Contents of Class

I. Nanofabrication and Characterization

II. Nanomaterials and Nanostructures

III. Nanoscale and Molecular Electronics

V. Nanotechnology in Integrative Systems

VI. Nanoscale Optoelectronics

VII. Nanobiotechnology

Contents of Class

I. Nanofabrication and Characterization

II. Nanomaterials and Nanostructures

III. Nanoscale and Molecular Electronics

V. Nanotechnology in Integrative Systems

VI. Nanoscale Optoelectronics

VII. Nanobiotechnology

I. NANOFABRICATION AND CHARACTERIZATION

I. Nanofabrication and Characterization : TOC

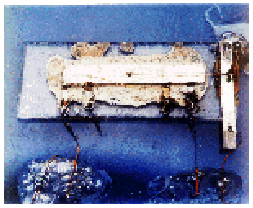
- Chap. 1 : Nanolithography
- Chap. 2 : Self-Assembly
- Chap. 3 : Scanning Probe Microscopy

I. Nanofabrication and Characterization : TOC

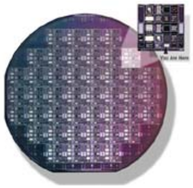
Chap. 1 : Nanolithography

The Si revolution…

First Transistor
Bell Labs (1947)



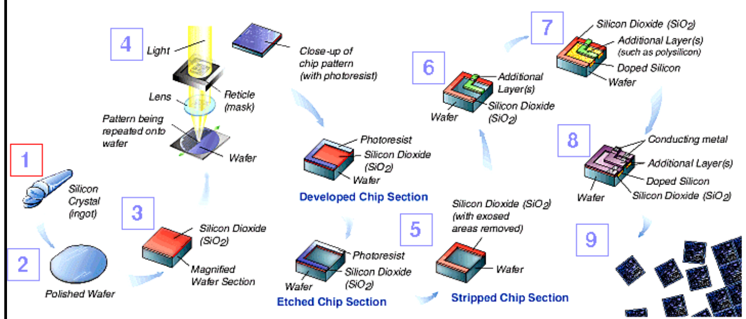
Si integrated circuits
Texas Instruments (~1960)



Modern ICs

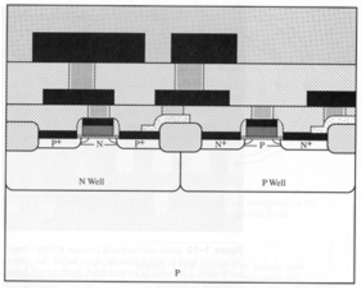
More ? Check out:
http://www.pbs.org/transistor/background1/events/miraclemo.html
http://www.ti.com/corp/docs/company/history/firstic.shtml

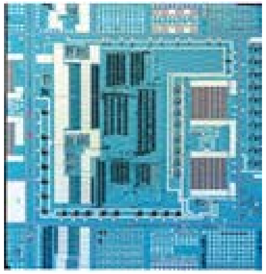
IC manufacturing



Source: http://www.cae.wisc.edu/~chauhan/nanolith2.shtml

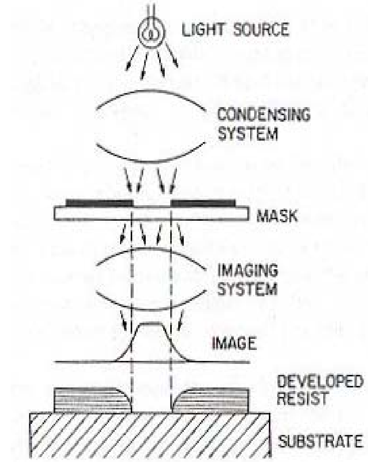
The need of micropatterning

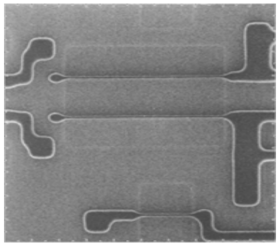




The batch fabrication of microstructures requires a low-cost, high throughput surface patterning technology

Overview of photolithography





Overview of photolithography (ctnd.)

