Overview of the main nano-lithography techniques

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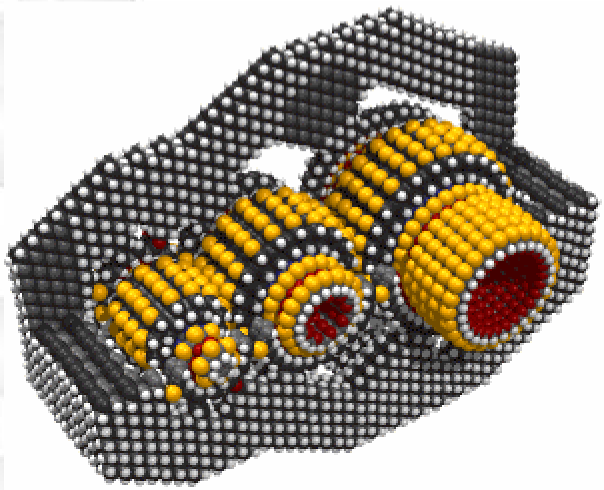
Outline

- Introduction: Nanotechnology.
- Nano-lithography techniques:
    - Masked lithography techniques:
        - ✓ Photolithography.
        - ✓ X-ray lithography.
        - ✓ Nanoimprint lithography.
    - Maskless lithography techniques:
        - ✓ Electron beam lithography.
        - ✓ Ion beam lithography.
        - ✓ Scanning probed based lithographies.
- Summary.

Introduction: Nanotechnology

What is Nanotechnology?

- The study of the controlling of matter on an atomic and molecular scale.
- Generally nanotechnology deals with structures sized between 1 to 100 nanometer in at least one dimension.
- Nanotechnology involves developing or modifying materials or devices within that size.



With 15,342 atoms, this gear is one of the largest nanomechanical devices ever modeled in atomic detail.

http://www.crnano.org/whatis.htm

Introduction: Nanotechnology

Some key dates in Nanotechnology:

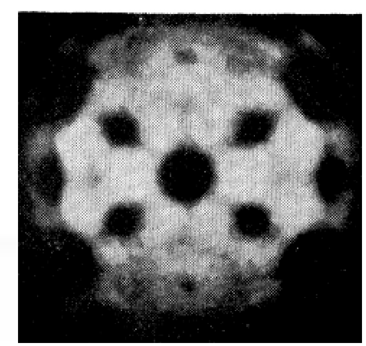
1857

- 1857: Michael Faraday discovered "ruby" gold colloid.

Introduction: Nanotechnology

Some key dates in Nanotechnology:

- 1936: Erwin Müller invented the field emission microscope.



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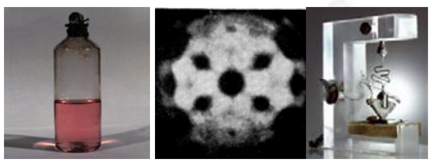

- 1947: Bardeen, Shockley and Brattain discovered the semiconductor transistor.

Introduction: Nanotechnology

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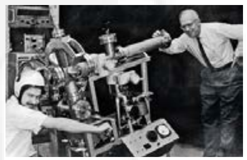

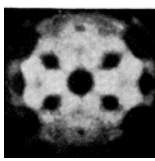

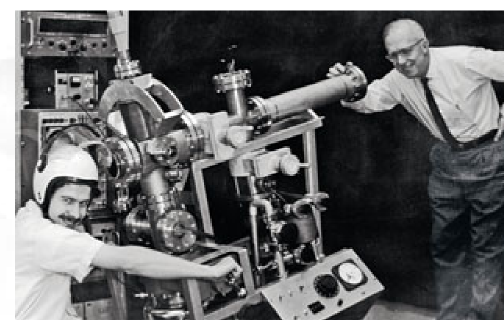

- 1951: Erwin Müller pioneered the field ion microscope.

Introduction: Nanotechnology

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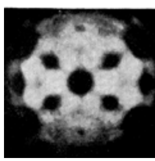
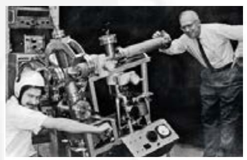
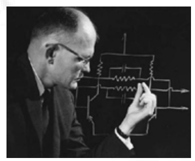
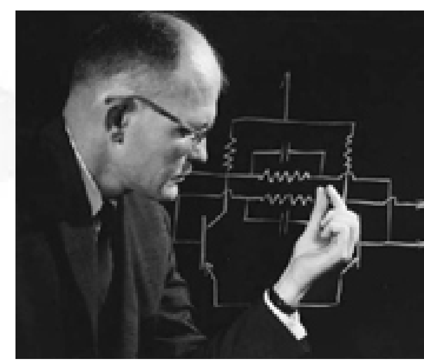






1857 1936 1947 1951 1958

- 1958: Jack Kilby built the first integrated circuit.



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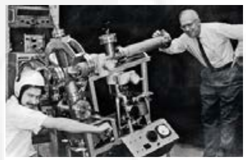
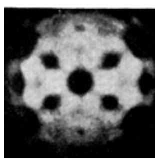
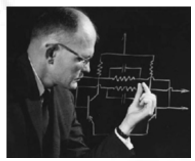


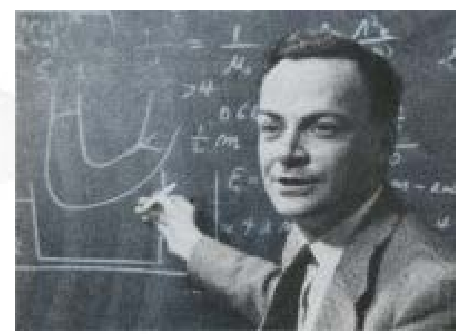






1857 1936 1947 1951 1958 1959

- 1959: Richard Feynman gave the first lecture on technology and engineering at the atomic scale. http://calteches.library.caltech.edu/1976/1/1960Bottom.pdf



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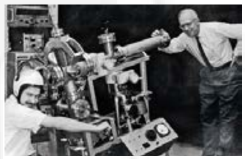


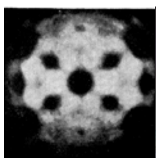

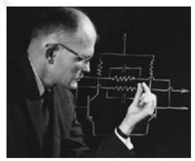
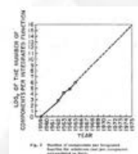


1857 1936 1947 1951 1958 1959 1965

- 1965: Gordon Moore described a trend in electronics known as "Moore's law".

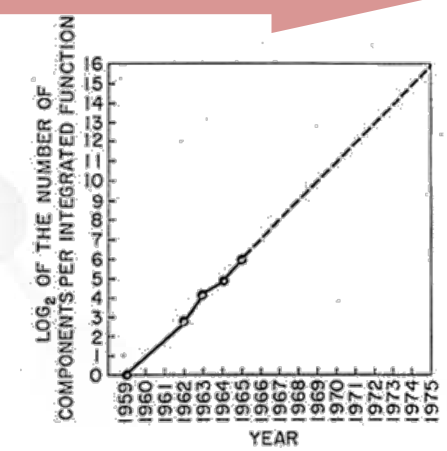

Fig. 2 Number of components per integrated function for minimum cost per component extrapolated vs time.

Introduction: Nanotechnology

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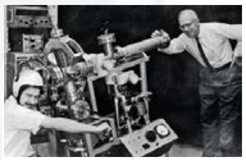
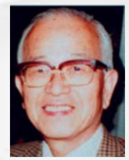
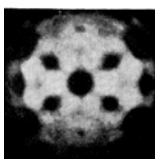
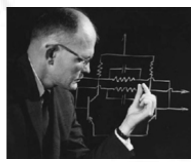
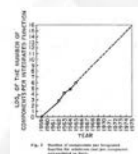


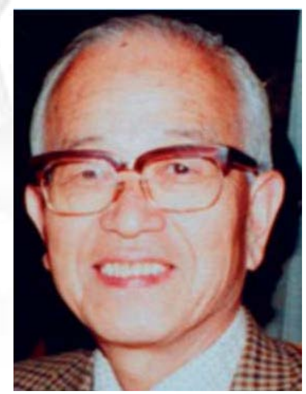




1857 1936 1947 1951 1958 1959 1965 1974

- 1974: Norio Taniguchi coined the term Nanotechnology.



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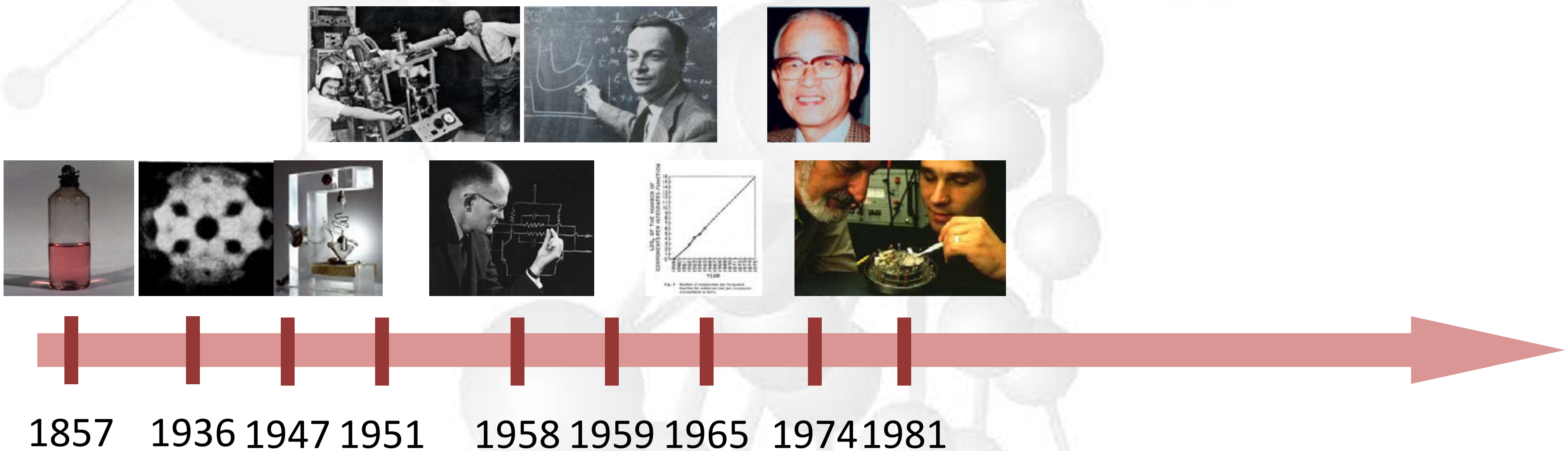
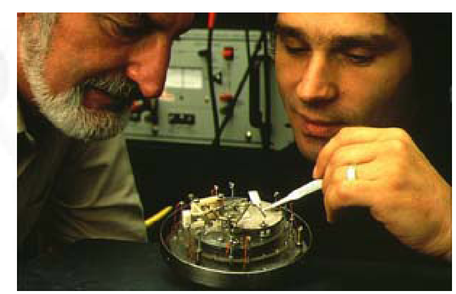


- 1981: Binnig and Rohrer invented the scanning tunneling microscope.



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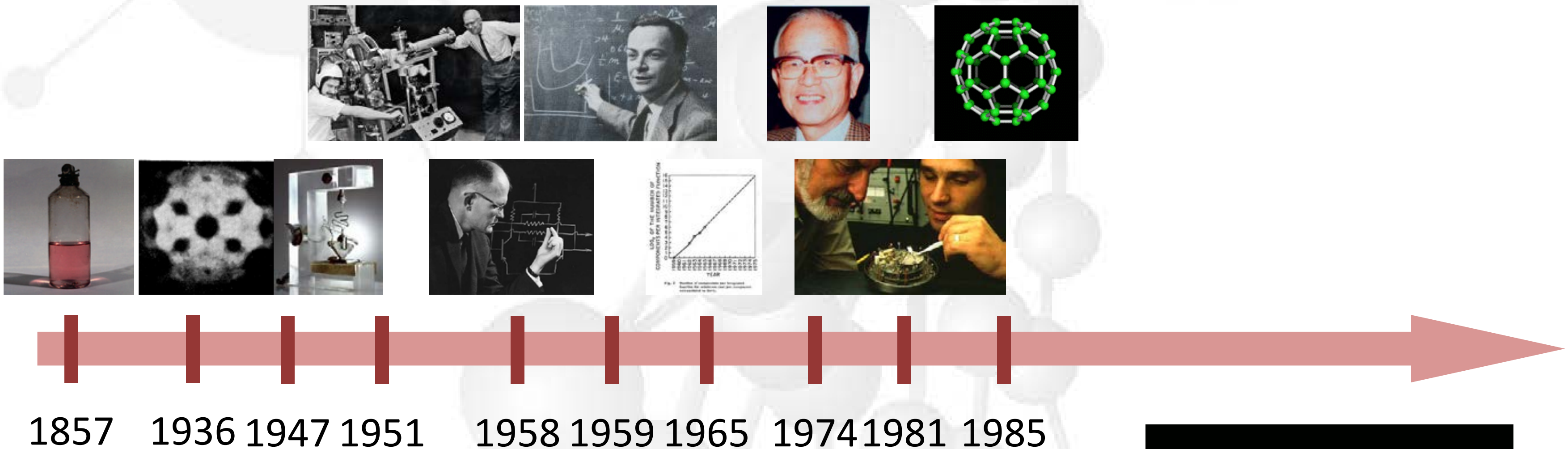
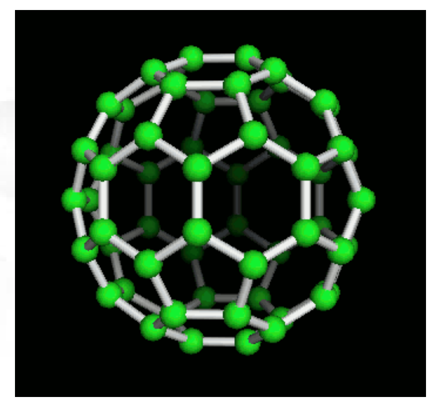


- 1985: Discovery of the Buckminsterfullerene (C_{60} or buckyball).



