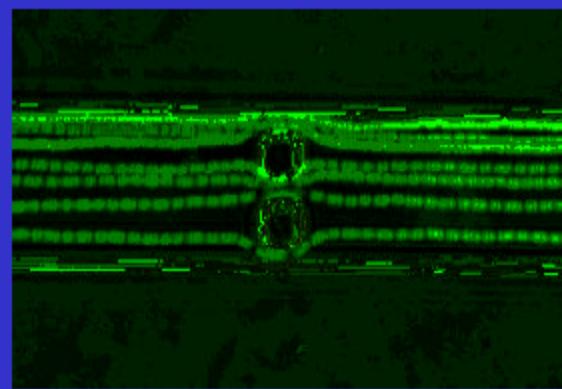
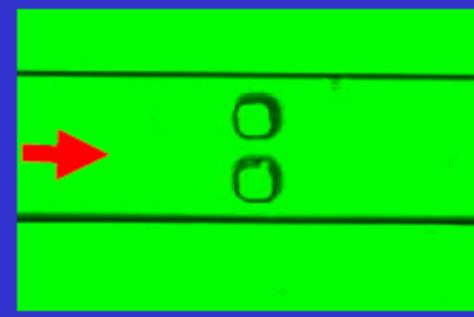
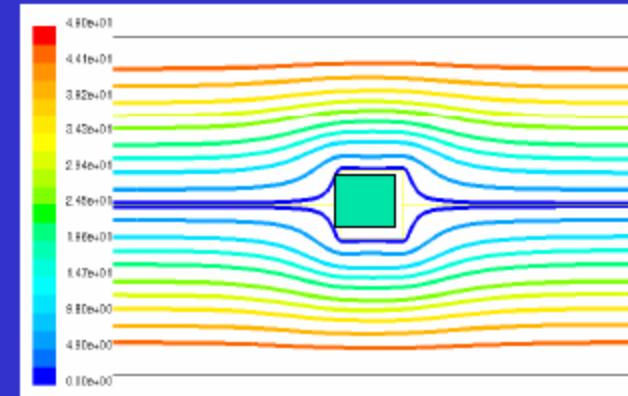
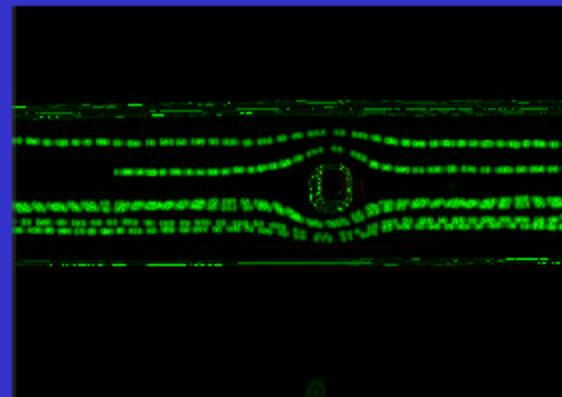
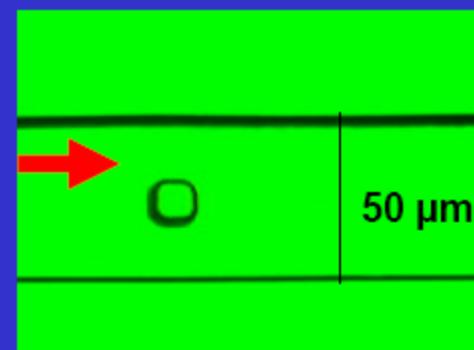
Dot array
150 nm diameter
(60 nm Ni)



Si₂O₃/Si nanopillars
height 500 nm



LPN. Marcoussis



Observation

Simulation

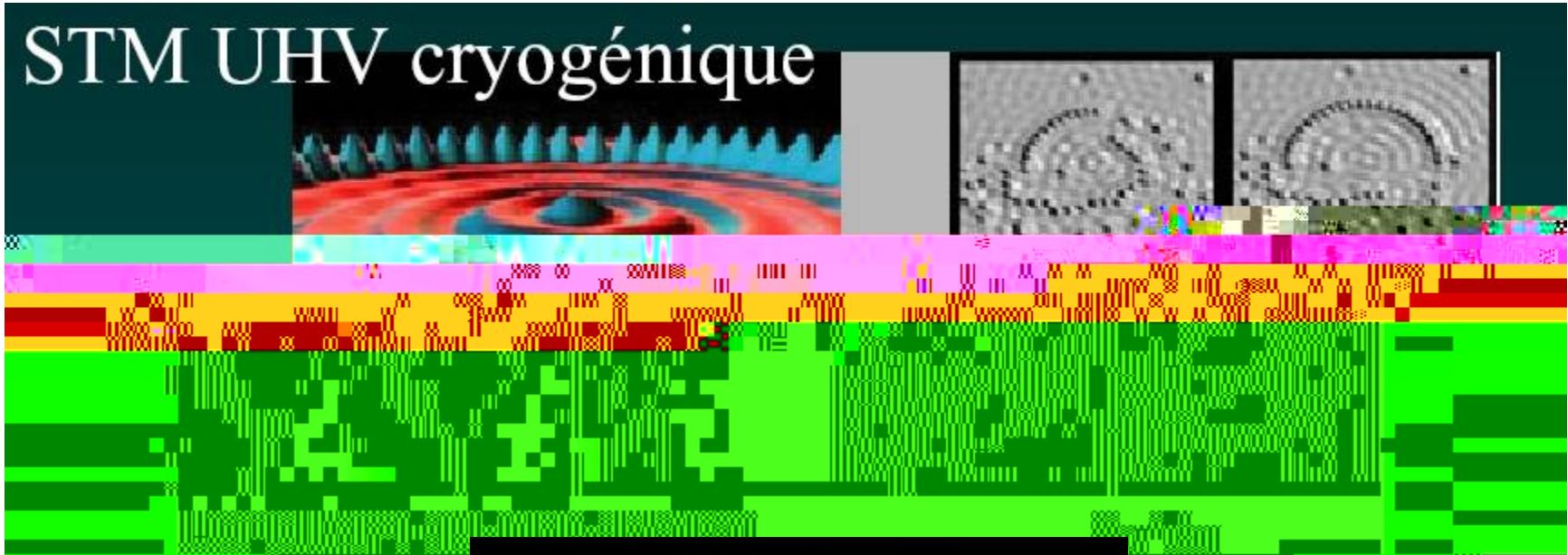
N.I.L

- Slow process
- Need 1:1 Mask (e-Beam)
- Low Aspect ratio
- Chip
- Resolution down to 10 nm !!!