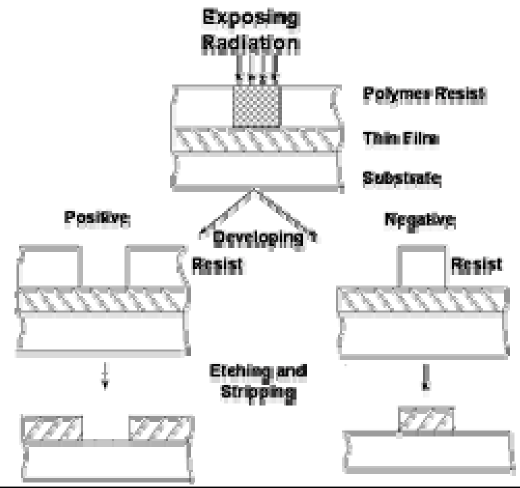
- *Lithography* consists of patterning substrate by employing the interaction of beams of photons or particles with materials.
- *Photolithography* is widely used in the integrated circuits (ICs) manufacturing.
- The process of IC manufacturing consists of a series of 10-20 steps or more, called *mask layers* where layers of materials coated with resists are patterned then transferred onto the material layer.

Overview of photolithography (ctnd.)

- A photolithography system consists of a light source, a mask, and a optical projection system.
- *Photoresists* are radiation sensitive materials that usually consist of a photo-sensitive compound, a polymeric backbone, and a solvent.
- Resists can be classified upon their solubility after exposure into: *positive resists* (solubility of exposed area increases) and *negative resists* (solubility of exposed area decreases).

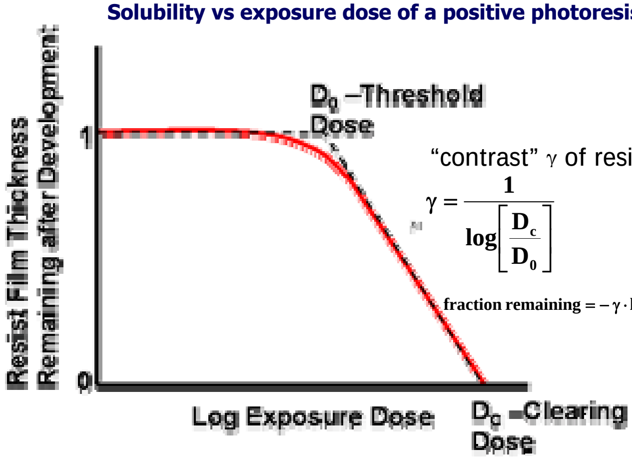
Chap. 1 : Nanolithography

Positive vs. negative photoresists



Threshold and clearing doses

Solubility vs exposure dose of a positive photoresist



"contrast" γ of resist :

$$\gamma = \frac{1}{\log\left[\frac{D_c}{D_0}\right]}$$

$$\text{fraction remaining} = -\gamma \cdot \log\left(\frac{\text{Dose}}{D_C}\right)$$

Threshold and clearing doses: example

Question:
A positive photoresist possesses a contrast γ = 5, and a clearing dose D_c = 300 mJ/cm^2. What dose is required to dissolve 50 % of the resist thickness ?

Answer: **The resist will have a threshold dose D_o:**

$$D_0 = D_C \cdot 10^{-\frac{1}{\gamma}}$$

$$= 300 \cdot 10^{-\frac{1}{5}}$$

$$= 189 \ \ \text{mJ/cm}^2$$

The contrast curve is analytically given by:

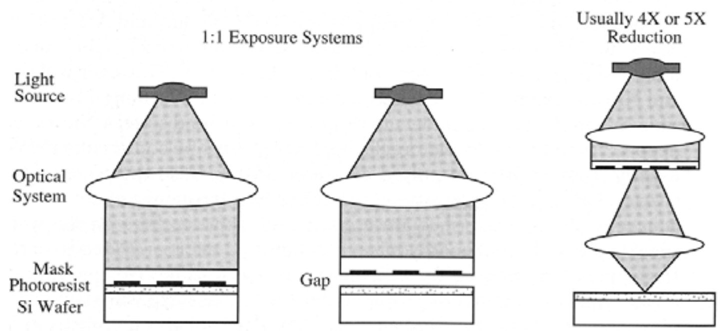
$$\text{fraction remaining} = -\gamma \cdot \log\left(\frac{\text{Dose}}{D_C}\right)$$