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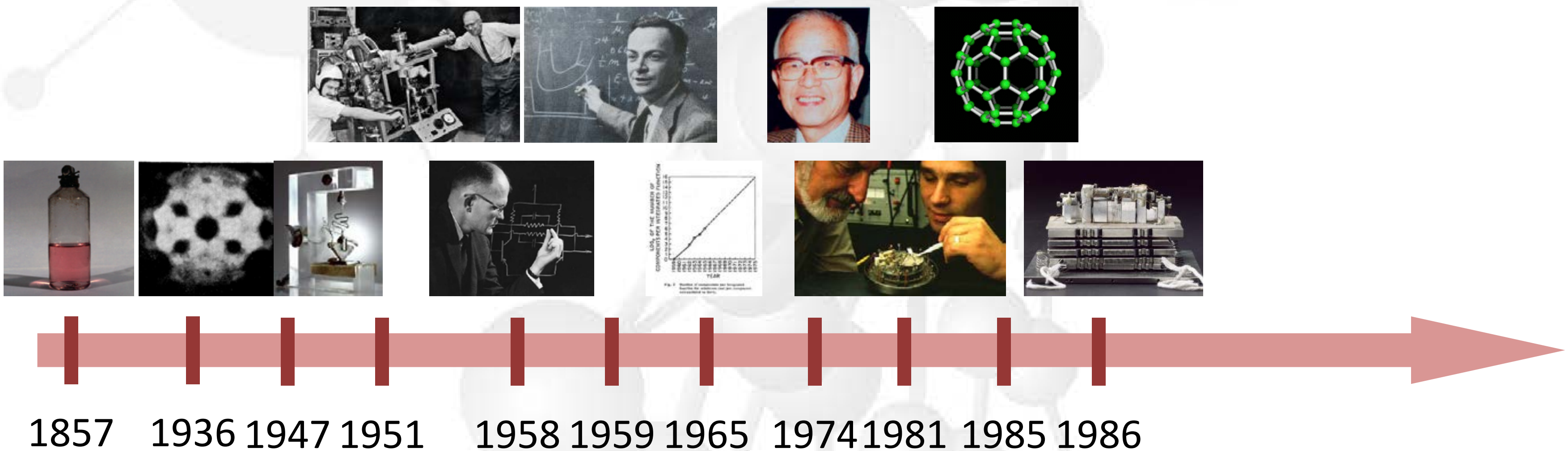
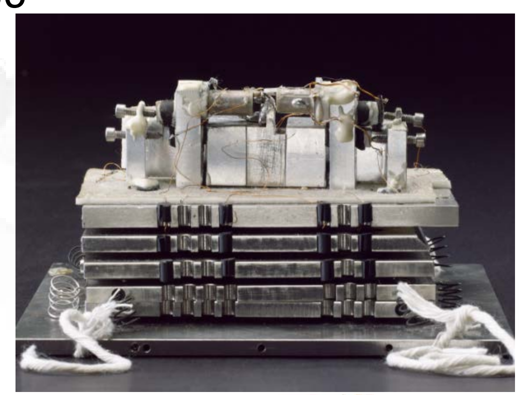


- 1986: Binnig, Quate and Gerber invented the atomic force microscope.



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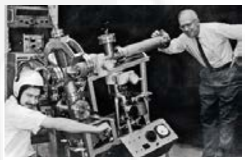
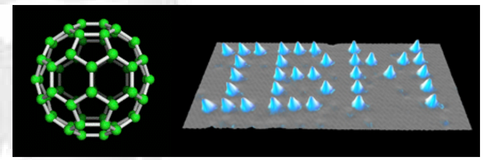
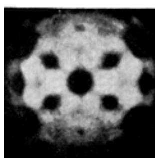
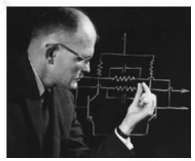
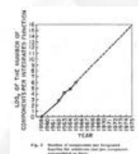


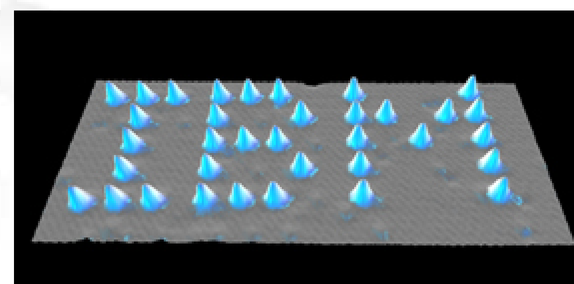





1857 1936 1947 1951 1958 1959 1965 1974 1981 1985 1986 1989

- 1989 Eigler and Schweizer demonstrated the atomic manipulation.



Introduction: Nanotechnology

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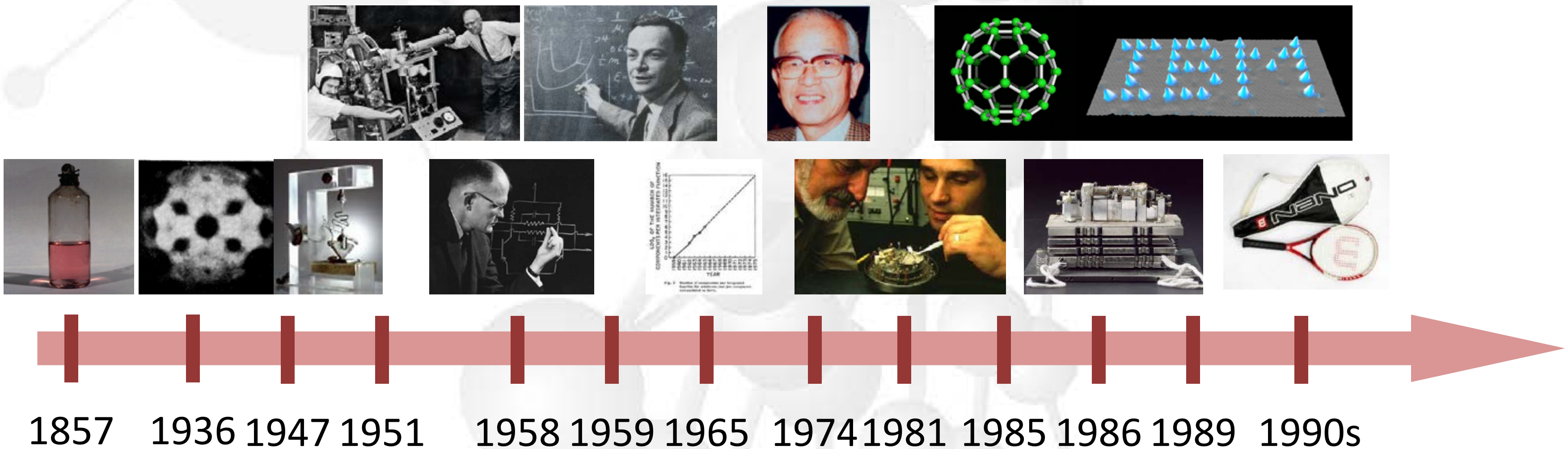
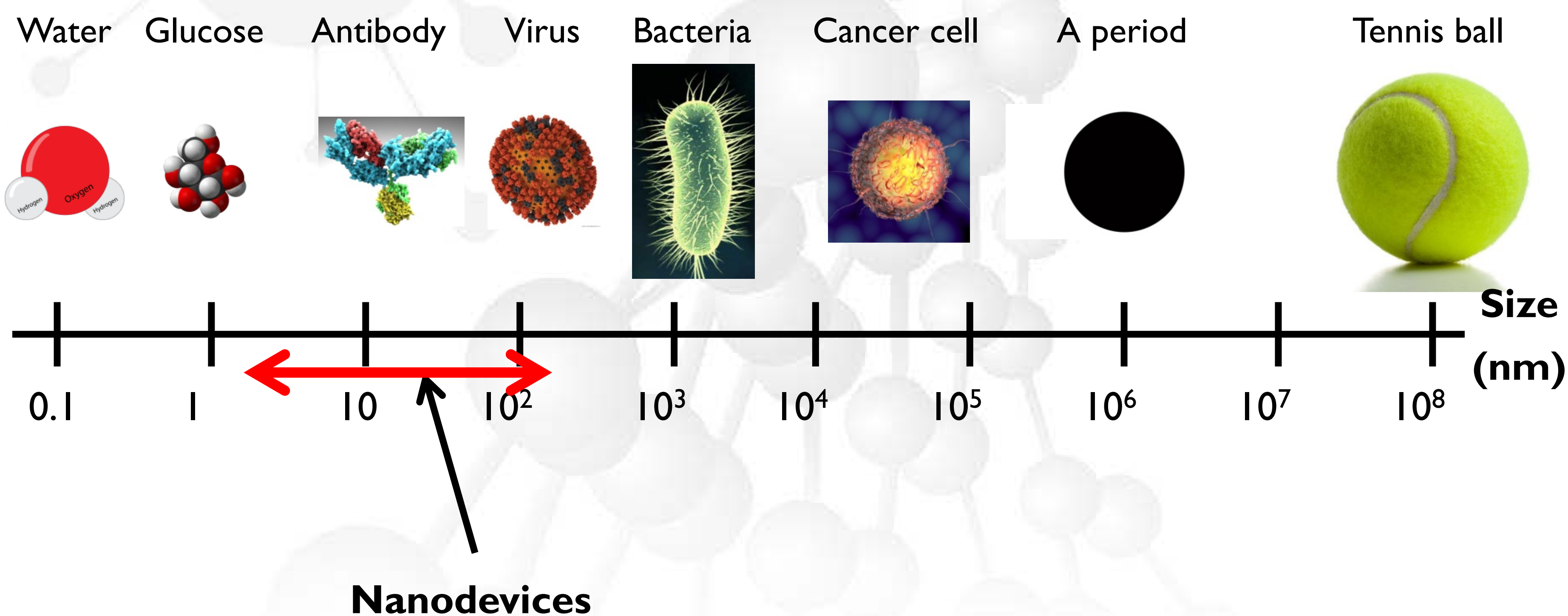


- 1990s: Consumer products making use of nanotechnology!

Introduction: Nanotechnology

How small is Nano?



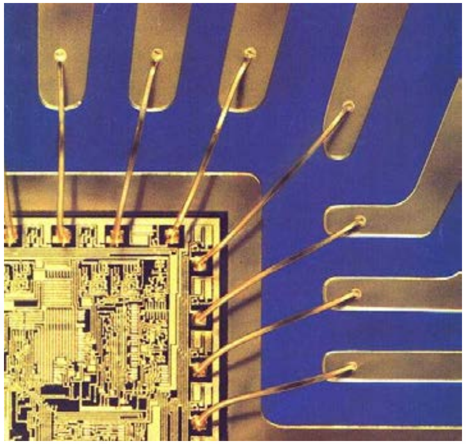
Nanolithography techniques

Nanolithography: Branch of nanotechnology concerned with the study and application of fabricating nanoscale structures, i.e. patterns with at least one dimension between 1 and 100 nm.

Why do we need Nanolithography?

We want to do nanopatterning and fabricated useful devices with nanometric dimensions.

Even though nature provides a few nanometric systems, in general we need to create them artificially.



Nanolithography techniques

Approaches to control matter at the nanoscale

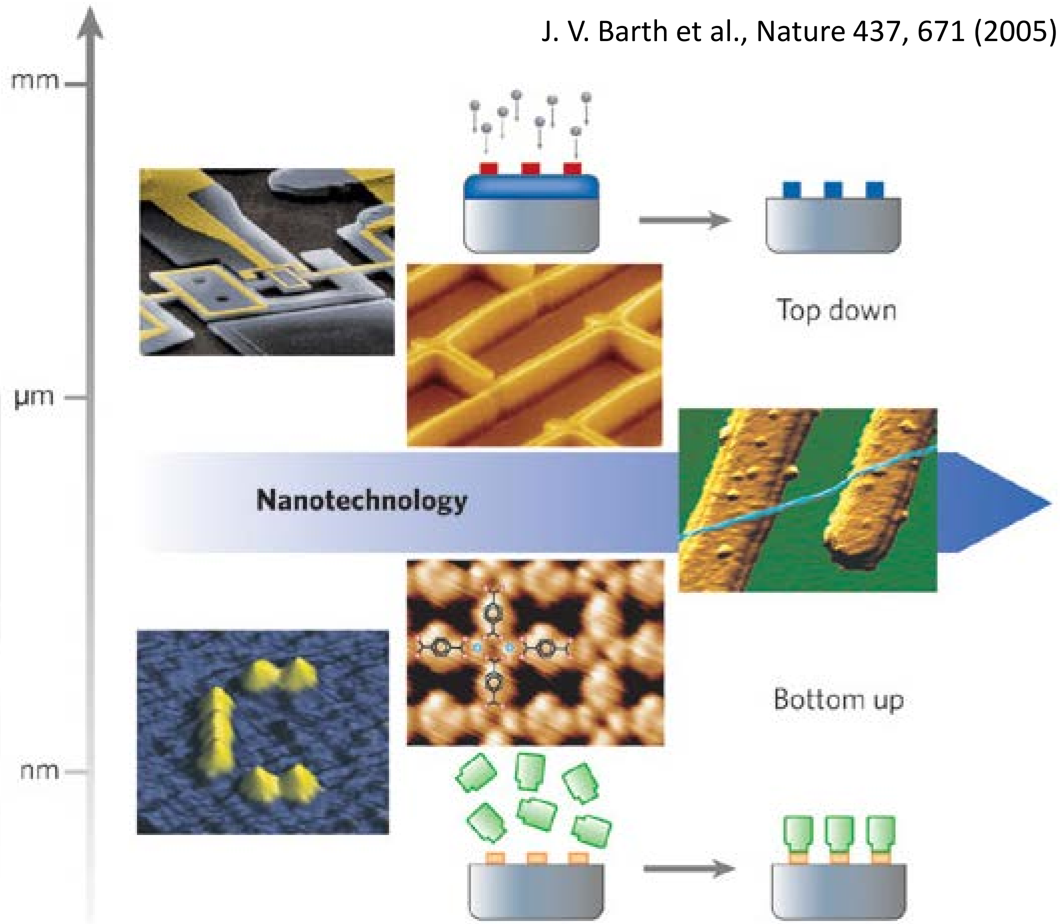
J. V. Barth et al., Nature 437, 671 (2005).