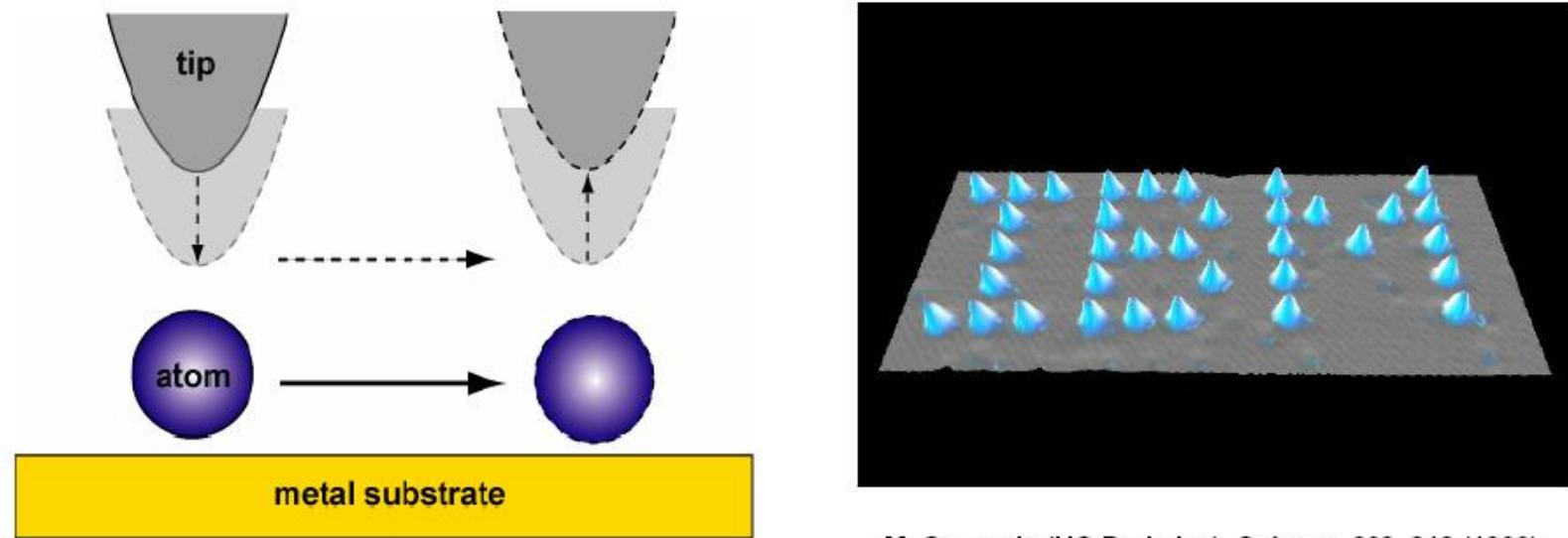
2-4 Emerging solutions

B-Near-Field Lithography

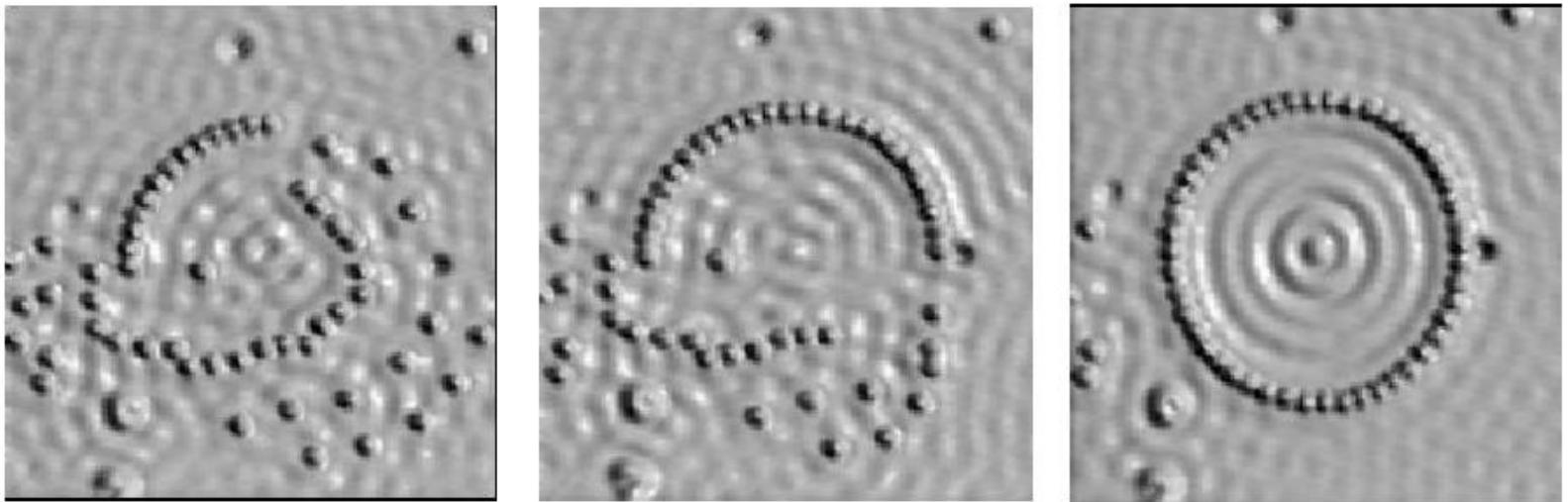
Near Field Lithography



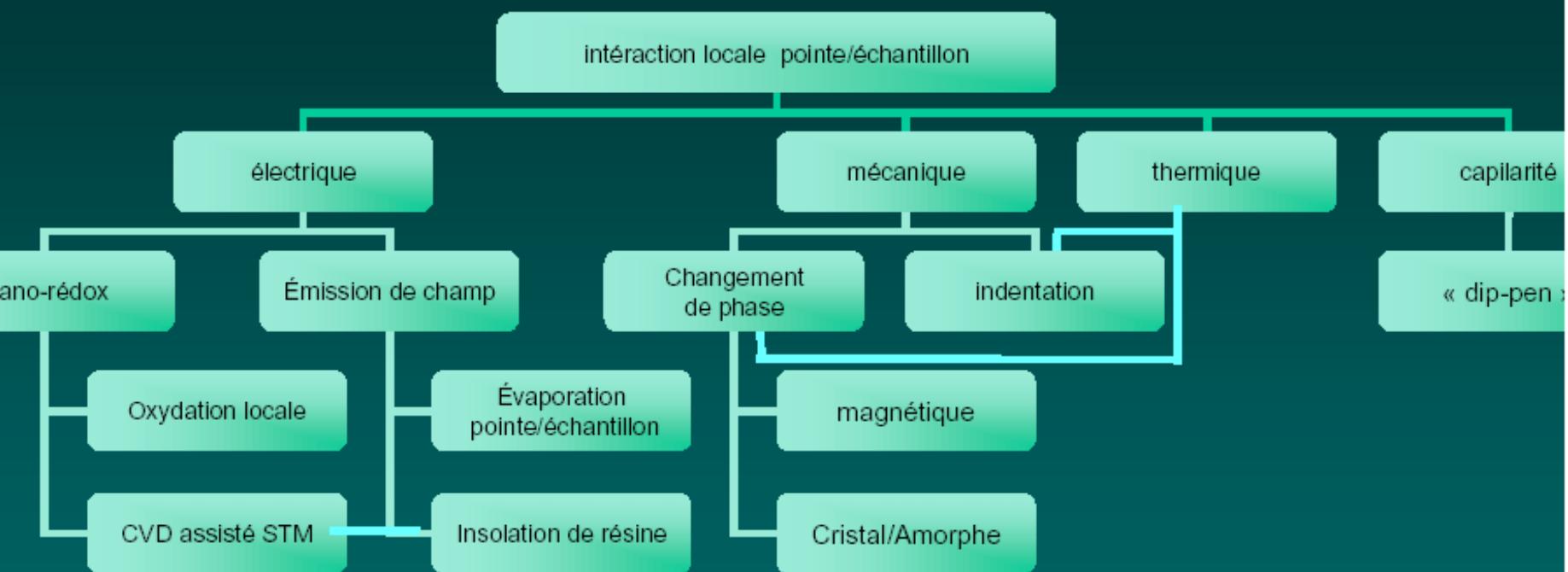
STM: manipulation of atoms



M. Crommie (UC Berkeley), *Science* 262, 218 (1993)

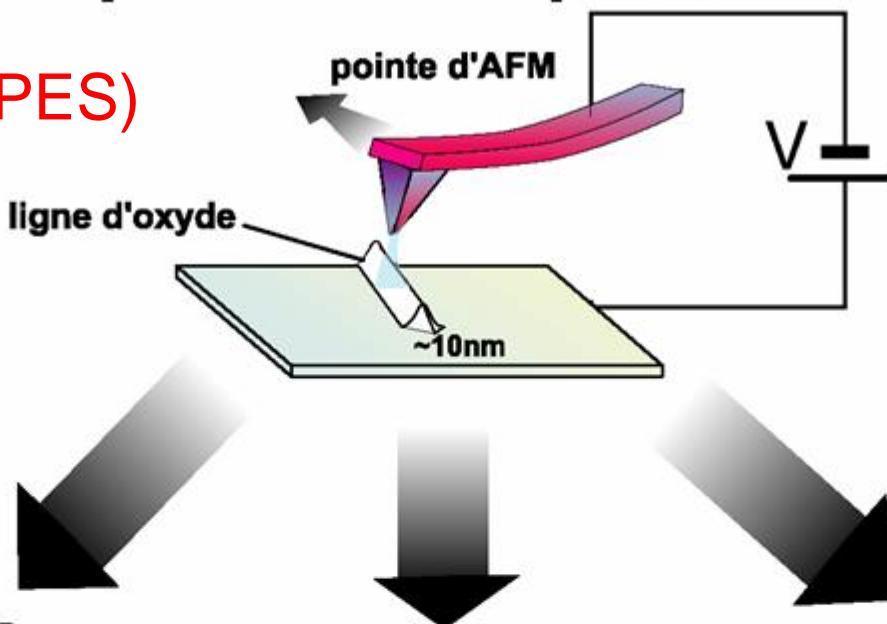


Panorama des techniques « nano-litho » AFM/STM

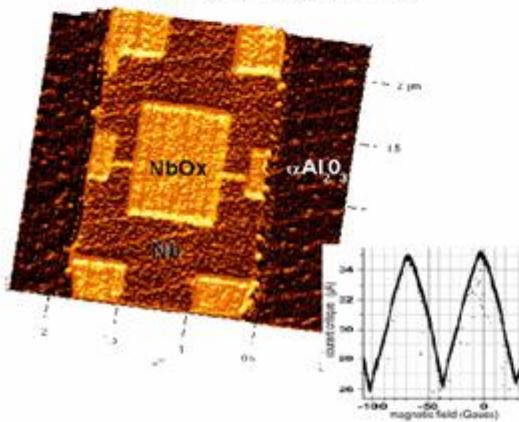


lithographie par microscopie à force atomique

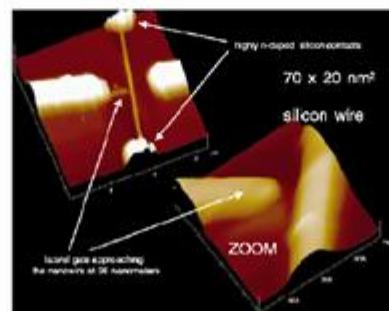
(CRTBT - LEPES)