$$0.5 = -5 \cdot \log\left(\frac{\text{Dose}}{300}\right)$$

$$\text{Dose} = 237 \ \text{mJ/cm}^2$$

The resist will be 50 % dissolved when using a dose of 237 mJ/cm^2

Types of photolithography



Contact Printing | Proximity Printing | Projection Printing

Resolution of photolithography

Contact lithography limited by Fresnel diffraction:

$$W_{min} = \sqrt{\lambda g}$$

where λ is wavelength employed and g is mask-resist gap.

Projection lithography limited by Rayleigh's criterion:

$$R = \frac{k_1 \lambda}{NA}$$

where λ is wavelength employed, NA is numerical aperture of lense (NA = sin α), and k_1 is a constant (typically k_1 = 0.6 - 0.8)

Resolution of photolithography: example

Question:
An x-ray contact lithography system uses photons of energy of 1 keV. If the separation between the mask and the wafer is 20 μm, estimate the diffraction-limited resolution that is achievable by this system

Answer:
The energy E_p of photons is related to their wavelength λ through:

$$E_p = \frac{hc}{\lambda}$$

where h = 6.626× 10^{-34} m^2 kg/s is Planck's constant, and c = 3 x 10^8 m/s is the speed of light.

Thus, the wavelength of the photons employed is:

$$\lambda = \frac{6.626x10^{-34} \cdot 3x10^8}{1000 \cdot 1.6x10^{-19}}$$

$$\lambda = 1.24\ nm$$

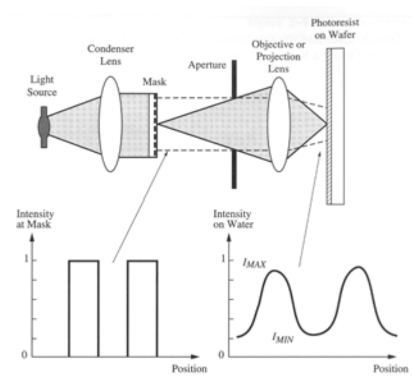
The minimum feature size that can be resolved is:

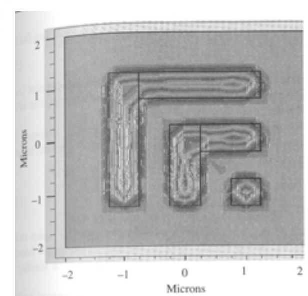
$$W_{min} = \sqrt{\lambda g}$$

$$W_{min} = \sqrt{1.24x10^{-9} \cdot 20x10^{-6}}$$

$$W_{min} = 157\ nm$$

Resolution of photolithography (ctnd.)