Top-down approach

Thin film deposition techniques
+
Lithography

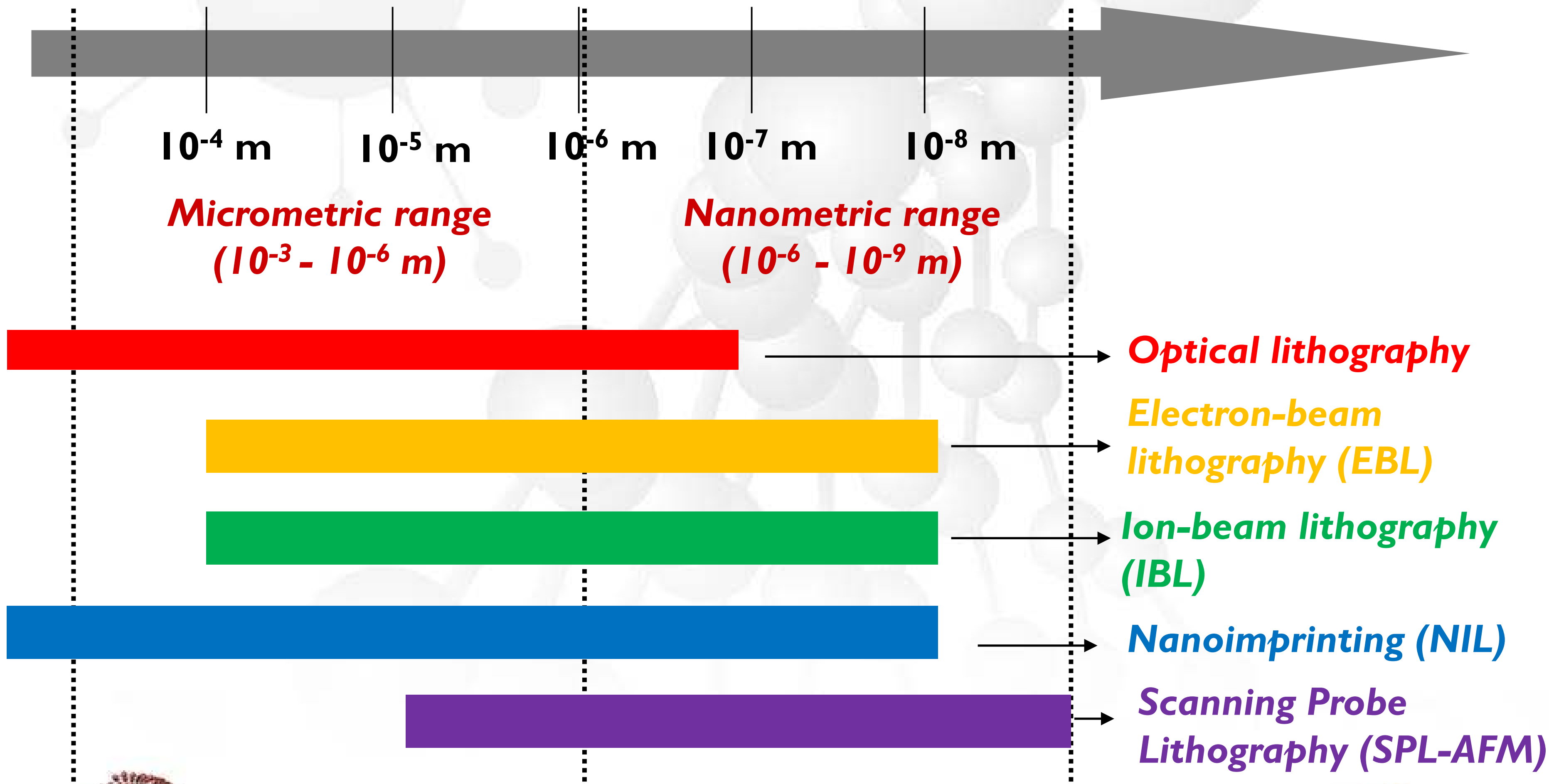
Bottom-up approach

Self assembly, self organization



Nanolithography techniques

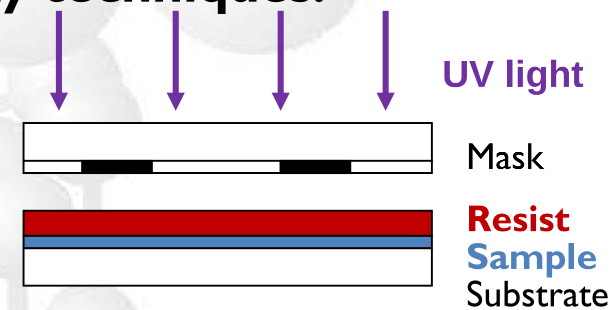
Resolution for micro- and nano- fabrication:

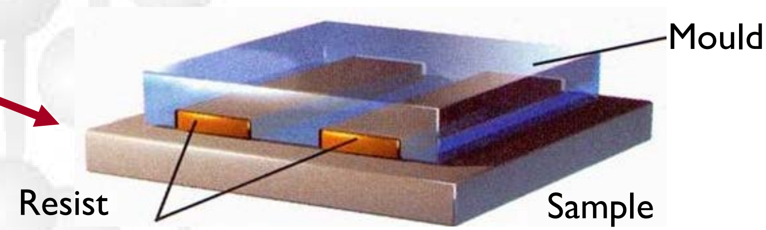


Nanolithography techniques

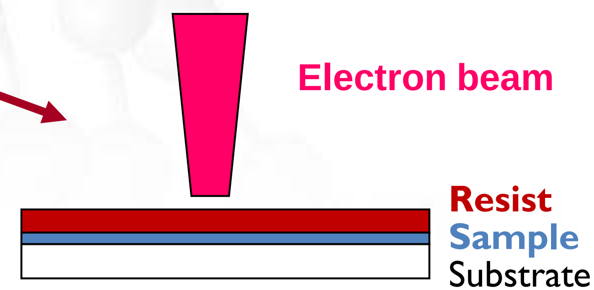
Possible classification of nanolithography techniques:

- Masked lithography techniques:
  - ✓ Photolithography.
  - ✓ X-ray lithography.
  - ✓ Nanoimprint lithography.





- Maskless lithography techniques:
  - ✓ Electron beam lithography.
  - ✓ Ion beam lithography.
  - ✓ Scanning probed based lithographies.



Photolithography

Schematically:

1) <u>Exposure</u>

The resist becomes sensitized

2) <u>Development</u>

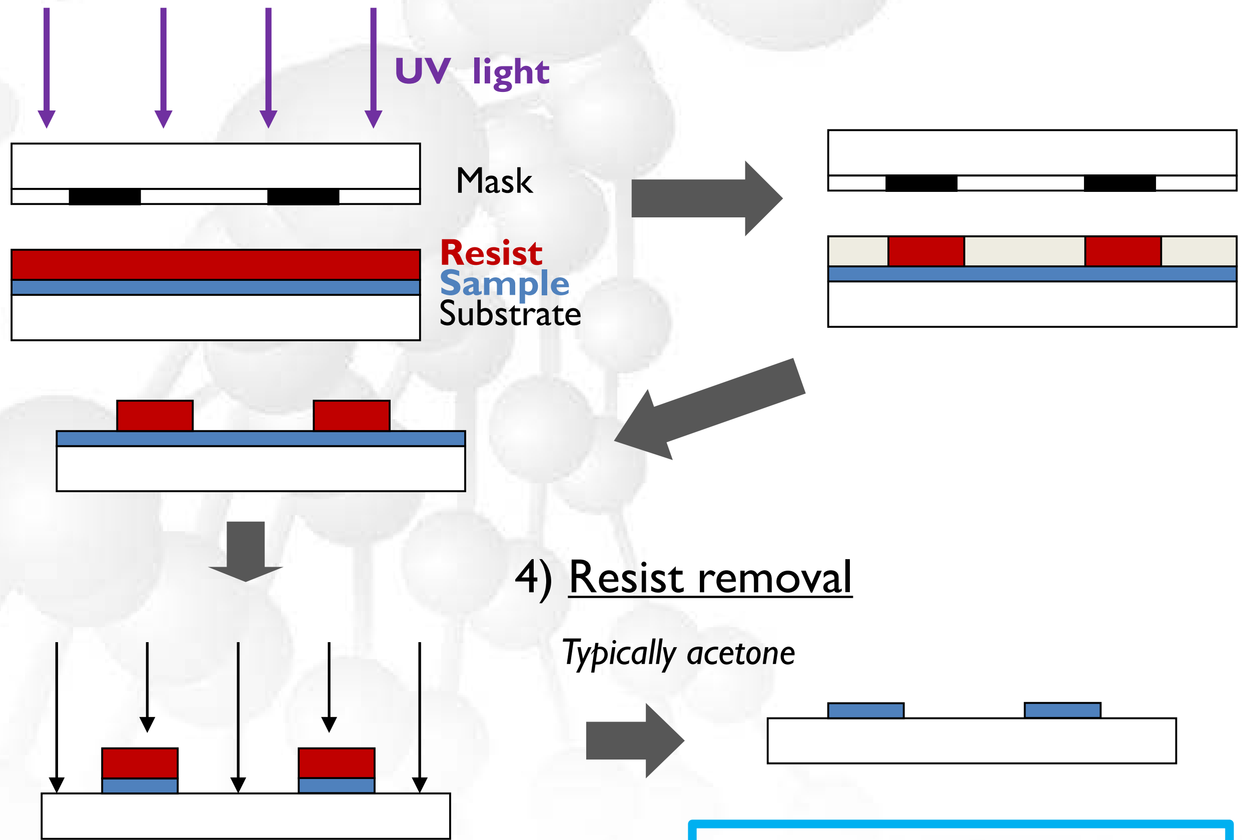
Immersion in developer fluid.

3) <u>Etching</u>

Dry or wet etching.

4) <u>Resist removal</u>

Typically acetone



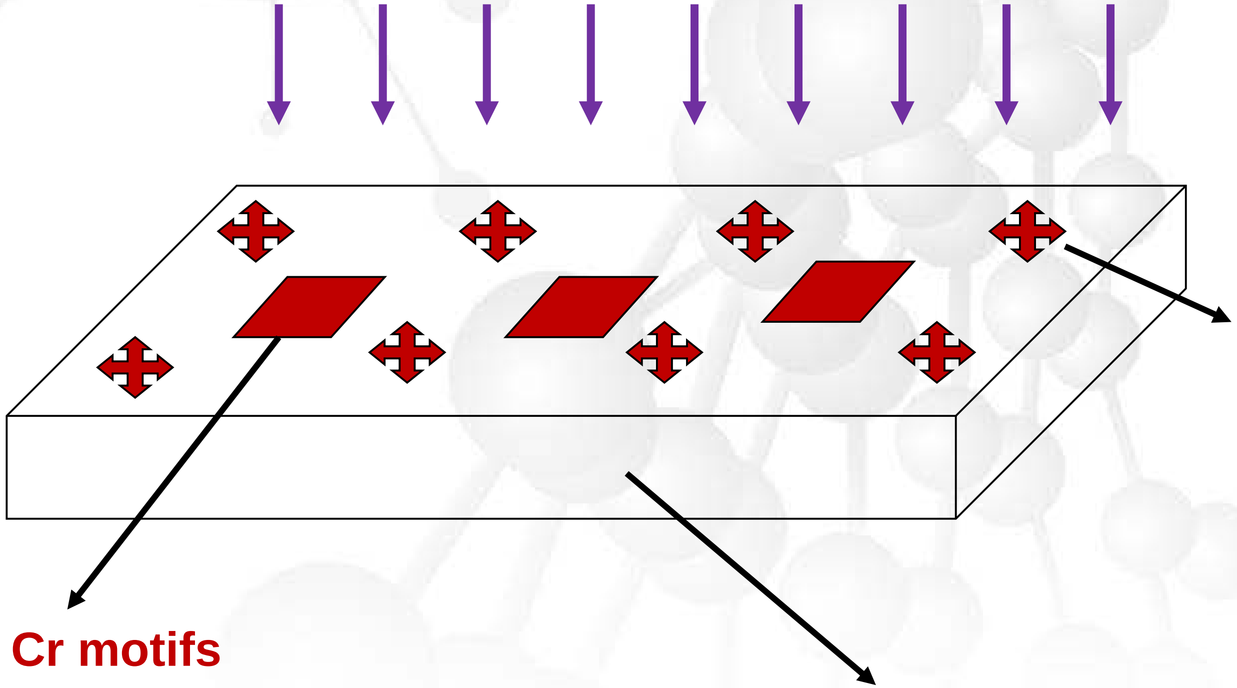
Result: Sample with the same pattern of the mask

Courtesy of J. M. De Teresa, ICMA-Unizar

Photolithography

Going over that a little more slowly:

- **Photolithography masks:**



UV light

Cr alignment crosses
(for subsequent steps)

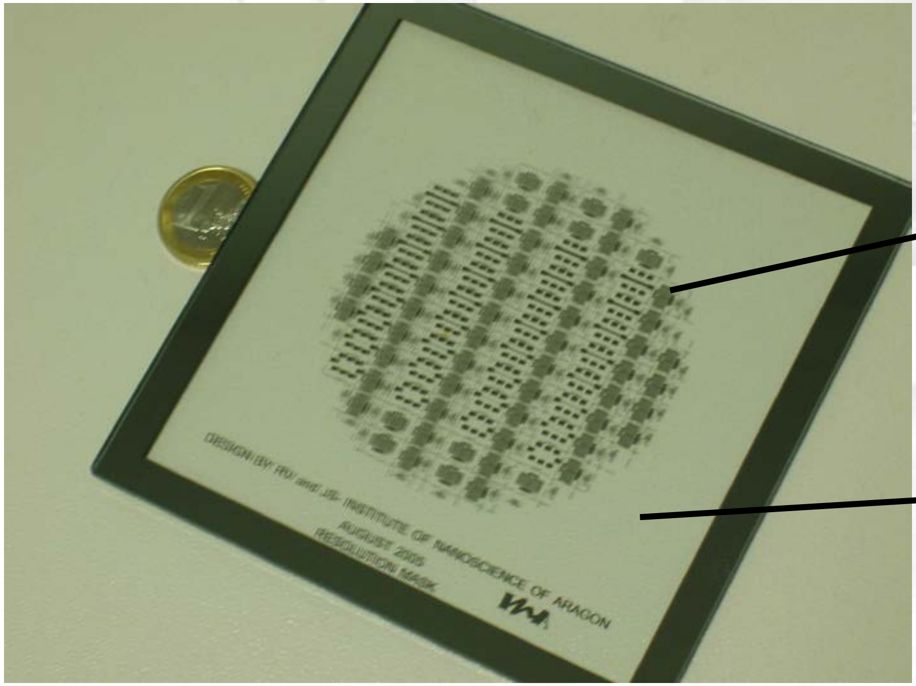
Cr motifs
(stopper of UV light)

Quartz support
(transparent to UV light)

Courtesy of J. M. De Teresa, ICMA-Unizar

Photolithography

- **Photolithography masks:**



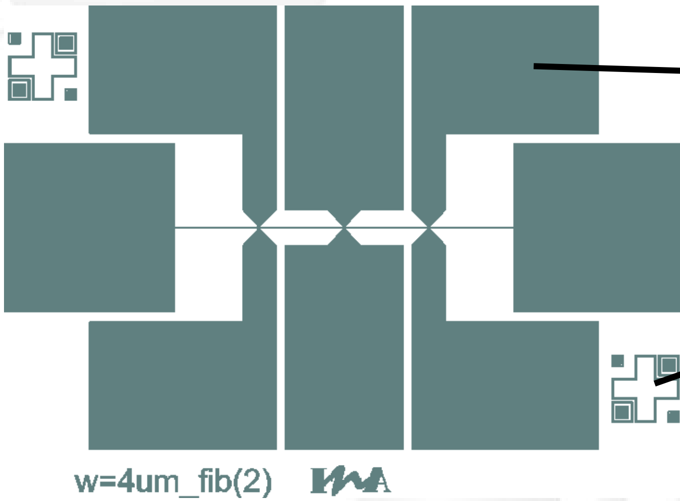
Cr motifs
(stopper of UV light)