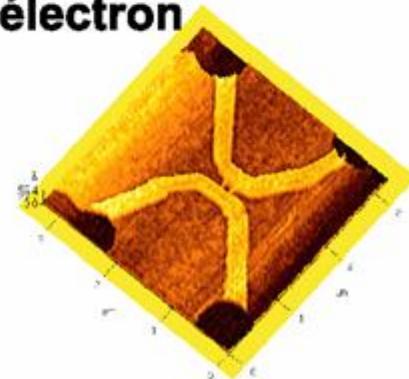
micro-SQUIDs



nanostructures Si

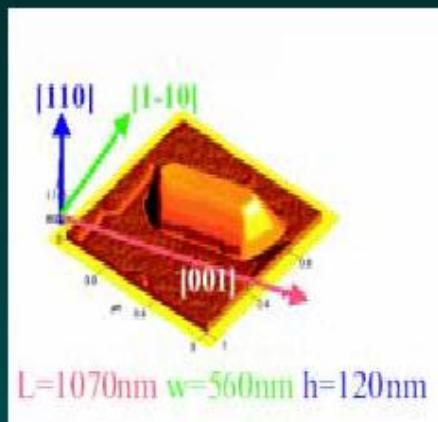


électronique à
1 électron



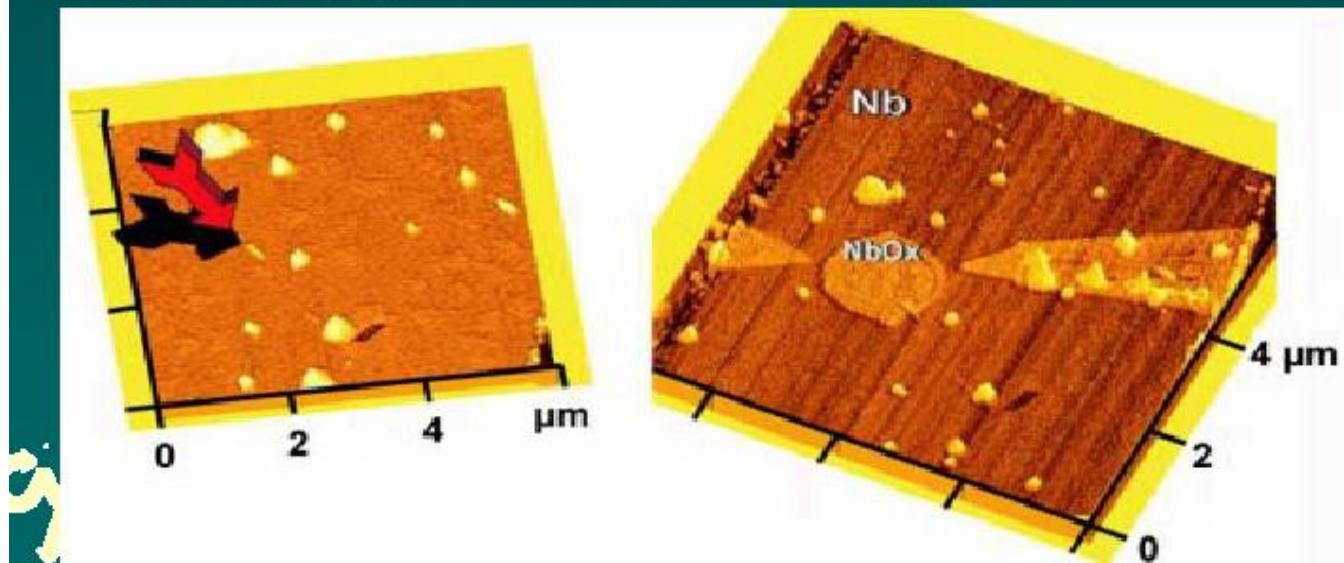
Nanomagnétisme

- mesures magnétiques par μ -Squid ebeam



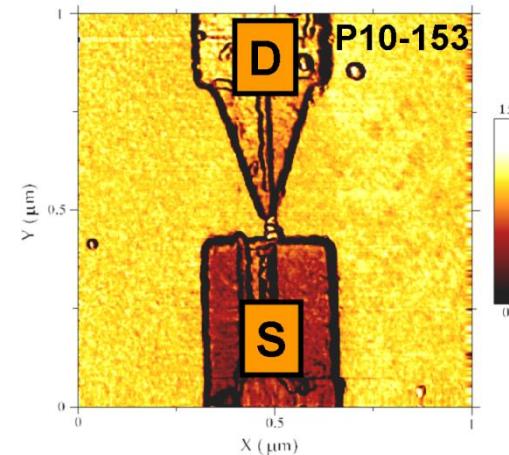
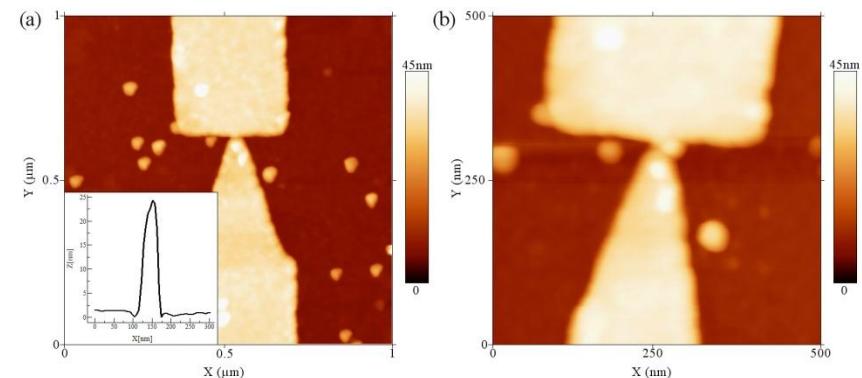
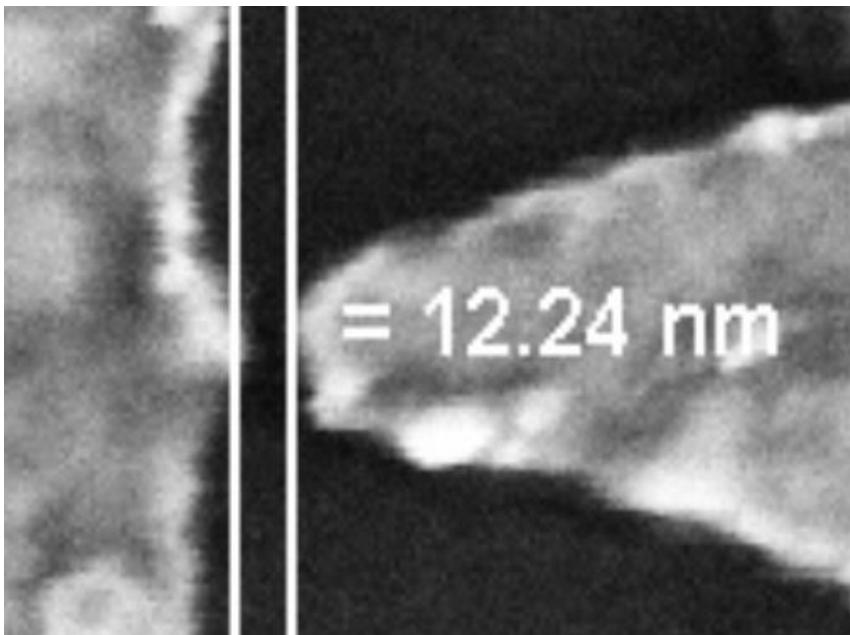
sensibilité:
10-4 Φ 0.Hz-1
1000 μ B
W.Wernsdorfer
&al Physica B:
Condensed
Matter, 280 (1-4)
(2000) pp. 264-
268

- alignement du Squid AFM autour d' une seule particule



Sensibilités attendues:
10-4 Φ 0
100 μ B

Top-Down et Bottom-Up

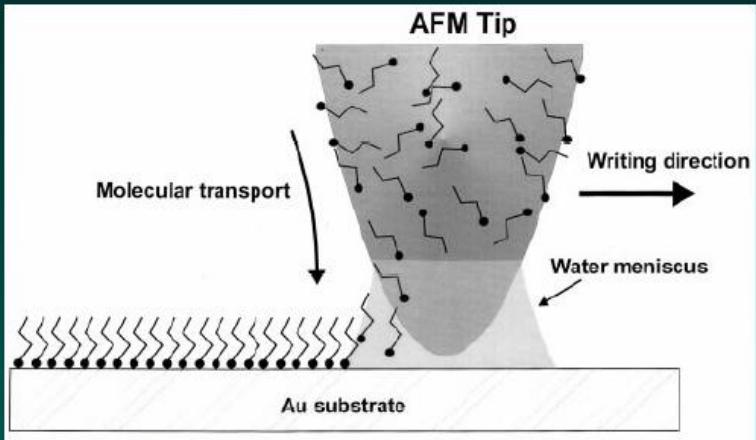


Fabrication électrode Ti/Au par lithographie électronique (CRTBT)

Manipulation de nano-grains de Si (LTM,LPM)

Dip Pen Lithography

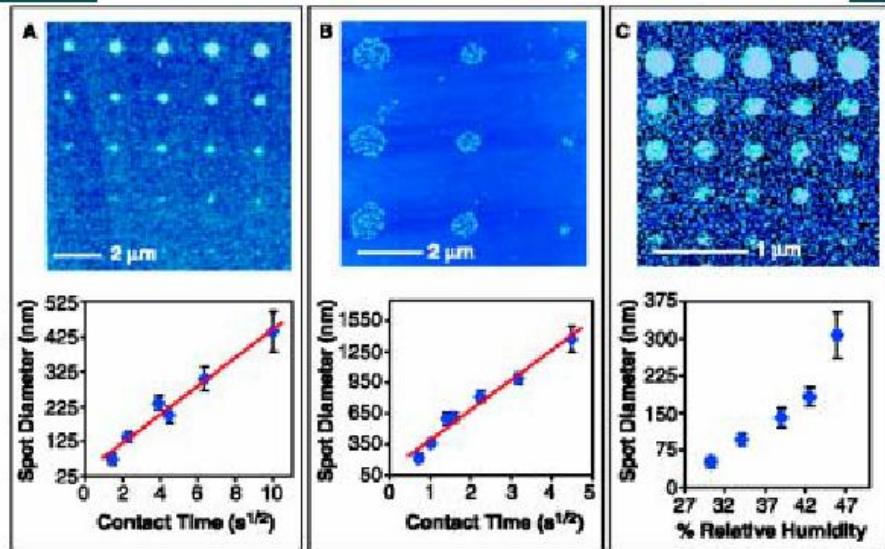
« nanoplume » (dip pen lithography)



Résolution 40 nm

Dépôt contrôlé d'oligo
nucléotides

: « nano-puces à ADN



Mirkin Group, Northwestern U.

Science , 296, 1836, 2002

LPN, 23 Ma

Conclusion

- Optical Lithography
 - contact: +Economical, present in all R&D Labs,
-**Mask and resist damages** 0.5 mic
 - Proximity +Economical, present in all R&D Labs,no mask damage 2 mic
 - Projection +Constant evolution and progress 45 nm?
 - EUV + Next technique?
-**Very expensive, not industrial at the moment** 15-30nm
- Electron Beam Lithography
 - +No mask, Flexible, Useful in R&D Labs, Low prices solutions
-**Low throughput, Proximity effect** 1nm
- Ion Beam lithography
 - + Direct writing (no mask, no resist), 3D etching, diagnostic
-**No proximity effect, Low Throughput** 10nm
- Near Field lithography
 - + Atomic resolution, Economical, no mask, R&D .1-10nm
-**Very low**
- Nanoimprint, softlithography
 - +Economical, Fast,
-**alignment, need 1:1 mask, Mask damages** 10 nm

Transfer

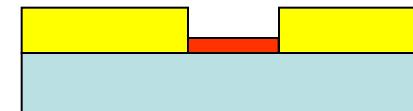
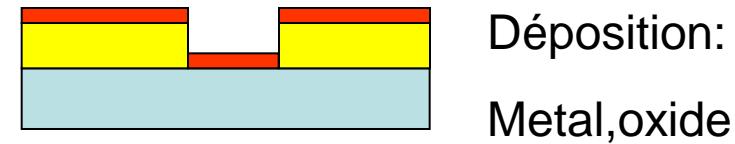
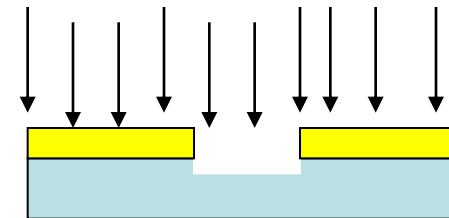
3-Transfert

Etching

- Wet chemical
- Ion Beam
- Reactive Ion Etching

- Lift-Off

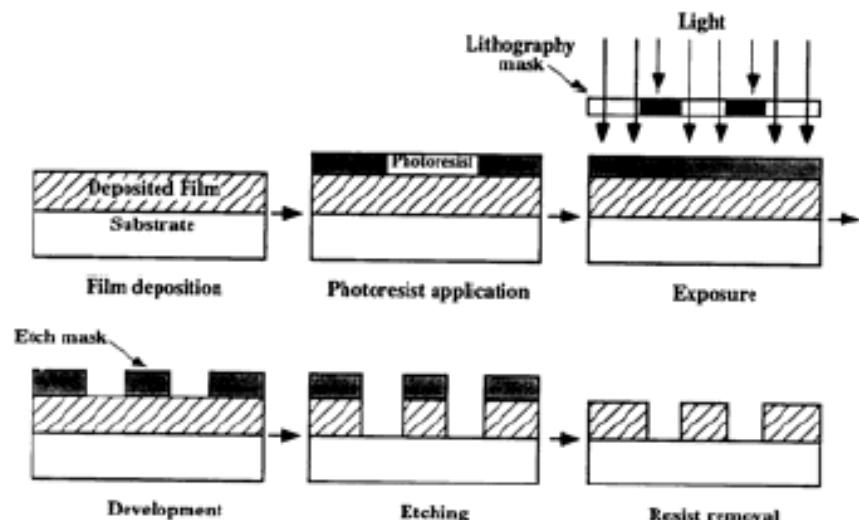
- Electrolytic growth



3-1 Etching

Introduction

- **Etching** is selective removal of thin film(s) resulting in a desired thin film(s) pattern
- The **Etch Mask** is usually photo-resist or oxide/nitride
- Multi-layer structures can be etched sequentially using same masking layer
- Etching can be done in either “wet” or “dry” environment
 - Wet etching = liquid etchants
 - Dry etching = gas phase etchants in a plasma.