Quartz support
(transparent to UV light)
5” by 5” in area
0.25” in thickness

Courtesy of J. M. De Teresa, ICMA-Unizar

Photolithography

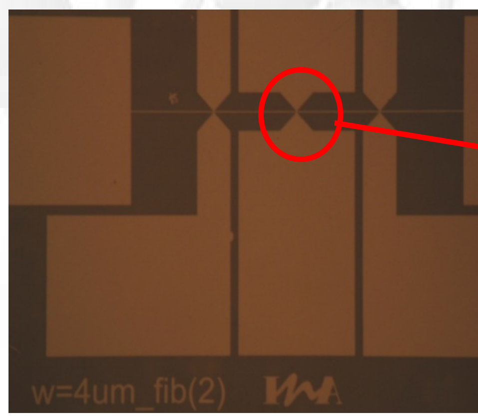
- **Photolithography masks:**

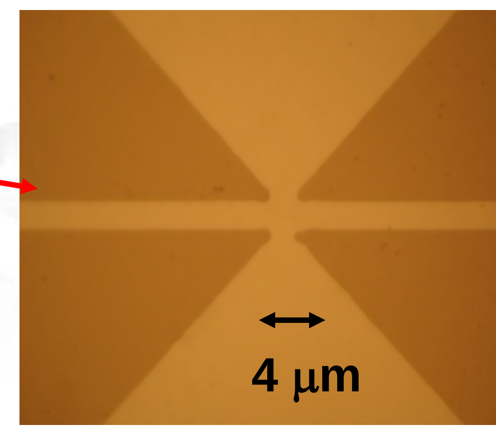


Cr motifs
(stopper of UV light)

Cr alignment crosses
(for subsequent steps)

Final sample:
(Optical microscope image)





Courtesy of J. M. De Teresa, ICMA-Unizar

Photolithography

- **Resists (Photoresists):** Viscous fluid formed by a polymer, a photosensitive component and a solvent.

Polymer: It provides the properties of viscosity, adherence and resiliance to chemical etching.

Solvent: It permits to keep the polymer in solution, allowing its application on the sample. Its concentration changes the viscosity/final thickness.

Photosensitive complex: It provides the sensitivity to the UV radiation. This molecule is able to change the solubility of the polymer in the developer.

Photolithography

- **Two types of photoresists:**

Negative photoresist

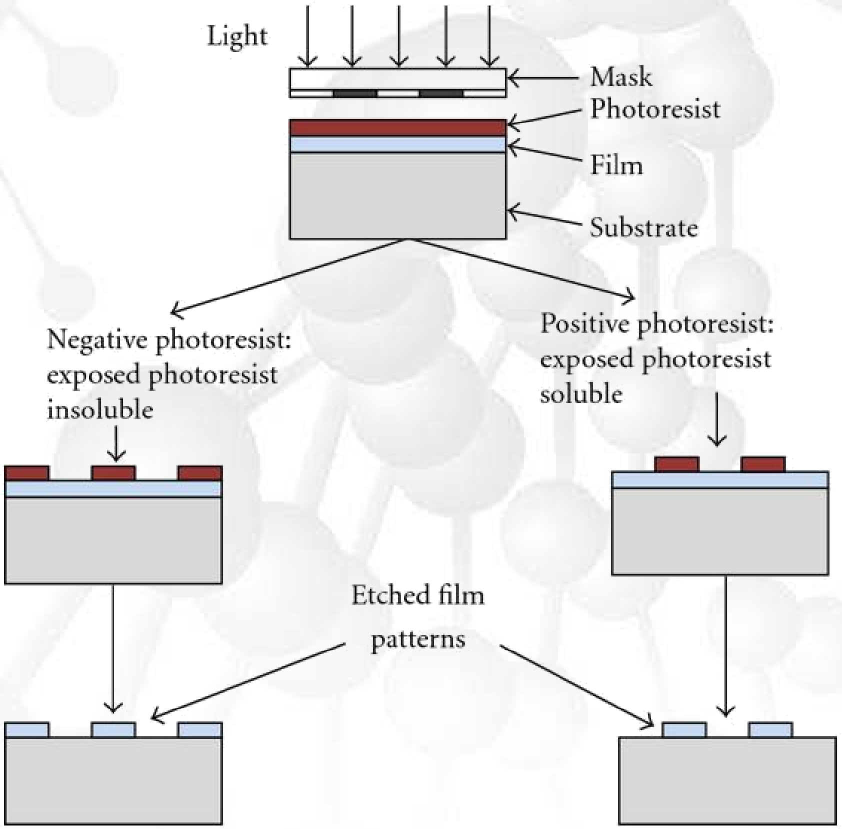
- Exposure to UV light causes it to polymerize and thus be more difficult to dissolve.

↓

- Developer removes unexposed resist.

↓

- It results in a pattern supplementary to that of the mask.



Positive photoresist

- Exposure to UV light makes it more soluble in the developer.

↓

- Exposed resist is washed away by developer so that the unexposed sample remains.

↓

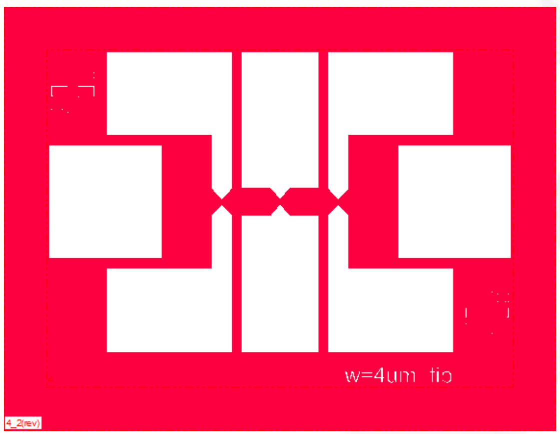
- It results in an exact copy of the original design.

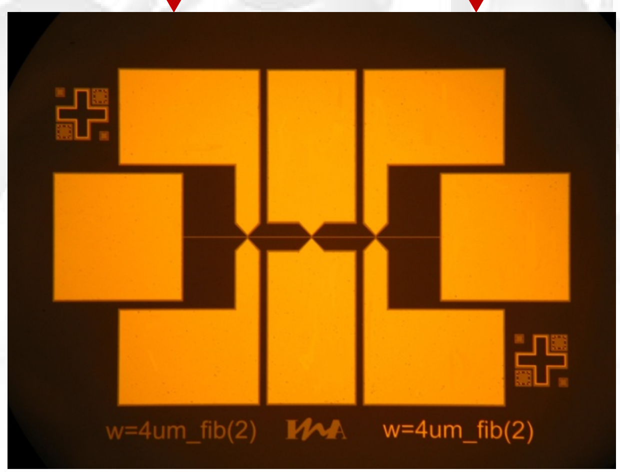
Photolithography

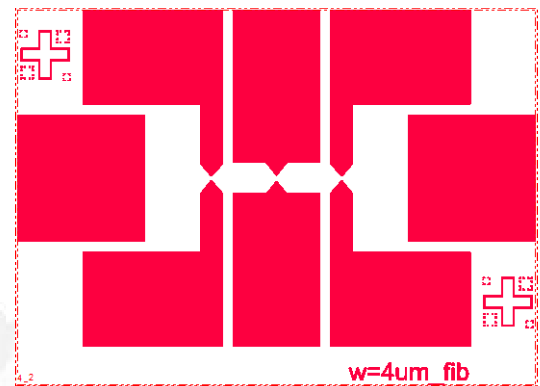
- **Two types of photoresists:**

Negative photoresist
+
Mask #1

Positive photoresist
+
Mask #2
(supplementary to mask #1)



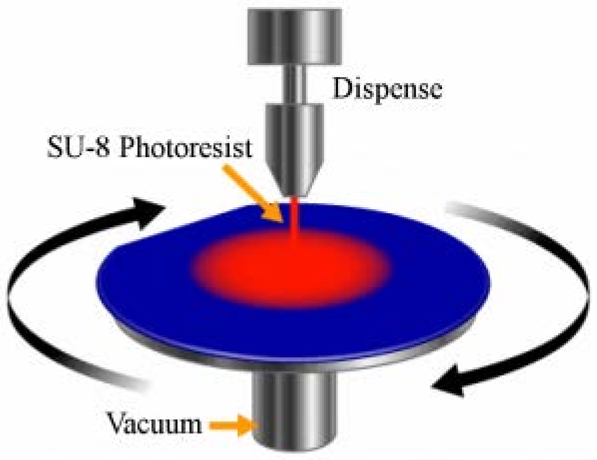




Courtesy of J. M. De Teresa, ICMA-Unizar

Photolithography

- **Spin coating**

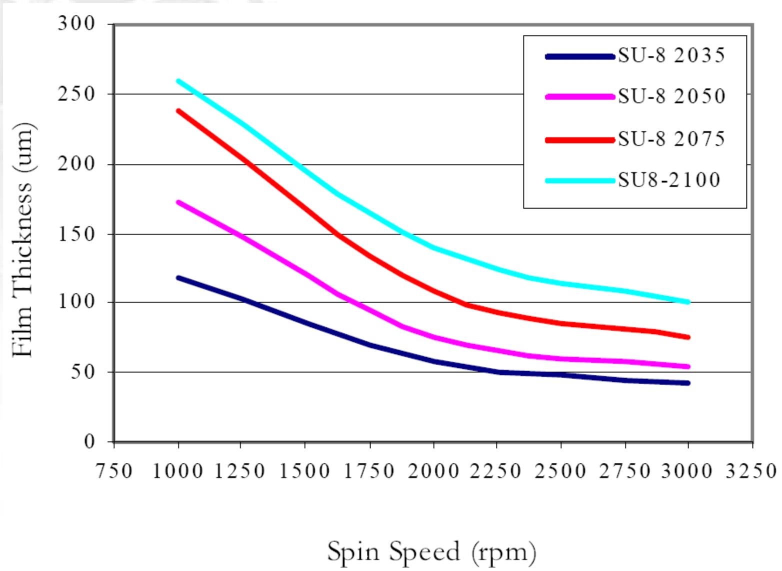


Spin speed:
usually in the range 1000 – 6000 rpm

Final resist thickness:

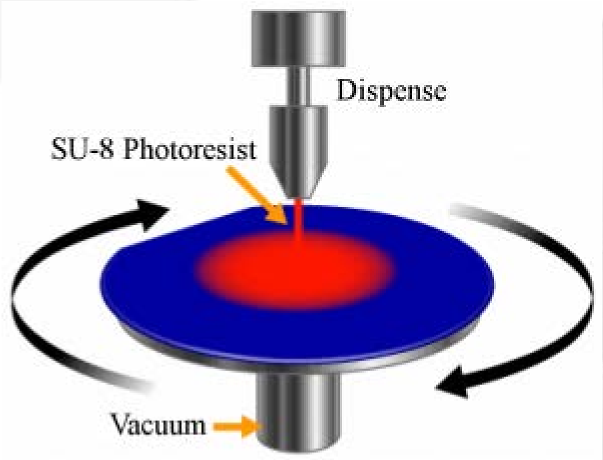
$$t \propto \frac{\eta^2}{\sqrt{s}}$$

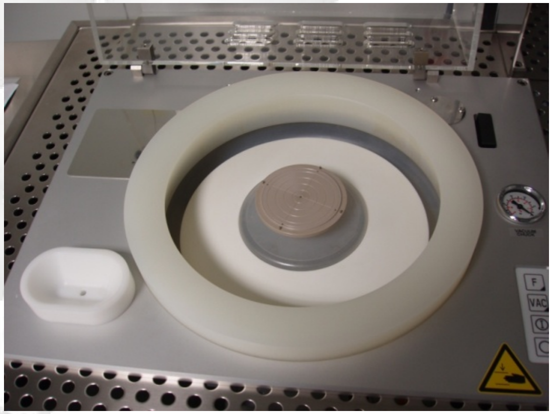
η = viscosity.
s = spin speed.



Photolithography

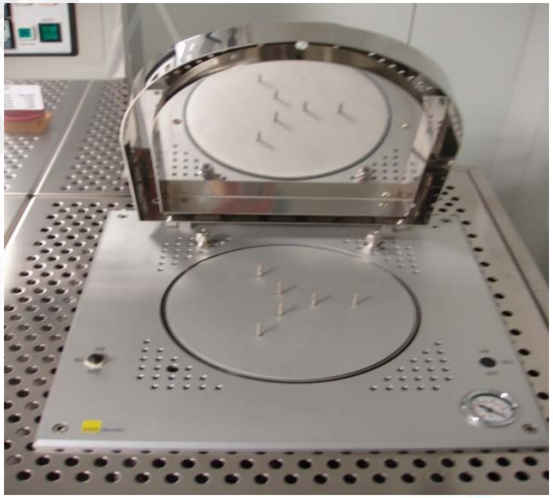
- **Real equipment for spin coating:**





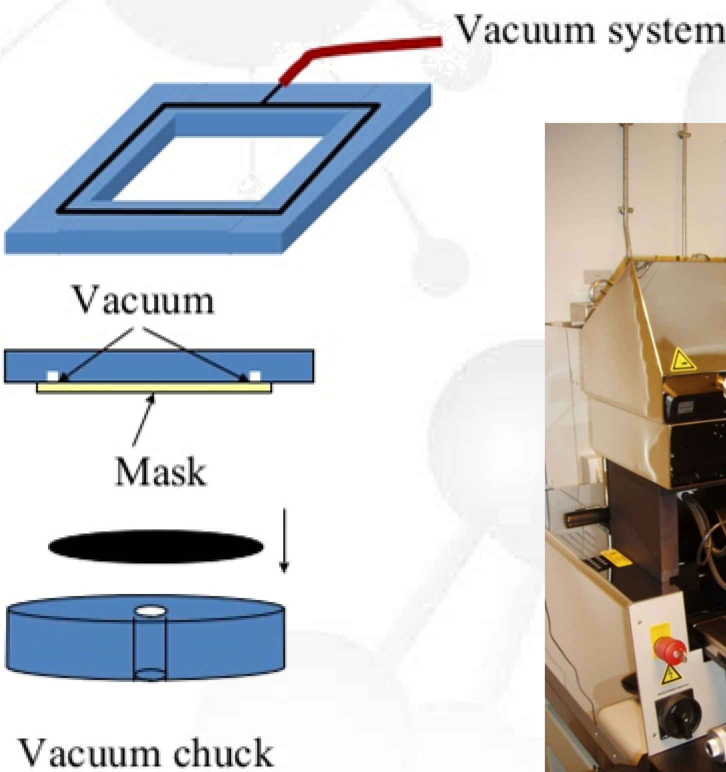
-Soft-bake step:

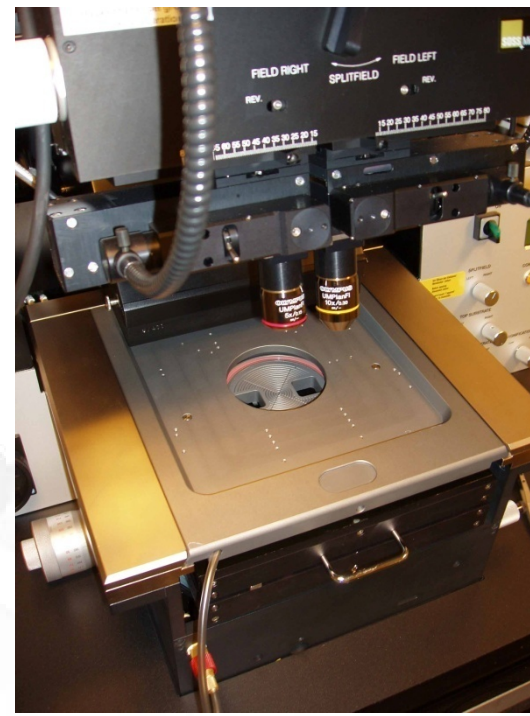
Heating at T around 100°C to eliminate the solvent.



Photolithography

- **Mask aligner: (Exposure system).**

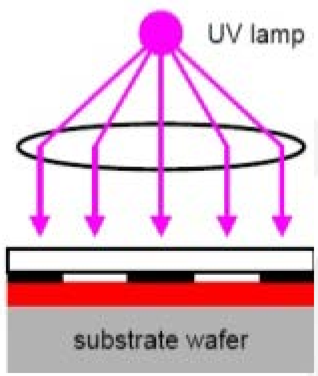




Photolithography

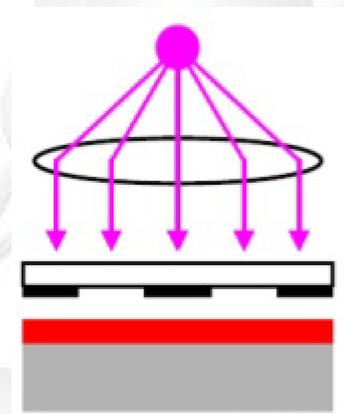
- **Exposure modes:**

Contact:



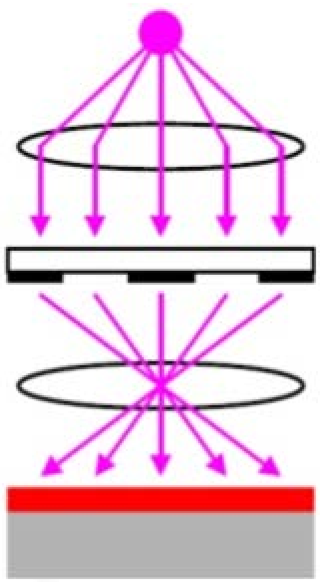
Mask in contact with the photoresist film (gap ~ 0 μm)

Proximity:



Gap ~ 10 μm between mask and photoresist.

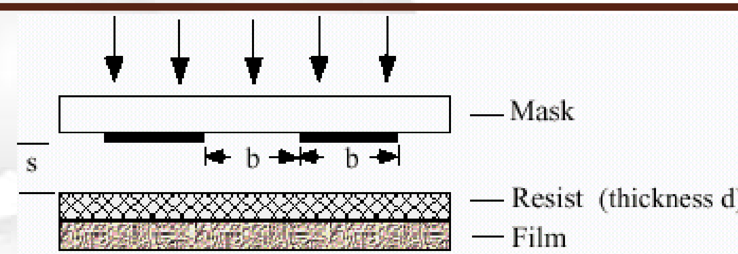
Projection:



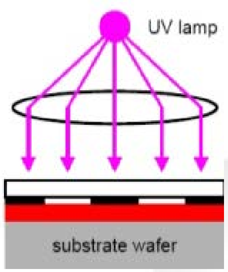
Imaging optics in between the mask and the wafer

Photolithography

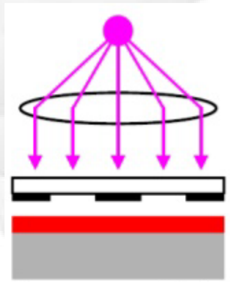
- **Exposure modes: Resolution**



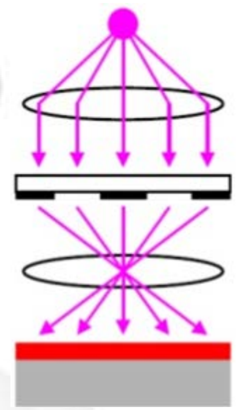
Contact:



Proximity:



Projection:



Depth of focus:
σ=kλ/(NA²)

$\sigma = k\lambda/(NA^2)$

Resolution:

	Contact	Proximity	Projection
Resolution:	$2\, b_{min} = 3\sqrt{\lambda d/2}$	$2\, b_{min} = 3\sqrt{\lambda s}$	$b_{min} = k\lambda/(NA)$
Example:	d=1 μm, λ=365 nm	s =10 μm, λ=365 nm	k=0.45, λ=248 nm, NA=0.7
	b_{min} ≈ 640 nm	**b_{min} ≈ 2866 nm**	**b_{min}≈160 nm**

Photolithography

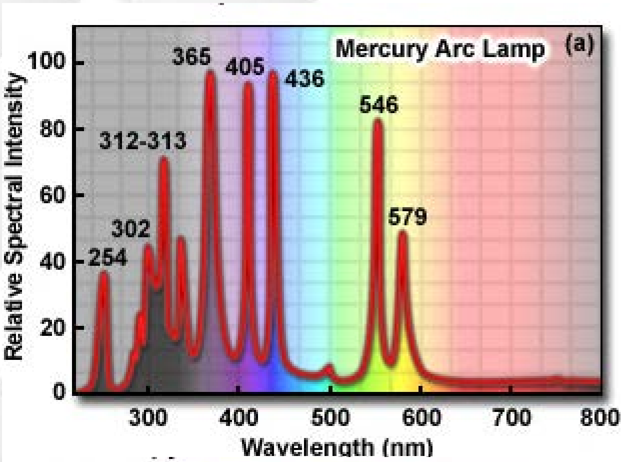
- **Mask aligner: Exposure source.**

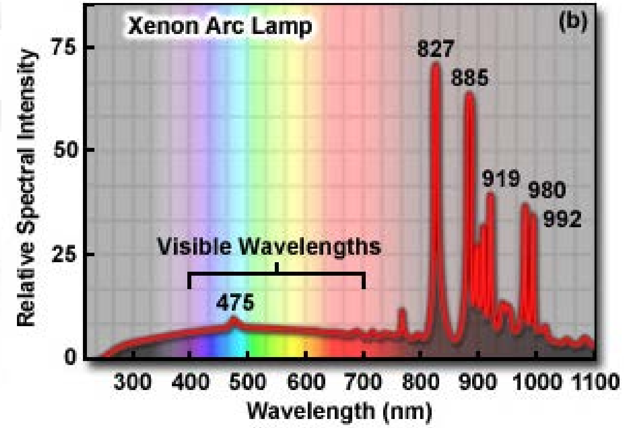
Exposure sources (UV):

-Xe arc lamps: Near continuuos spectrum in the visible 200-750 nm with Xe lines above 800 nm.

-Hg arc lamps: High energy output in the UV with intense lines between 240-600 nm.

-Hg-Xe arc lamps: Combination of the spectra from Hg and Xe (Xe gas improves start-up and extends operating life).



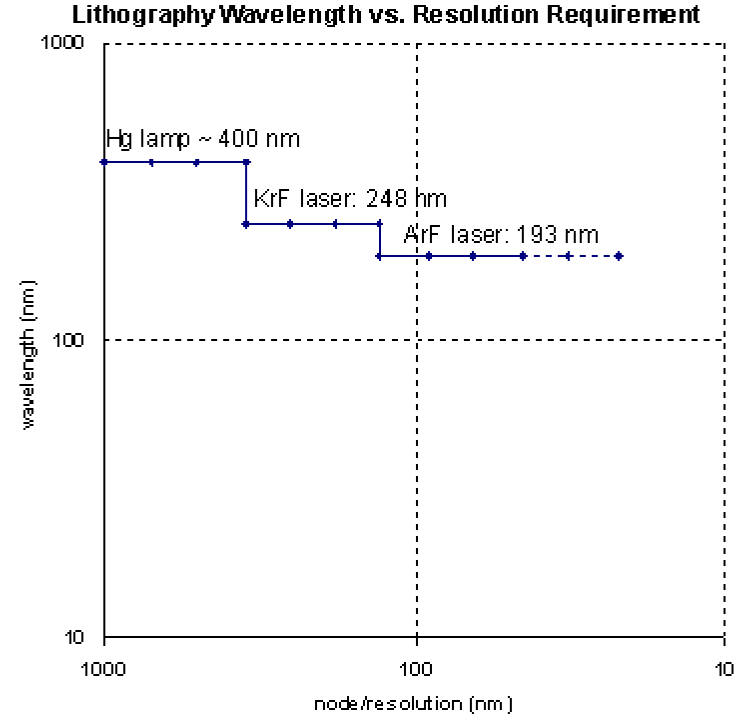


Photolithography

- **Mask aligner: Exposure source.**

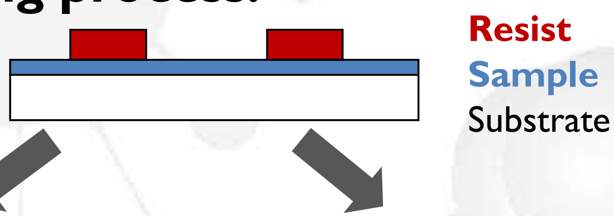
Exposure sources (DUV):

By 1996, transition from an I-line Hg arc lamp to deep-UV excimer laser – KrF (248 nm). The physics of excimer laser allows scaling to higher powers, narrower spectral widths and shorter wavelengths.



Photolithography

- **Etching process:**

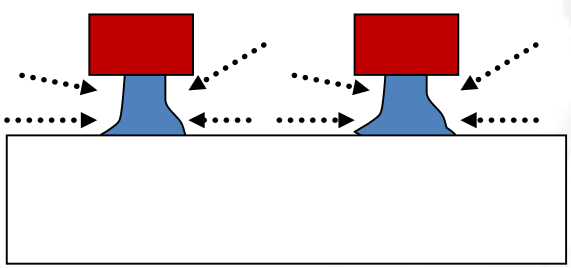


Wet etching:

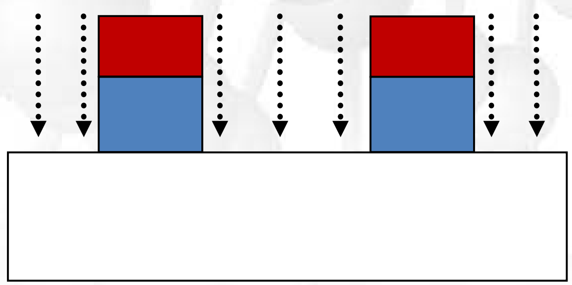
By means of reactive liquids

Dry etching:

By means of physical etching (sputtering/ionic bombardement) or chemical etching (plasma / RIE).



Isotropic etching profile



Anisotropic etching profile

Courtesy of J. M. De Teresa, ICMA-Unizar

Comparison:

Property	Wet	Dry
Anisotropy	-	+
Resolution	-	+
Homogeneity	-	+
Reproducibility	-	+
Profile	-	+
Risk of burns	-	+
Cost	+	-

Photolithography

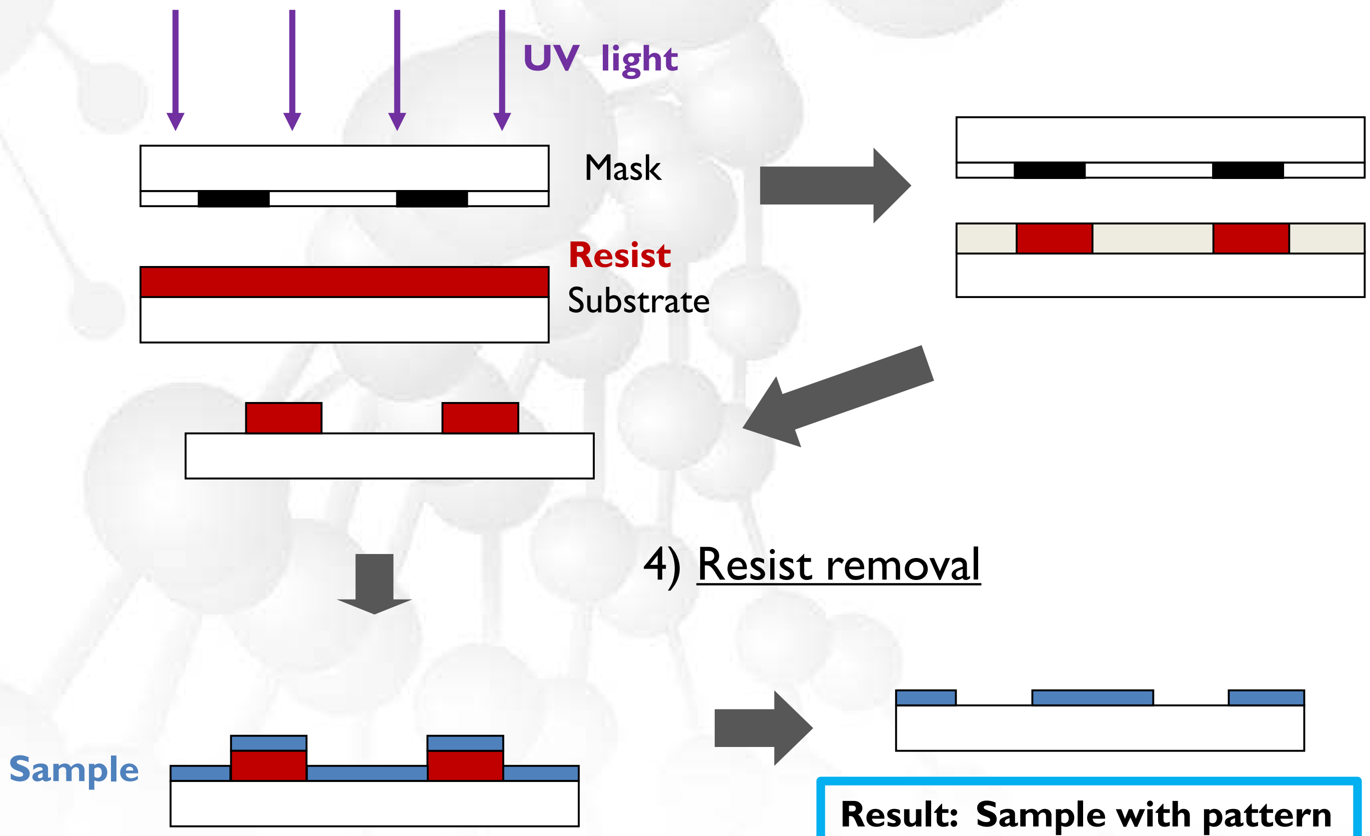
- **Lift-off process:** (positive resist).