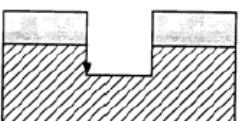
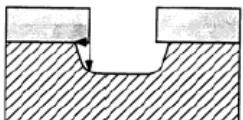
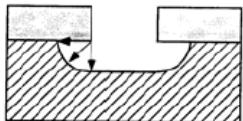


Plummer, Fig. 10-1

Wet Etch — chemical process only
Dry Etch — chemical and physical (sputtering) process

Some definitions

Definition of Terms



Plummer, Fig. 10-3

More directional etching

Etch Directionality	Measure of relative etch rates in different directions usually vertical vs. lateral
Isotropic Etching	Etch rates are same in all directions. It is usually related to chemical processes
Anisotropic Etching	Highly directional etching with different etch rates in different directions. It is usually related to physical processes such as ion bombardment and sputtering

- Anisotropic etching is the preferred process
- Step coverage problems ??

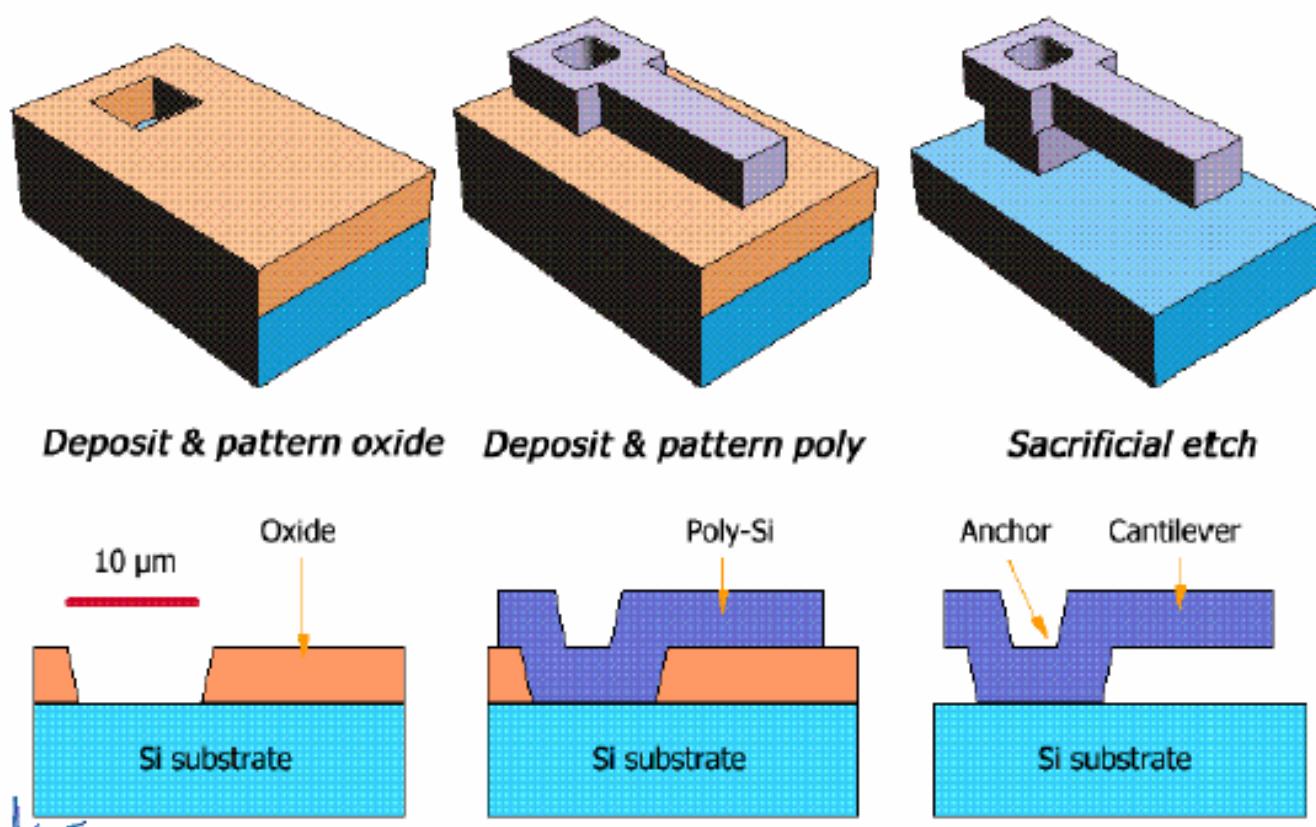
Etch Rate (R)	Rate of film removal, typically 1000 Å/min.
Etch Uniformity (U)	% change in etch rate across a wafer, lot, etc
Selectivity(S_{fm} , S_{fs})	Ratio of the etch rate of various materials e.g. Film to PR S_{fm} : Film to mask selectivity; S_{fs} : Film to substrate selectivity
Anisotropy, A	Measure of directionality of the etch. A=1 corresponds to perfect anisotropic etch A=0 corresponds to isotropic etch
Undercut	Measure of the lateral extent of the etch per side
Substrate Damage	Physical and/or chemical damage of the substrate.

Summary of wet etch

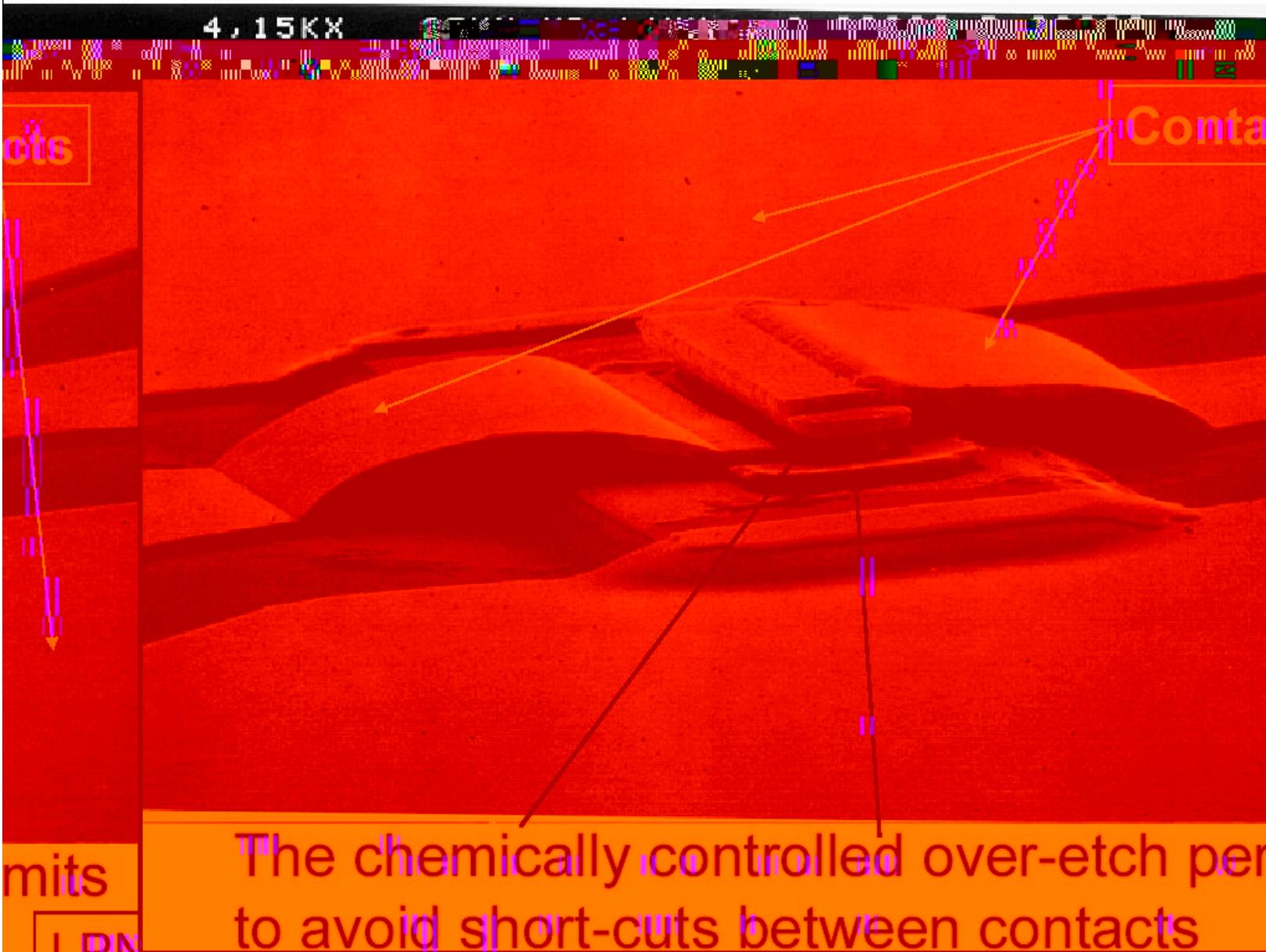
- +ADVANTAGES
 - Simple, Fast, Economical
 - Selectivity
 - No irradiation damage
 - Reproducibility
- - DISADVANTAGES
 - Isotropic (Size Control, Density...)
 - Particles
 - Security



Surface Micromachining



W. Tang - DARPA

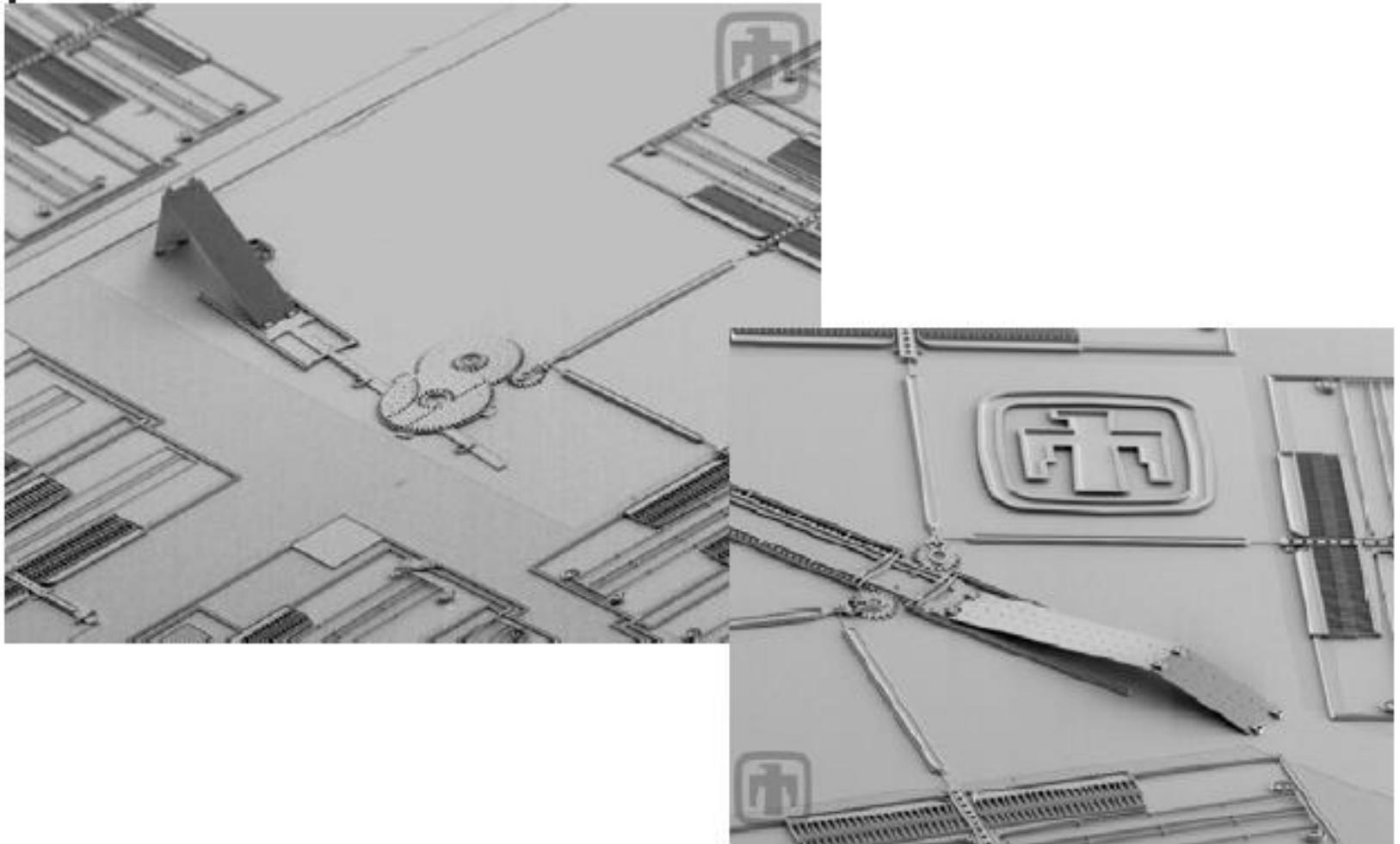


The chemically controlled over-etch period
to avoid short-cuts between contacts

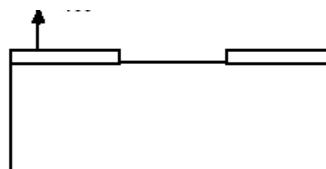
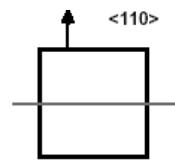
LPN MARCOUSSIS



Sandia MEMS

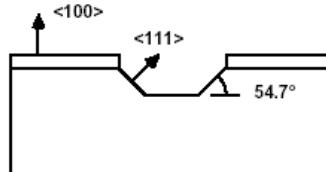
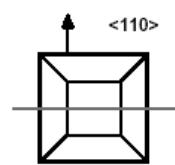


Silicon 100



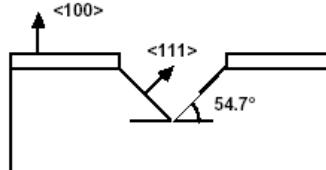
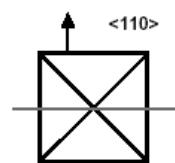
-KOH/Acool/H₂O

Usual Mask: SiN

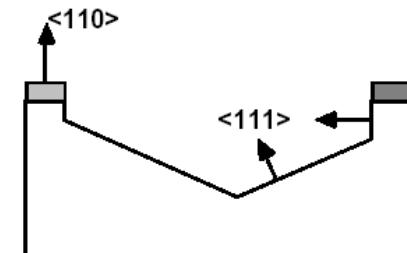
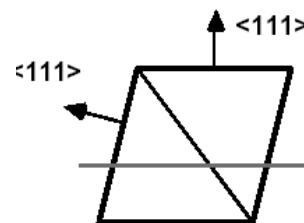
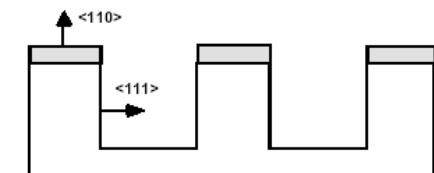
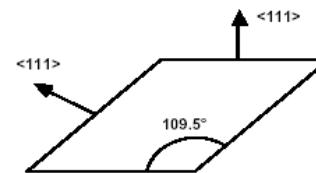


-Pyrocatechol

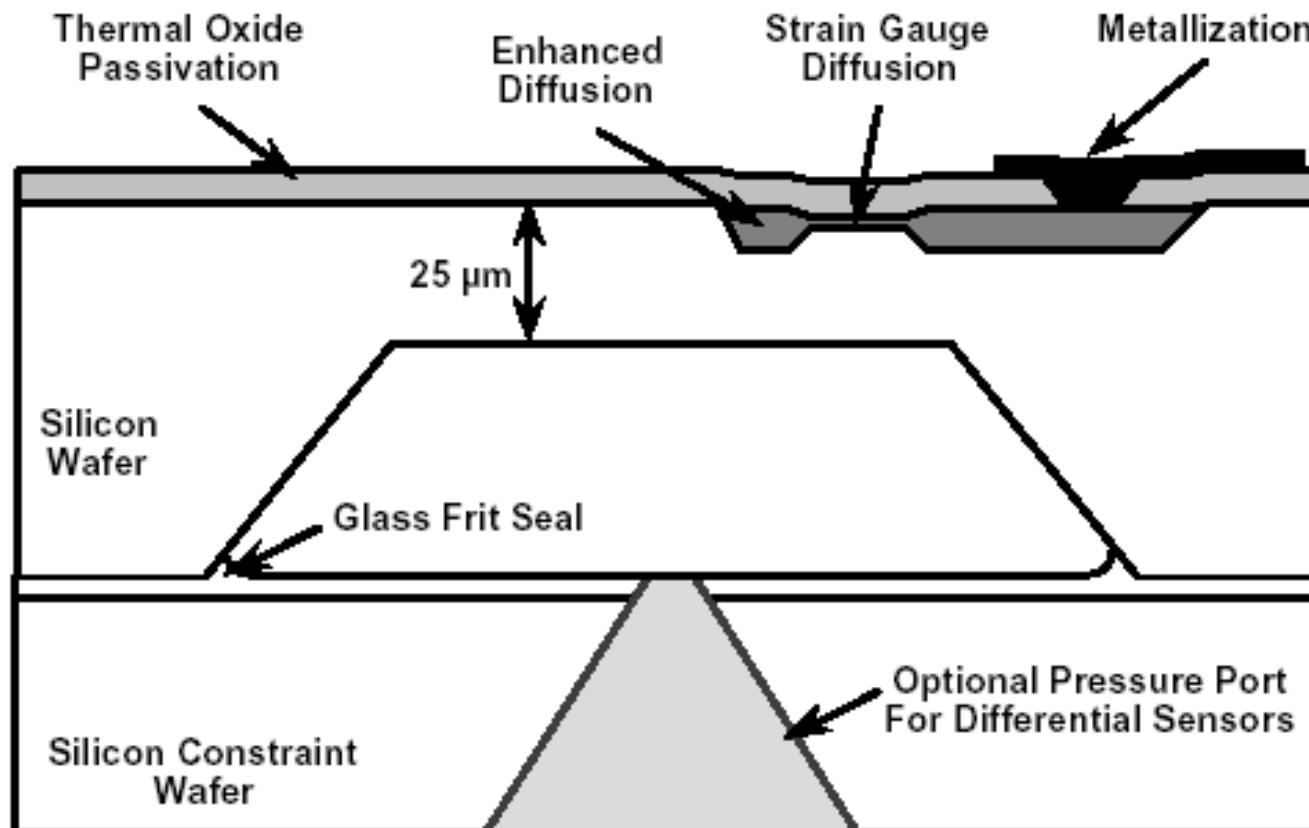
Usual Mask: SiO₂



Silicon 110



Pressure Sensors



Gas Phase (Plasma) Etching

- Plasma etching has largely replaced wet etching because of the directional etching possible with plasma etch systems
 - Directional etching: Presence of ionic species in the plasma and electric field
 - System can be designed so reactive chemical components or ionic components dominate
 - Plasma systems use combination of ionic and reactive chemical species
 - – Etch rate is much faster than individual etch rates
 - Reactive Component → High selectivity
 - Ionic Component → Directionality
 - Both components → Compromise !