1) Exposure

2) Development

3) Sample growth

4) Resist removal



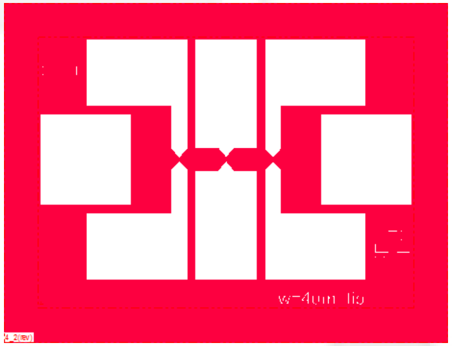
Result: Sample with pattern supplementary to that of the maks, without etching!

Courtesy of J. M. De Teresa, ICMA-Unizar

Photolithography

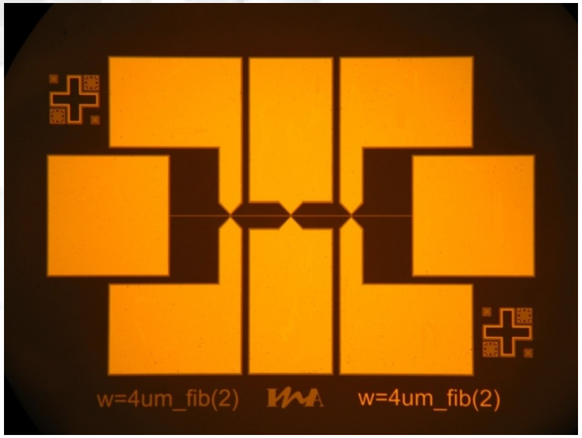
- **Lift-off process:** Real example.

Mask:



+ Positive resist.

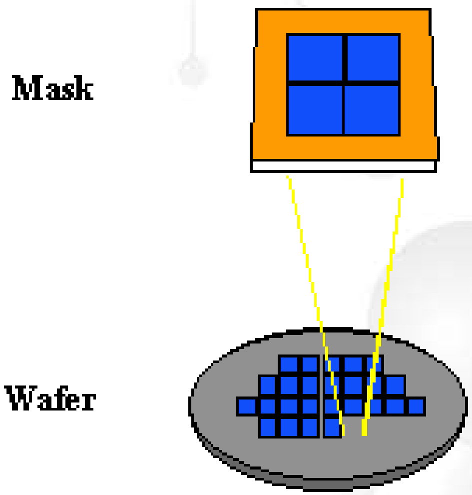
After growing the sample and removing the resist:



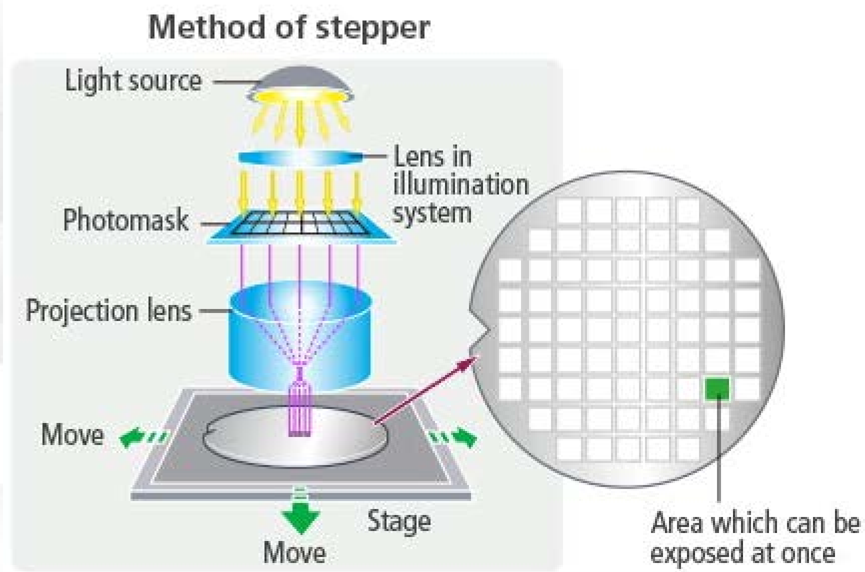
Courtesy of J. M. De Teresa, ICMA-Unizar

Photolithography

- **Photolithography in IC industry: Stepper.**

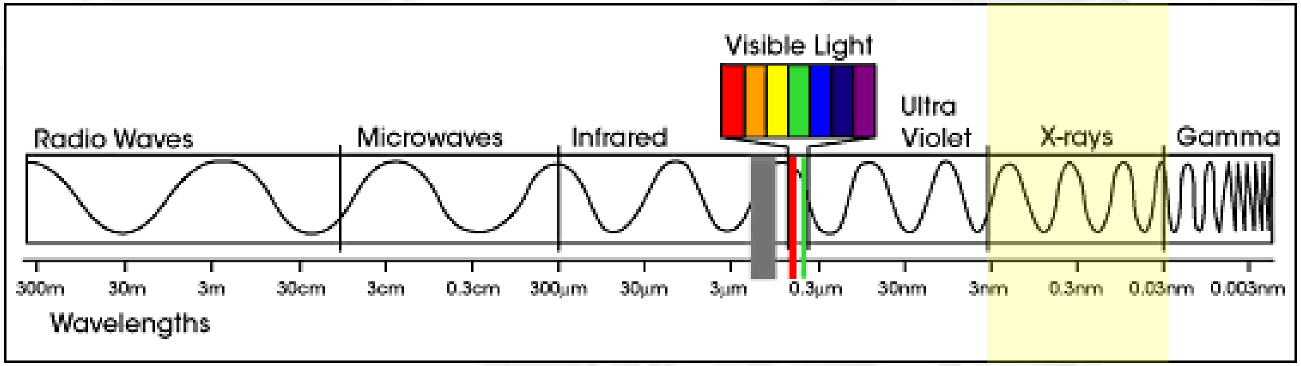


Reduction Stepper



X-ray lithography

- **X-rays:**



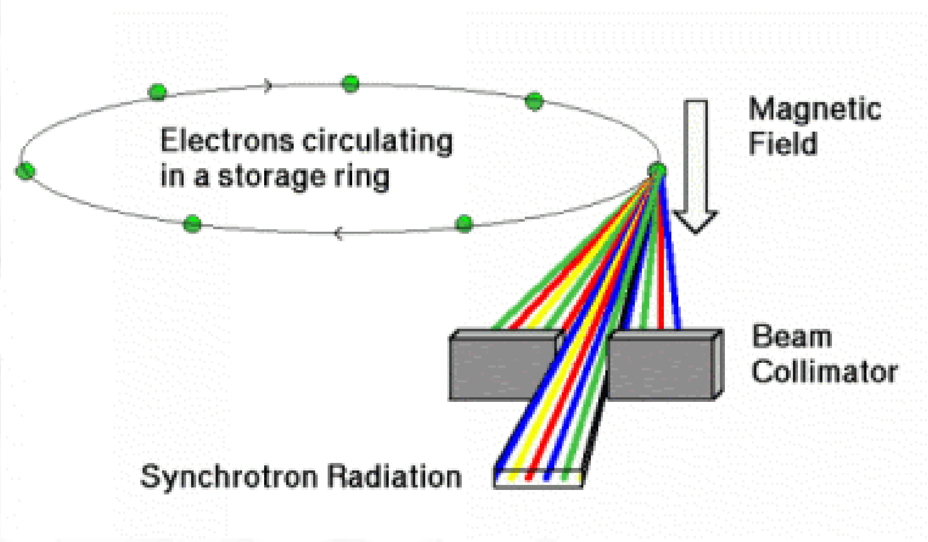
- Shorter wavelength than UV light ➔ Little diffraction effects.
- Fine features with vertical sidewalls.
- Very large depth of focus ➔ Non-flat wafer is OK.
- No optics needed: "Just" an **x-ray source**, an **x-ray resist** and an **x-ray mask**.

X-ray lithography

- **X-ray source:**

Requirements: Strong, stable, collimated, single frequency…

Synchrotron radiation: Electromagnetic radiation emitted when charge particles are radially accelerated.



High cost!!
But…

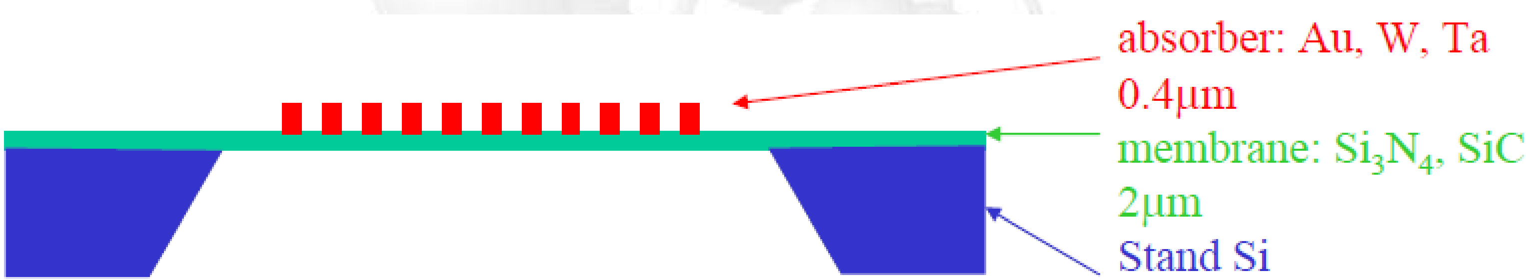
- Extremely high intensity.
- Tunable.
- Very low divergence.

X-ray lithography

Silicon	0 (50% transmission at 5.5 μ m thickness).
SiC	0 (50% transmission at 2.3 μ m thickness).
Diamond	0 (50% transmission at 4.6 μ m thickness).

X-ray mask:

- **Mask substrate**: Low atomic number thin membrane.
- **Absorber**: High attenuation, stability under radiation, low microstructural defect density: Au, W, Ta, alloys.



X-ray lithography

- **X-ray resist:**
  - Absorption of x-ray does not produce resist modification.
  - Photelectrons and Auger electrons are responsible for resist modification.

    ⬇

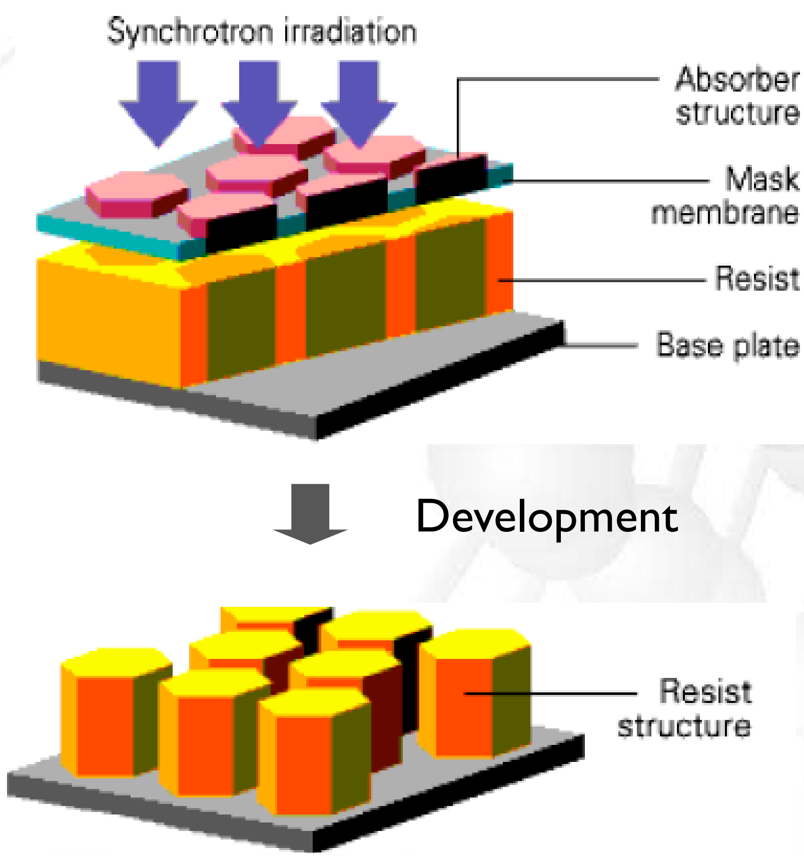
  - Any resist for electron beam lithography (PMMA) can be used.

Exposure to x-ray (that generates Auger electrons…) cut the PMMA chains, leading to smaller molecular weight that dissolves faster in developers.

Novolak-based resist	EBL sensitivity ($\mu C/cm^2$)	EBL contrast	XRL sensitivity (mJ/cm^2)	XRL contrast
PMMA	100	2.0	6500	2.0

X-ray lithography

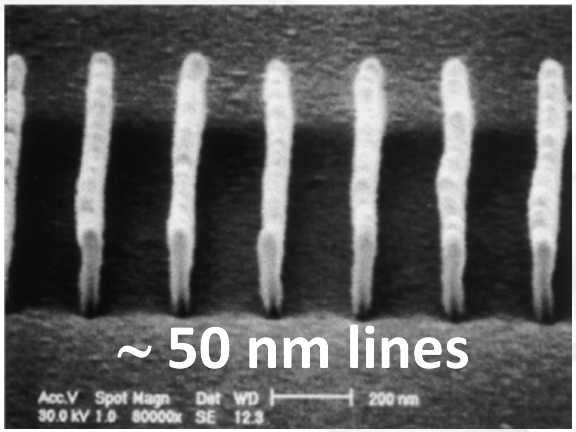
- **Basic process:**

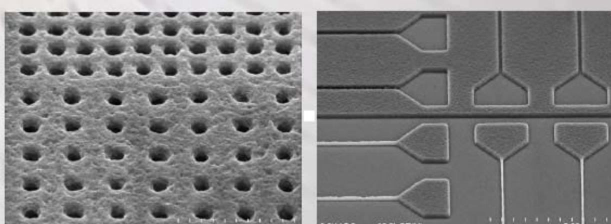


Ideal to pattern high resolution and high aspect ratio nanostructures!