Chemistry

Material	Etchant	Comments
SiO ₂	CF ₄ , SF ₆ , NF ₃	near isotropic (large undercutting), poor or no selectivity to Si
	CF ₄ /H ₂ , CHF ₃ , CHF ₃ /O ₂ , C ₂ F ₆	very anisotropic, selective to Si
Si ₃ N ₄	CF ₄ /O ₂	isotropic, selective to SiO ₂ but not to Si
	CF ₄ /H ₂	very anisotropic, selective to Si but not to SiO ₂
	CHF ₃ /O ₂ , CH ₂ F ₂	very anisotropic, selective to Si and SiO ₂
Al	Cl ₂	near isotropic (large undercutting)
	Cl ₂ /CHCl ₃	very anisotropic
Polysilicon	CF ₄ , SF ₆ , NF ₃	near isotropic (large undercutting), poor or no selectivity to SiO ₂
	CF ₄ /H ₂ , CHF ₃	very anisotropic, non-selective to SiO ₂
	CF ₄ /O ₂	isotropic, selective to SiO ₂
	HBr, Cl ₂ , Cl ₂ /HBr/O ₂	very anisotropic, selective to SiO ₂
Single crystal Si	same etchants as polysilicon	
W	CF ₄ , SF ₆	high etch rate, non-selective to SiO ₂
	Cl ₂	selective to SiO ₂
Ti	Cl ₂ , Cl ₂ /CHCl ₃ , CF ₄	
TiN	Cl ₂ , Cl ₂ /CHCl ₃ , CF ₄	
TiSi ₂	Cl ₂ , Cl ₂ /CHCl ₃ , CF ₄ /O ₂	
Organic photoresist	O ₂	

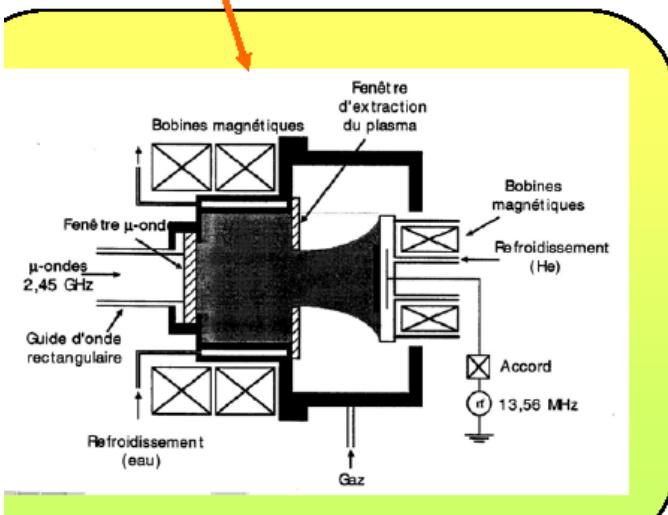
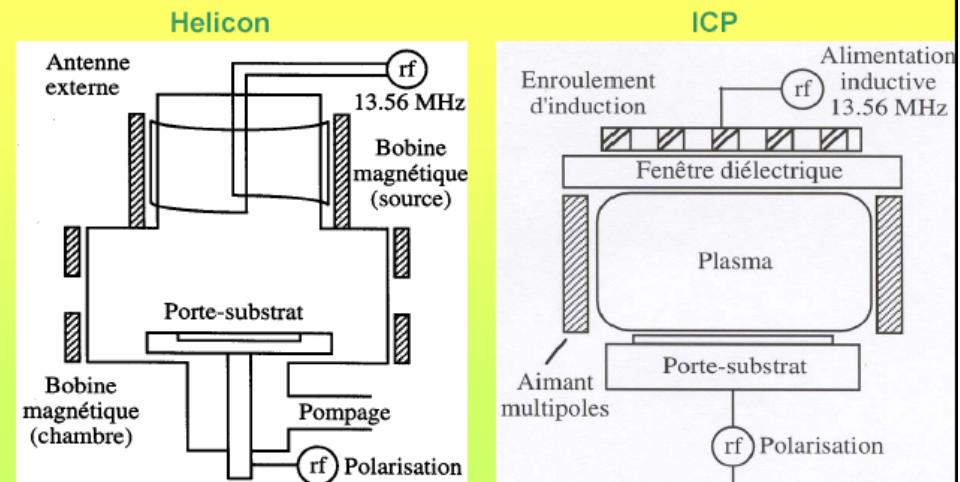
- Conditions

- Presence of chemically active ions/species under plasma conditions
- Presence of volatile reaction products
 - SiF₄, SiCl₂
 - AlCl₃, Al₂Cl₆
 - CO, CO₂
- Control of T, P

High Density Plasma (HDP) reactors

Inductive coupling:
Helicon or ICP

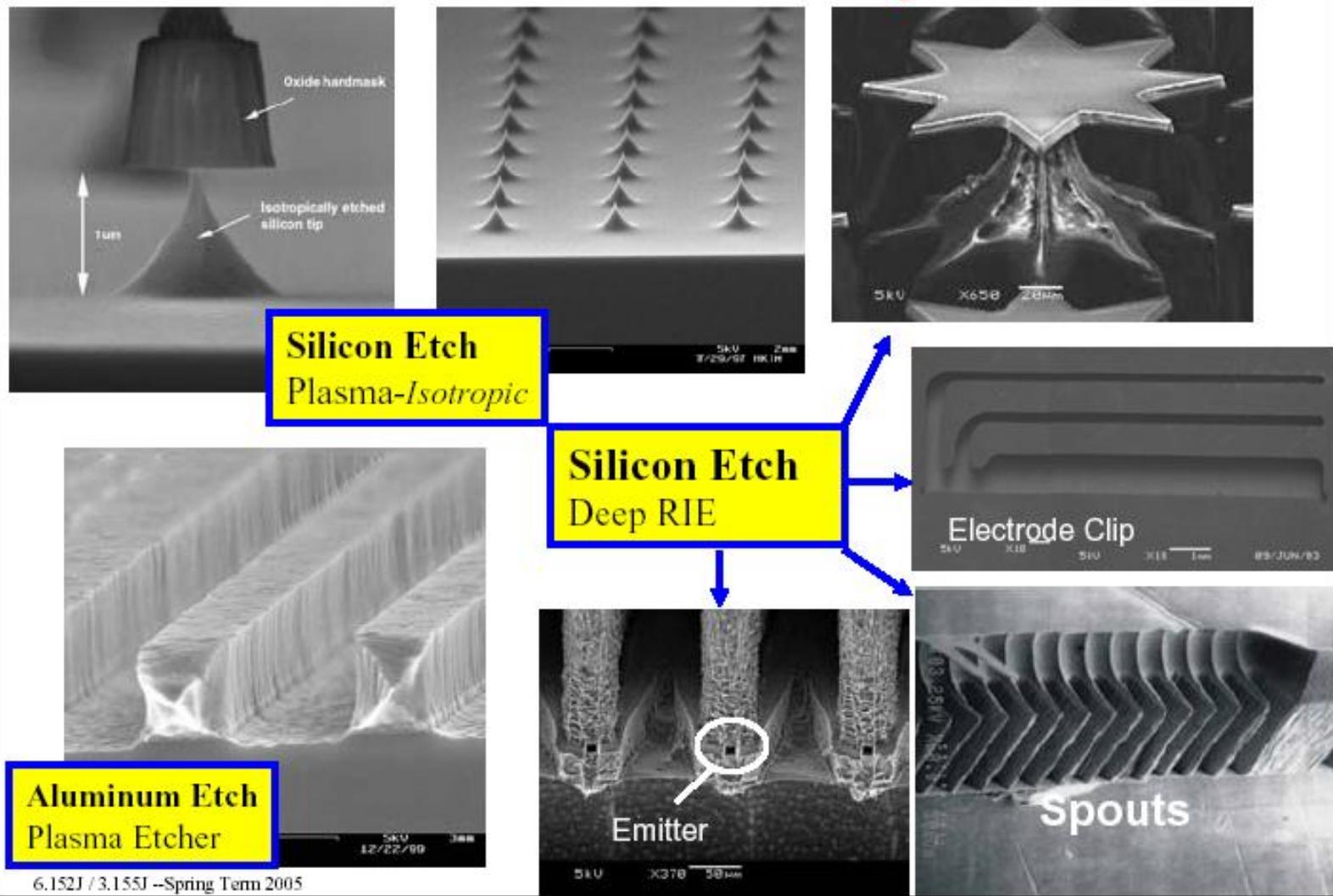
Microwave coupling:
ECR



- high ion density
 - ⇒ faster process
 - ⇒ deeper etching
- ion energy controlled by bias
- energy and density are decoupled

Deep RIE

Picture Gallery



RIE

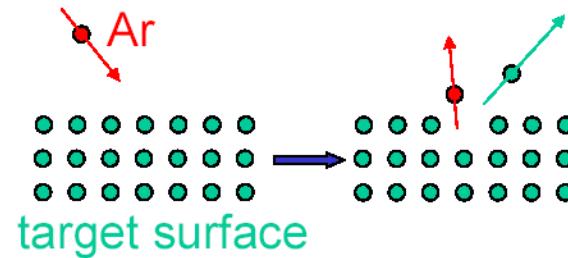
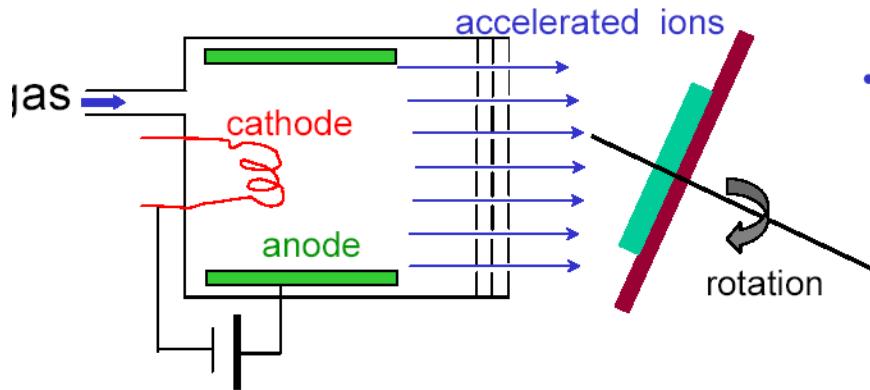
- +
 - Controlled selectivity and anisotropy
 - No redeposition
 - Dry process
 - Fast process
- -
 - Complex chemistry, security
 - Few materials are concerned
 - Sensitive to pollution, memory effect
 - Energy and pressure are linked

Ion Beam Etching

- IBE: Physical effect

Ion Beam Etching (IBE)

- Uses the impact of impinging ions
- Purely physical: linked to momentum exchange between particles
- Sources (ex. Kaufmann)



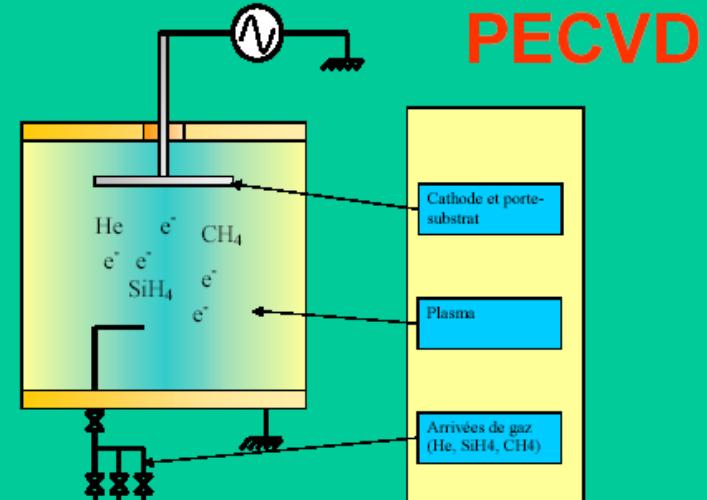
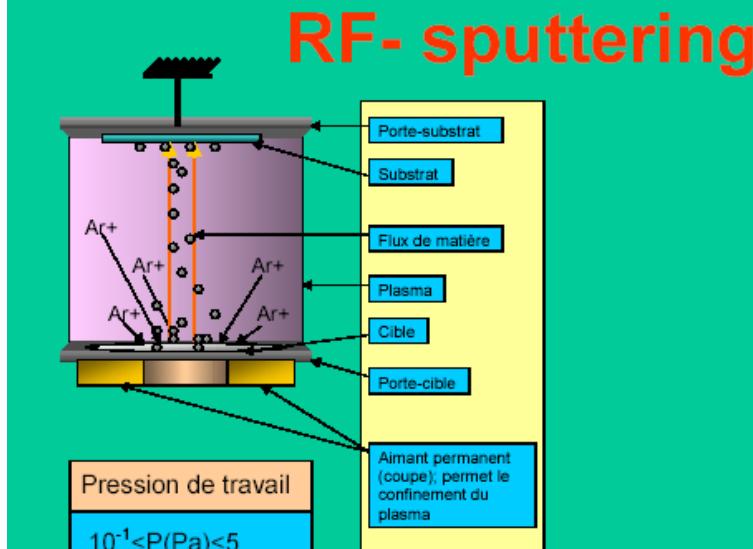
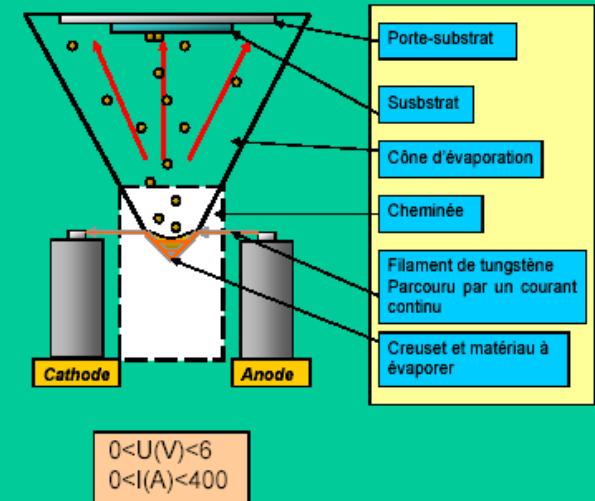
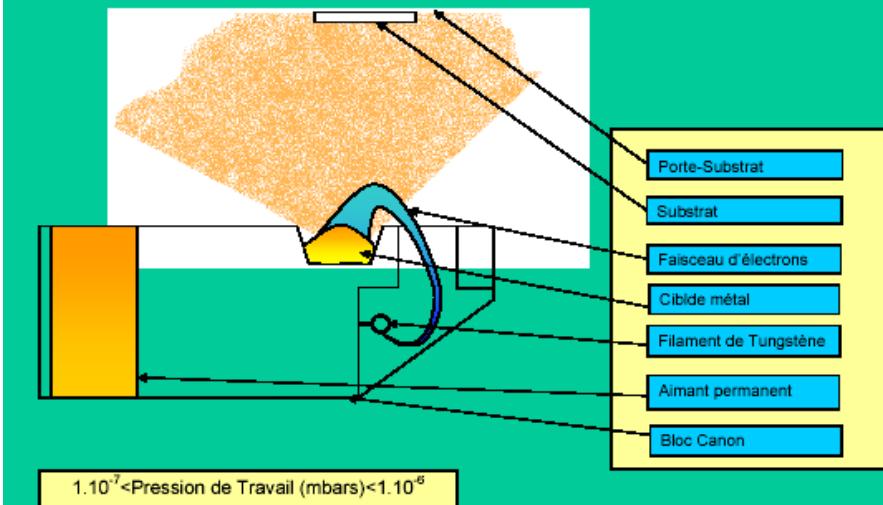
$$\bullet I_{\text{ionic}} \sim V_T^{3/2} \Rightarrow \text{low energy flux}$$

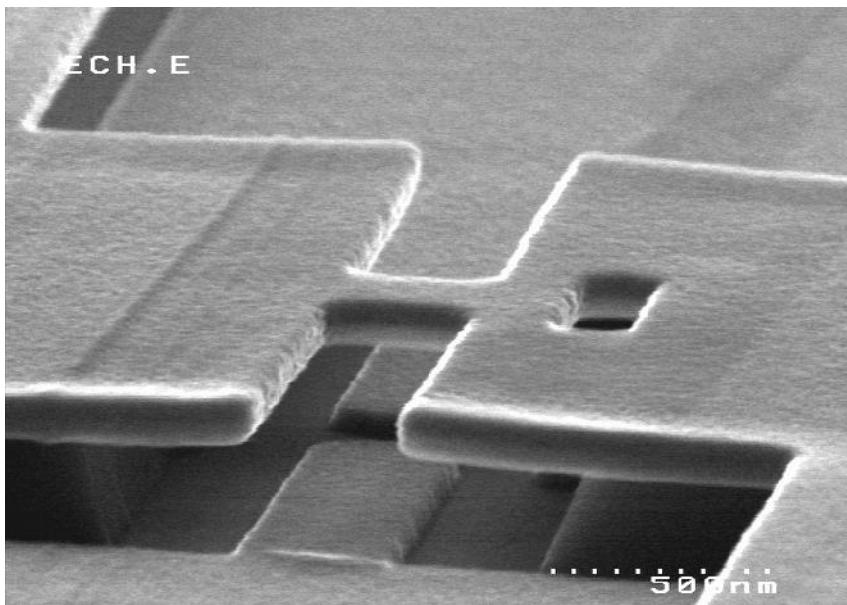
- Neutral gases:
Ar, Xe, Ne, He

Lift-off: deposition techniques

e-gun deposition

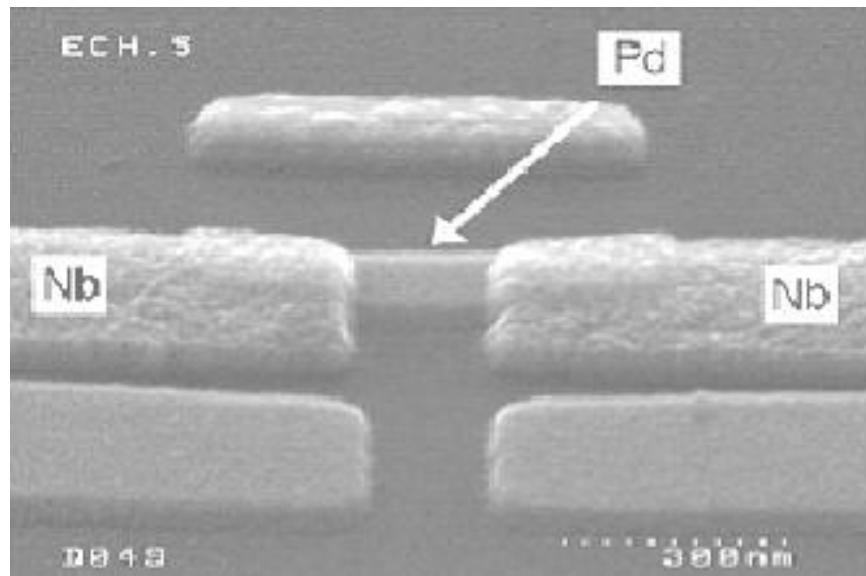
thermal evaporation





Angle Deposition

- Autoalignment
- Control of the interface



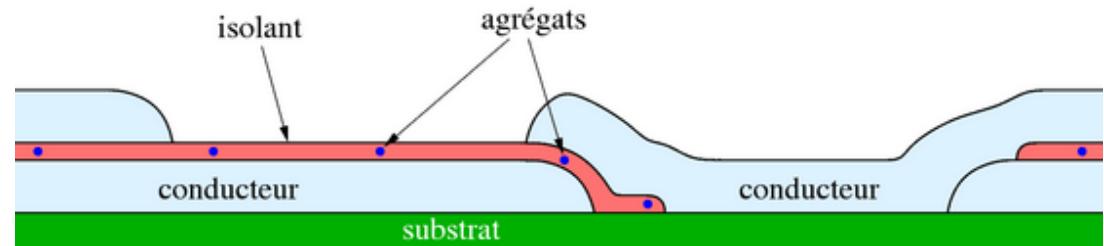
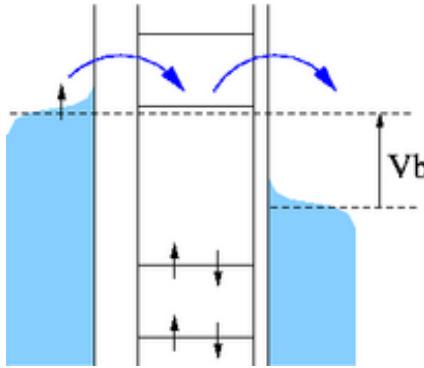
Lift-Off Deposition Techniques

- Thermal evaporation
 - +Low pressure,directive, cheap
 - Crucible, not fitted for all materials, uniformity
- E-gun deposition
 - + Low pressure,directive, no crucible
 - Uniformity
- RF-sputtering
 - +Uniformity, no crucible
 - No directivity, damage on resist
- PECVD
 - +Uniformity, no crucible
 - No directivity, Temperature, damage on resist

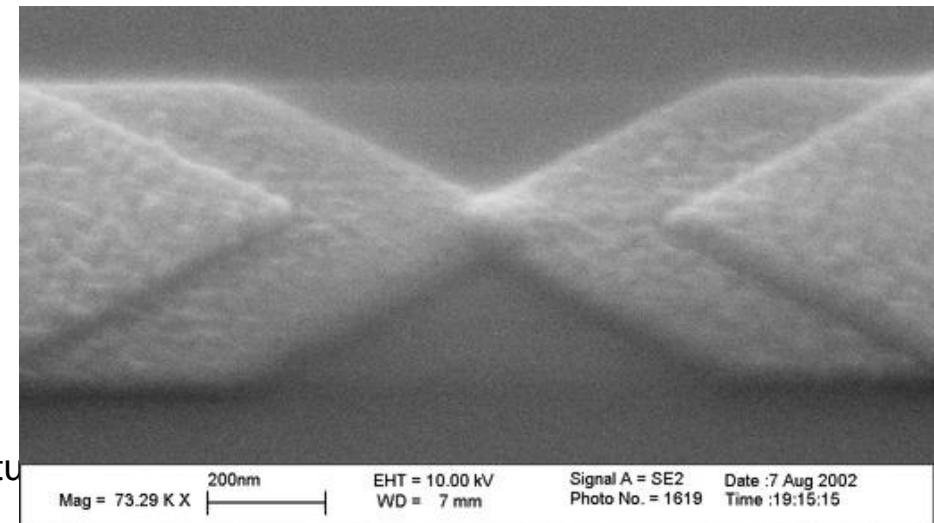
Transport électronique à travers une nanoparticule magnétique