X-ray lithography

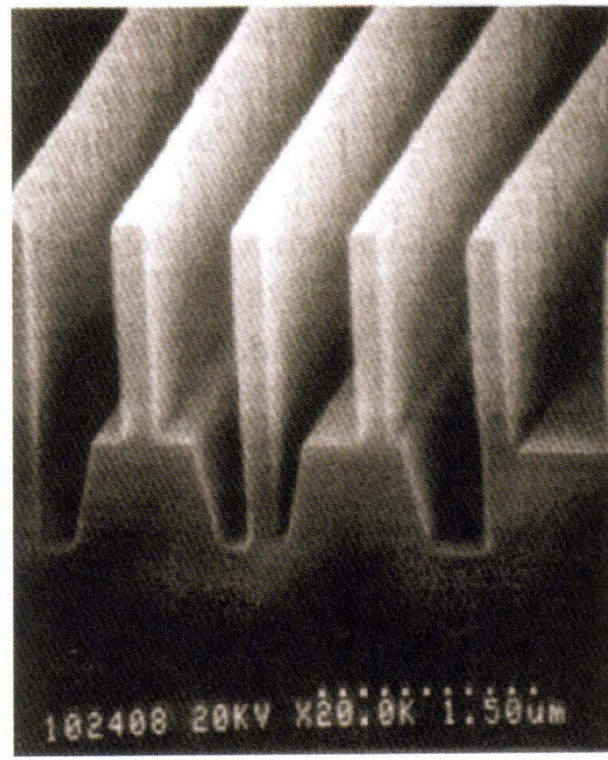
- **Examples:**





1x1 and 4x1 100 nm contact arrays – pitch independent imaging

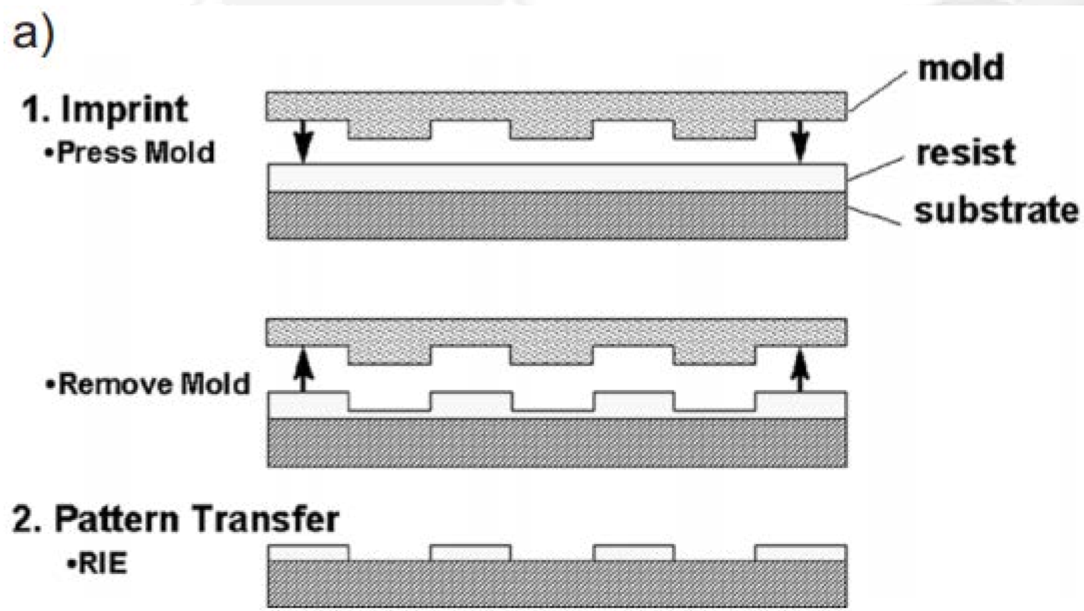
80 nm T line gates in > 3000 A resist



R.Waser (ed.), Nanoelectronics and Information Technology

Nanoimprint lithography

- **Basic process:**



- Much simpler in comparison to alternatives!
- High throughput.
- Low cost for a next-generation technology.

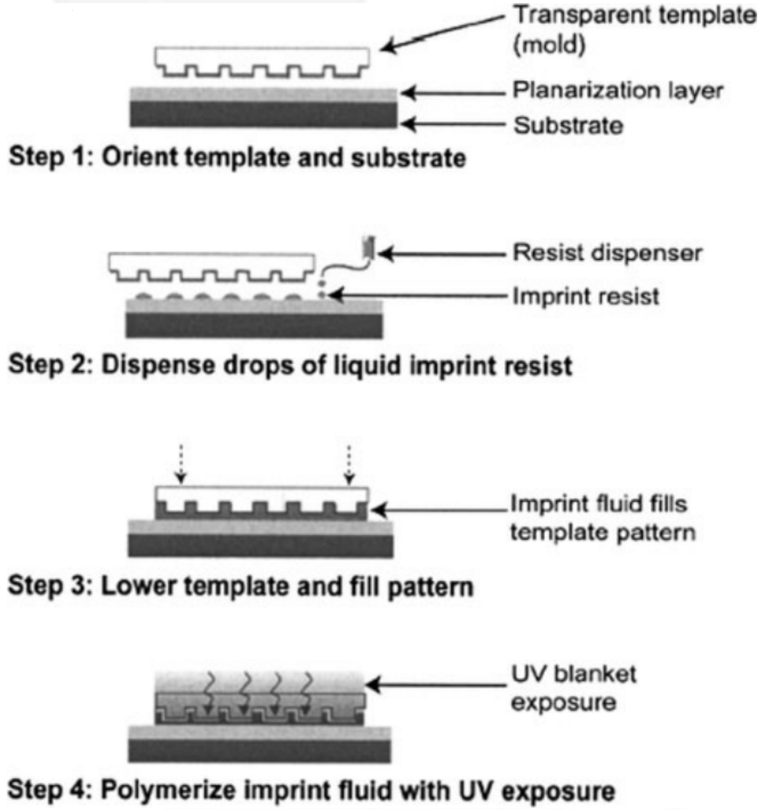
High resolution
+ high throughput
+ low cost!!

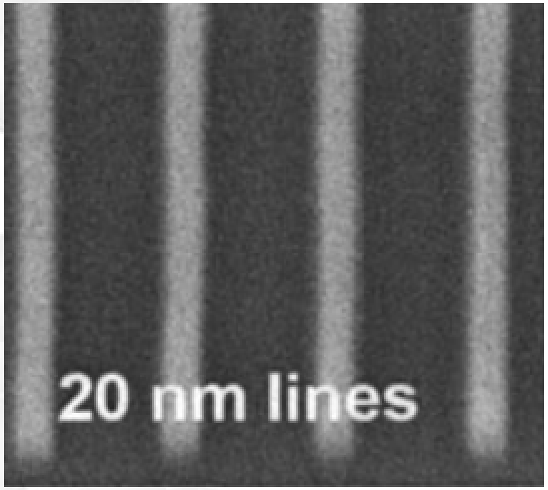
- Mechanical deformation of the imprint resist.

L. Jay Guo, Adv. Mater. 19, 495 (2007).

Nanoimprint lithography

- **Improved process: Step-and-flash imprint lithography (SFIL).**





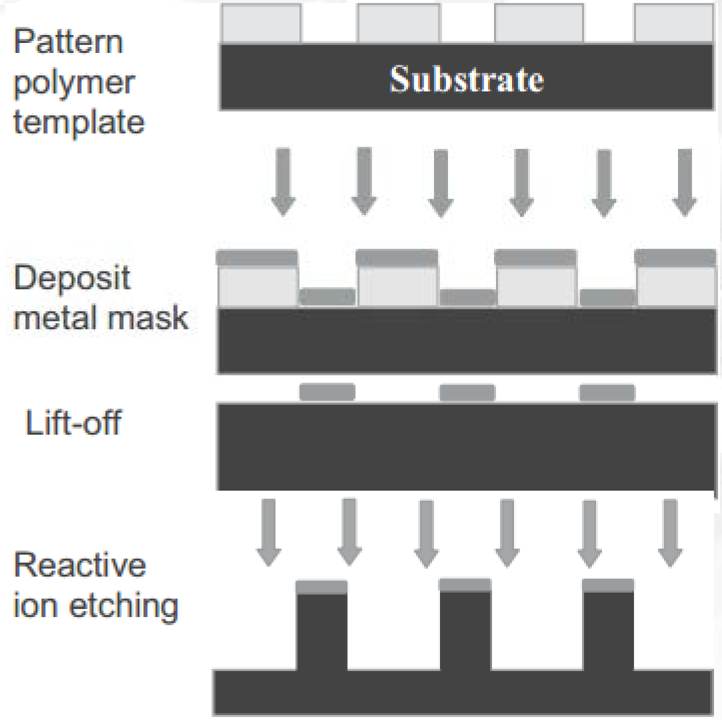
Candidate technology for future IC production.

L. Jay Guo, Adv. Mater. 19, 495 (2007).

Nanoimprint lithography

- **NIL molds:**

Fabrication:

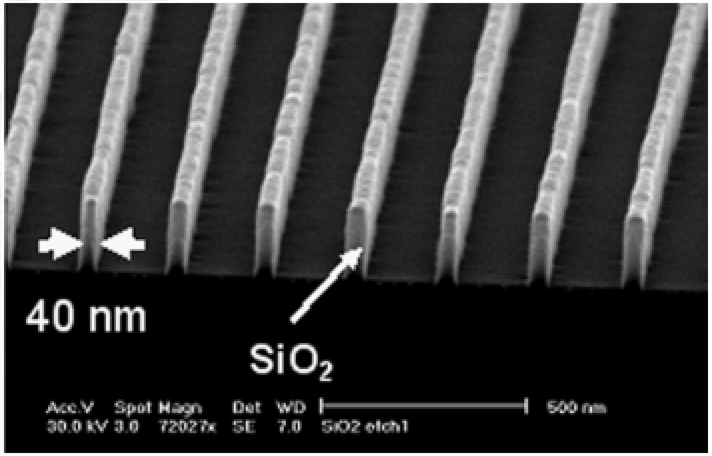


L. Jay Guo, Adv. Mater. 19, 495 (2007).

Material requirements:

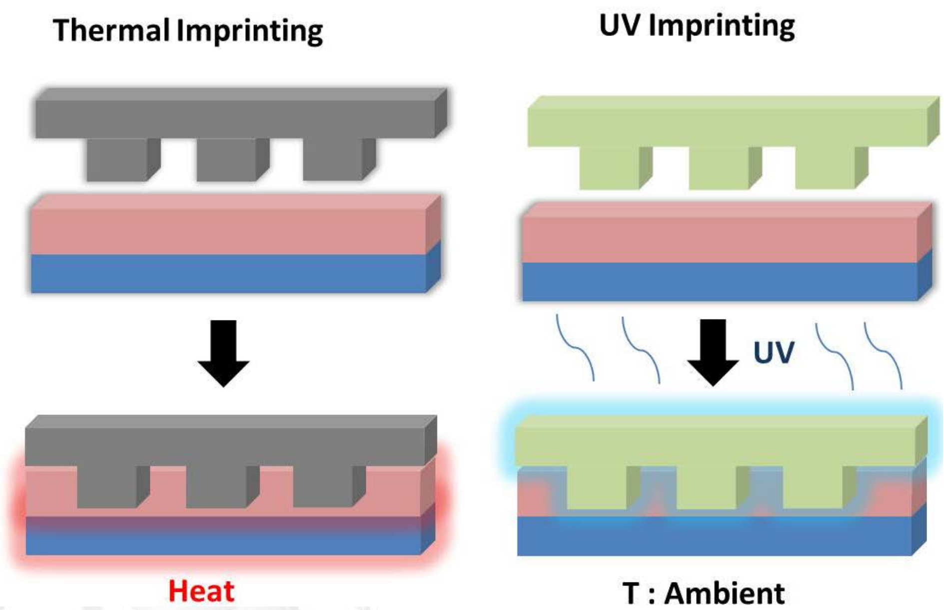
- Sufficient Young's modulus.
- High strength and durability.

SEM micrograph:



Nanoimprint lithography

- **NIL resits:**



Material requirements:

- Young's modulus lower than that of the mold.
- Sufficiently low viscosity.

$T > T_g$

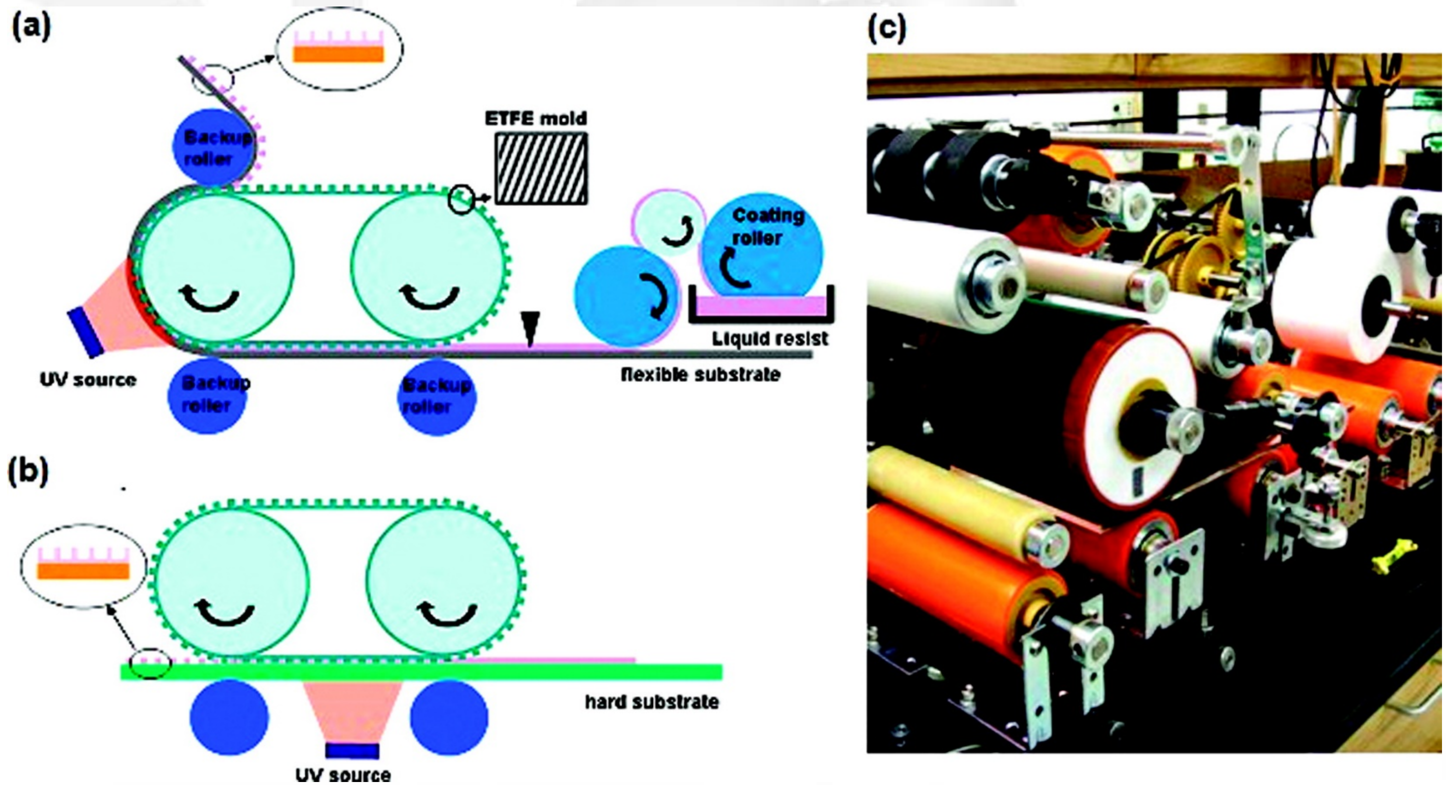
Resist cured by UV light.

- Good mold-releasing properties.
- Good plasma-etching resistance.

L. Jay Guo, Adv. Mater. 19, 495 (2007).

Nanoimprint lithography

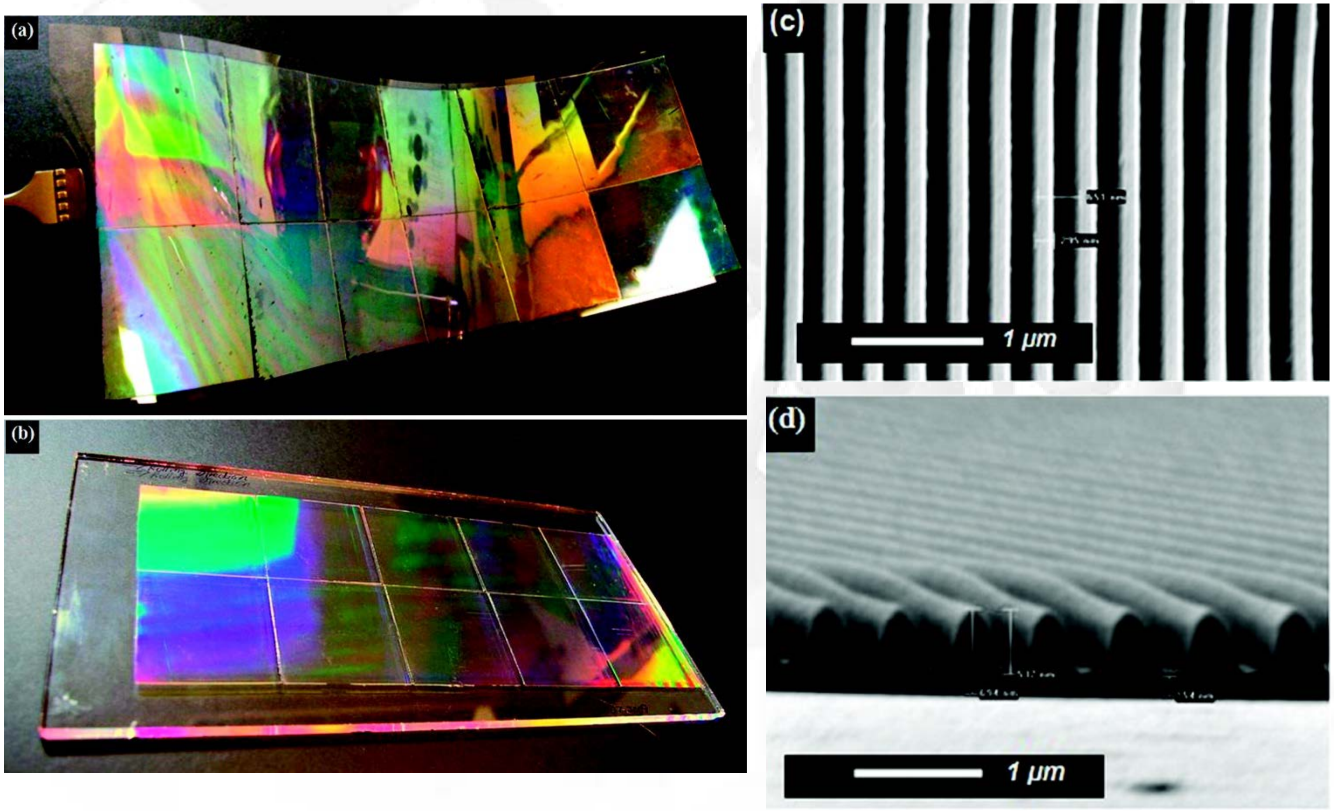
- **Large area Roll-to-Roll and Roll-to-Plate NIL:**
  High-Throughput application of continuous NIL



S. Hyun Ahn and L. Jay Guo, ACS Nano 3, 2304 (2009).

Nanoimprint lithography

- **Large area Roll-to-Roll and Roll-to-Plate NIL:**
  High-Throughput application of continuous NIL

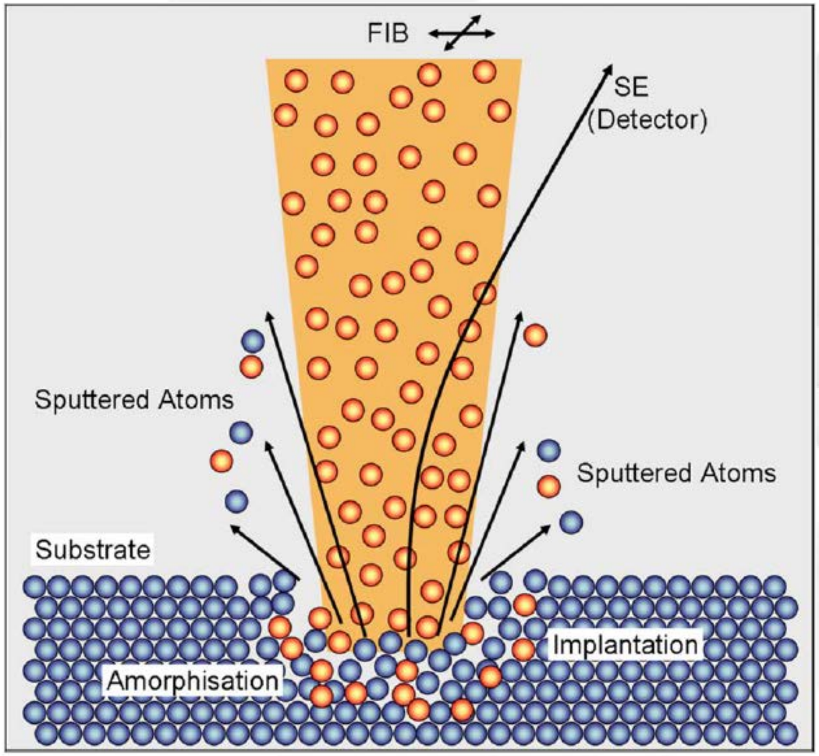


300 nm linewidth, 600 nm height with greatly enhanced throughput.

S. Hyun Ahn and L. Jay Guo, ACS Nano 3, 2304 (2009).

Ion beam lithography

- **Ion beams: Interaction with matter**



Focused ion beam (around 30 keV):

- **Slow heavy atoms**: Sputtering of atomic and molecular species from the surface.

Focused ion beam lithography:

- Direct writing lithography! (No mask)
- Sub-100 nm resolution.

I. Utke et al., Int. J. Vac. Sci. Technol. B 26, 1197 (2008).

Ion beam lithography

- **Focused Ion Beams sources:**

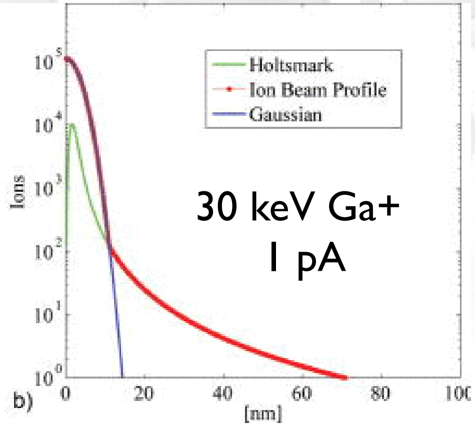
Type of ion source	Ion species	Unnormalized brightness (A/cm^2 sr)	Current density on sample (A/cm^2)	Minimum beam diameter (nm) (at 30 kV)
Liquid metal	Ga^+	3×10^6	10	10
Liquid metal alloy[a]	Au/Si/ Be	$\sim10^5$ depends on the % of the desired species in beam	0.1–1.0	50
Gas field ion (supertip)	He^+	5×10^9	1000	5
Gas field ion source	He^+	4×10^9	...	0.6
Multicusp plasma	Kr^+	0.55×10^3	1.2×10^{-2}	100

→ High brightness (Liquid metal)

→ Cryogenic temperature. (Gas field ion)

→ Less brighter but robust. (Multicusp plasma)

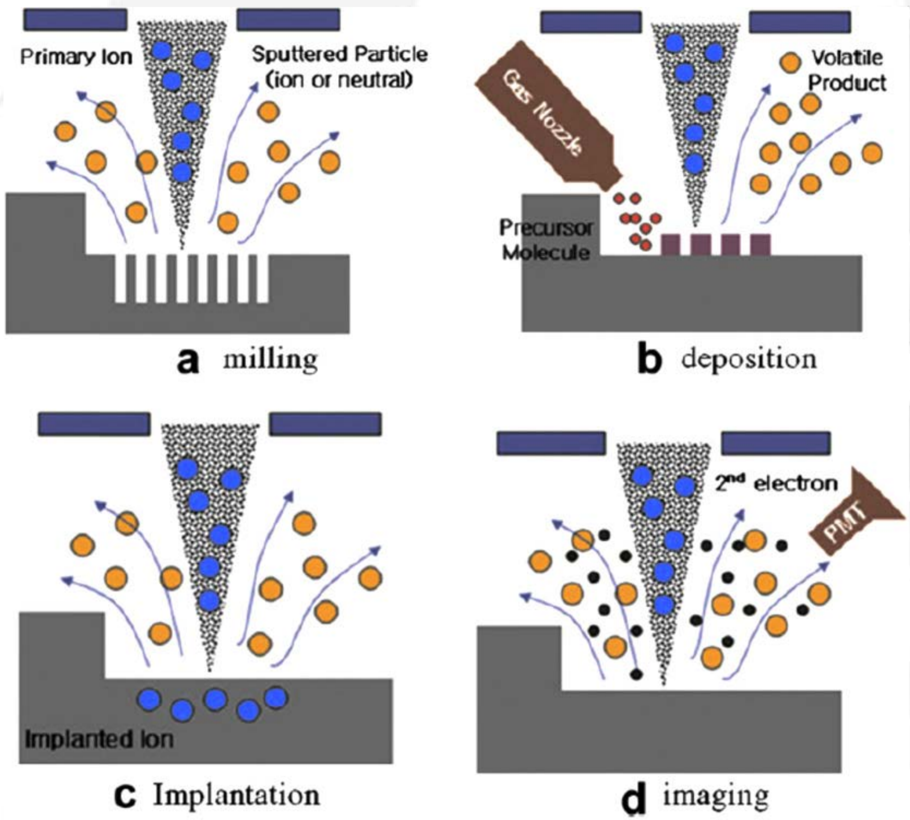
FIB profile:
(spatial distribution)



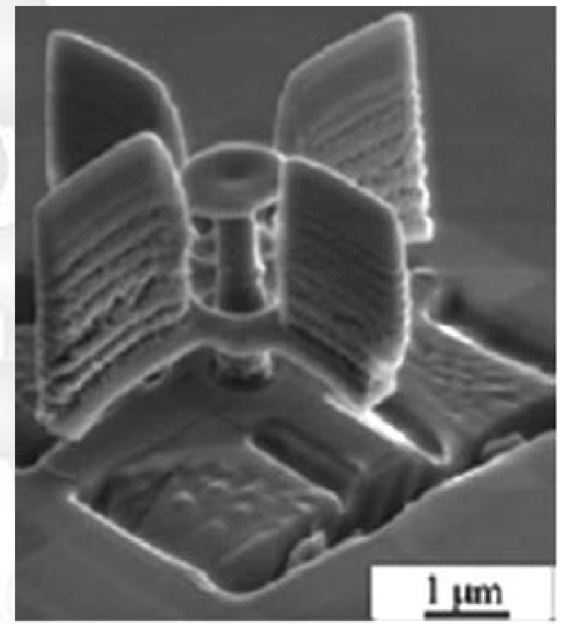
I. Utke et al., Int. J. Vac. Sci. Technol. B 26, 1197 (2008).

Ion beam lithography

- **FIB processes:**



A. Santos et al., Nanotechnol. 26, 042001 (2015).



Nanorotor produced by FIB.

X.Wang et al., Chem. Mater. 25, 2819 (2013).

Summary

Lithography Technique	Minimum Feature Size	Throughput	Applications
Photolithography (contact & proximity printings)	2-3 µm [22]	very high	typical patterning in laboratory level and production of various MEMS devices
Photolithography (projection printing)	a few tens of nanometers (37 nm) [2]	high - very high (60-80 wafers/hr) [1]	commercial products and advanced electronics including advanced ICs [1], CPU chips
Electron beam lithography	< 5 nm [23]	very low [1, 3] (8 hrs to write a chip pattern) [1]	masks [3] and ICs production, patterning in R&D including photonic crystals, channels for nanofluidics [23]
Focused ion beam lithography	~20 nm with a minimal lateral dimension of 5 nm [2]	very low [3]	patterning in R&D including hole arrays [125, 134], bull's-eye structure [132], plasmonic lens [137]
Soft lithography	a few tens of nanometers to micrometers [2, 13] (30 nm) [2]	high	LOCs for various applications [13, 96]
Nanoimprint lithography	6-40 nm [14, 15, 18]	high (> 5 wafers/hr) [1]	bio-sensors [17], bio-electronics [18], LOCs: nano channels, nano wires [97, 102, 104]
Dip-pen lithography	a few tens of nanometers [39, 40, 43]	very low – low, possibly medium [39]	bio-electronics [43], bio-sensors [40], gas sensors [42]

A. Pimpin et al., Enginner. J. 16, 37 (2011).

Thank you for your attention!