Labo L. Néel et LPMCN-Lyon

- Particule métallique de 3 nm \approx 1000 atomes, reliée à deux électrodes de mesure par des jonctions tunnel
- Conduction tunnel à travers les états quantiques discrets de la particule



- Masqueur -> possibilité d'avoir des électrodes magnétiques et des amenées de courant non magnétiques

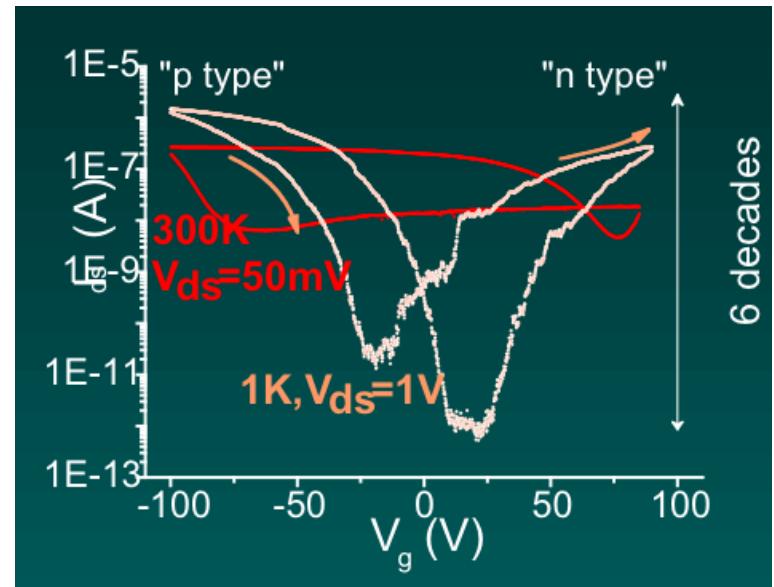
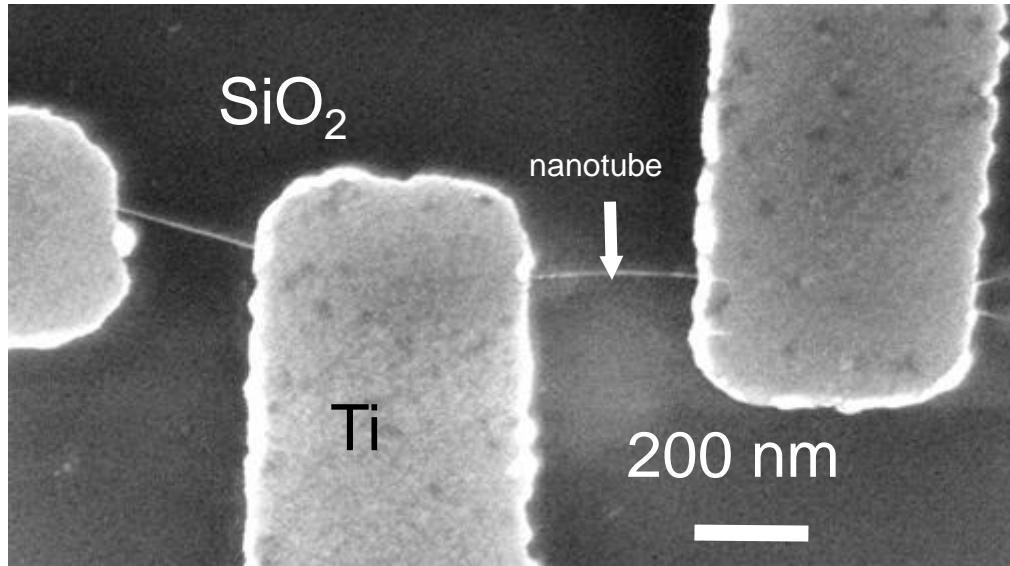


Architectures autoassemblées de nanotubes de carbone

A.M. Bonnot, C. Naud, V. Bouchiat

(CRTBT - LEPES)

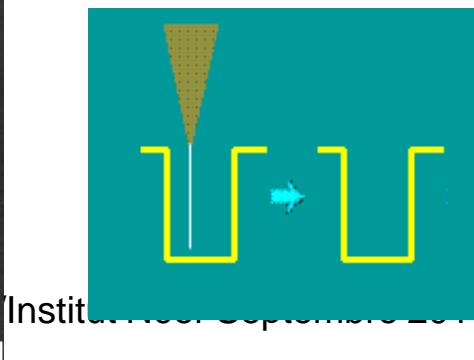
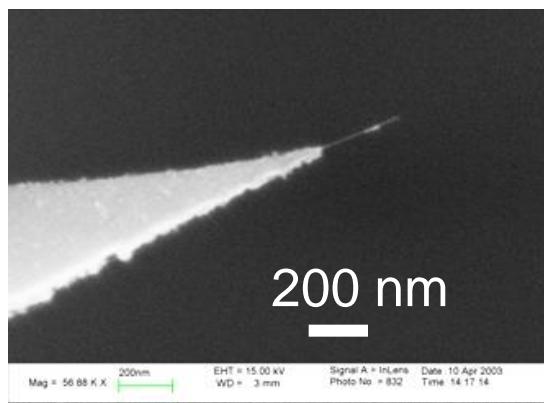
Transistors à effet de champ



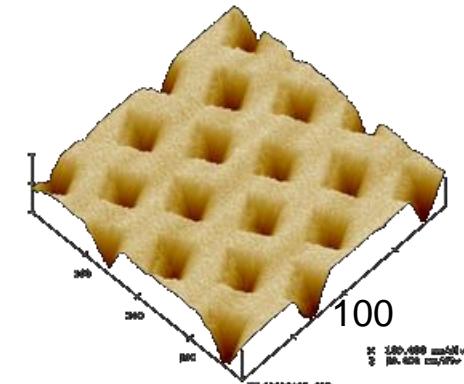
Auto-greffage sur pointes de microscopes à sonde locale

Nanoletters 3,
1115 (2003)

Brevet 17 04 2003



Institut



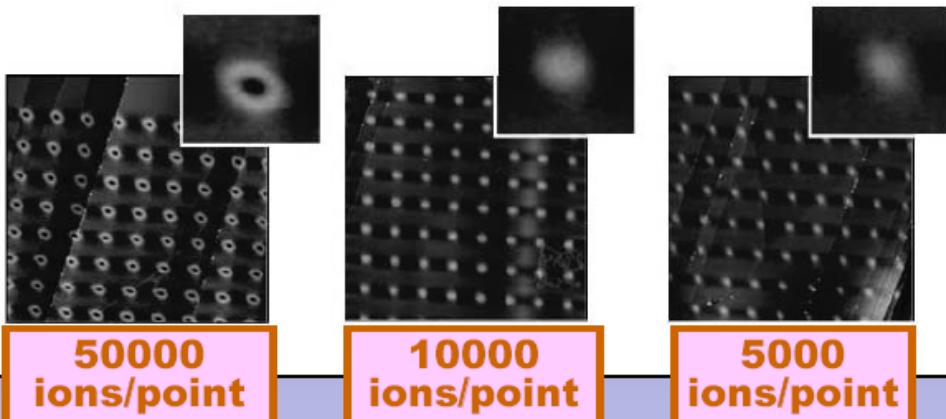
X: 200-800 nm/40

Y: 0-600 nm/40

Z: 0-100 nm/20

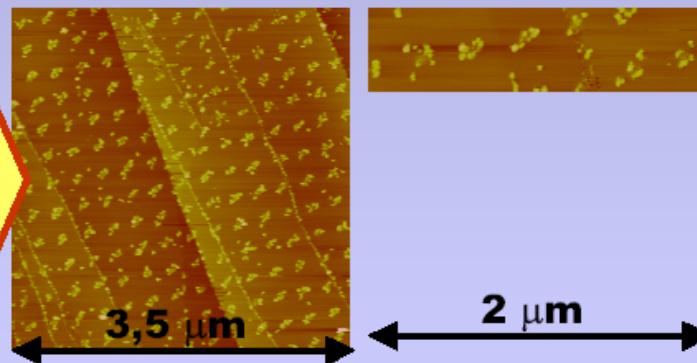
FIB Functionalized substrates

Images TMAFM $2,5 \mu\text{m} \times 2,5 \mu\text{m}$



Nanogravure FIB sur substrats HOPG :
- Ions Ga^+ 30 keV
- Période 300 nm

Réseaux 2D ordonnés d'agrégats magnétiques CoPt sur substrats HOPG gravés FIB
- Période : 300 nm

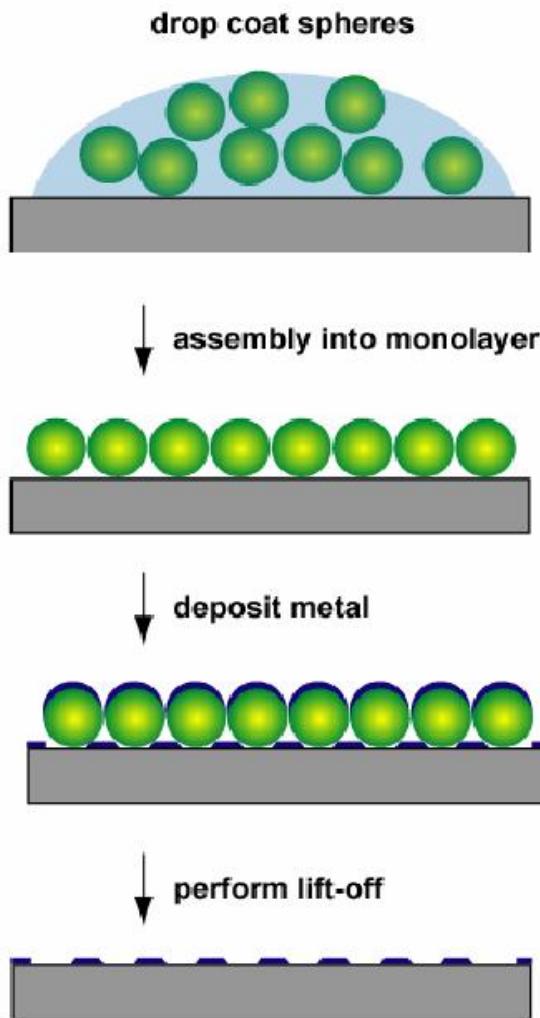


*) Collaboration avec le LPN de Marcoussis : G. Gierak, D. Mailly, G. Faini, et al.

**) voir : "Gold nanoparticles arrays on graphite surfaces", B. Prevel et al.
Appl. Surf. Sci., 226, 173 (2004).

LPMCN, Lyon

Nanosphere lithography



R. P. van Duyne (Northwestern)