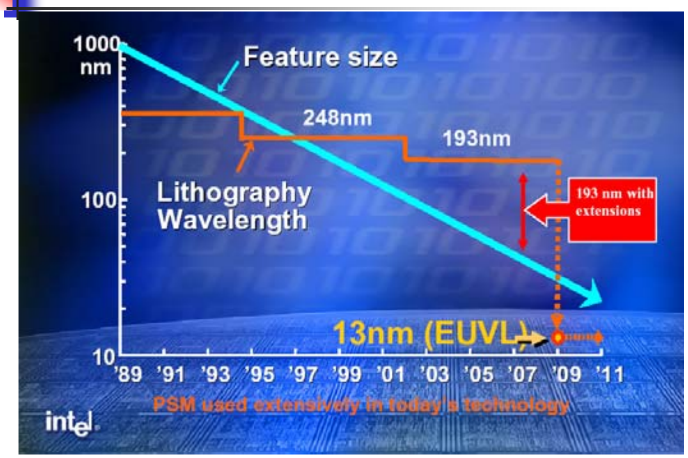


Chap. 1 : Nanolithography

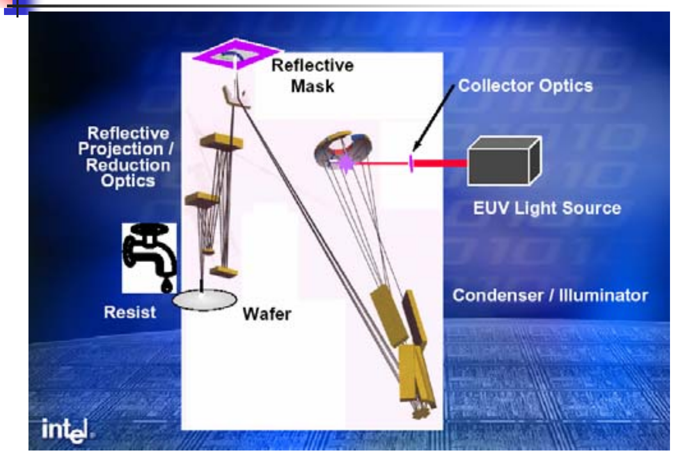
Micro- and nanolithography

- **Diffraction and other optical effects likely to limit the resolution of "standard" DUV (λ = 193 nm) lithography to the 75-100 nm range.**
- **Upcoming generation (2005) to employ DUV (λ = 193 nm) based 65 nm lithography and 35 nm gate lengths.**
- **Intel lithography roadmap will eventually skip λ = 157 nm technology and pursue well into the sub-100 nm region through EUV (λ = 13.5 nm) (~2009)**
- ***Exploratory* research in the sub-100 nm region may also be accomplished through alternate patterning techniques such as *x-ray-*, *ion-* and *electron beam-* lithography.**

Intel lithography roadmap (Nov 2004)

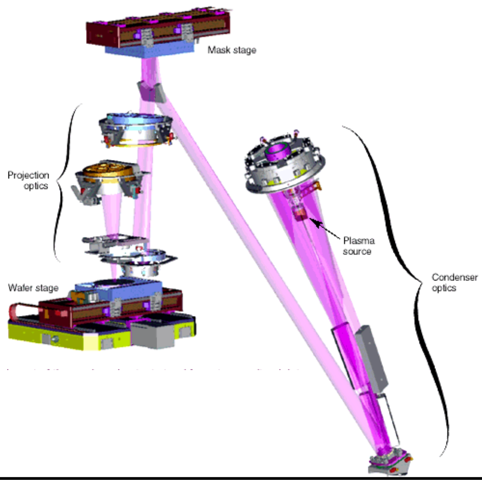


EUV lithography system

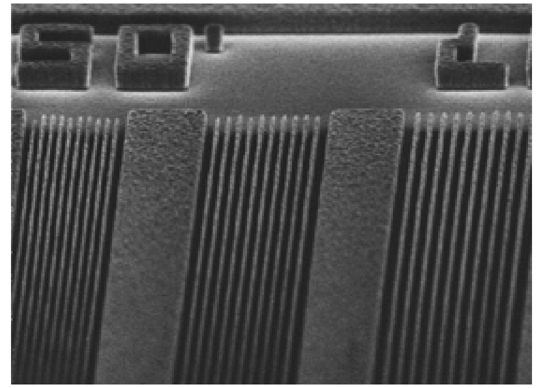


EUV Systems to employ reflective instead of refractive optics

EUV lithography system (ctnd.)



EUV lithography system (ctnd.)

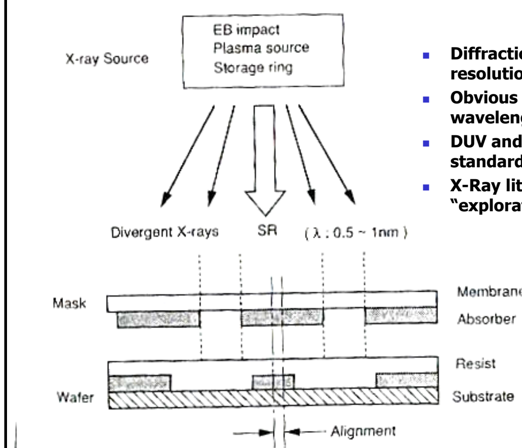


50 nm lines fabricated with EUV lithography (~1999)
30 nm features now routinely achieved

EUV lithography system (ctnd.)

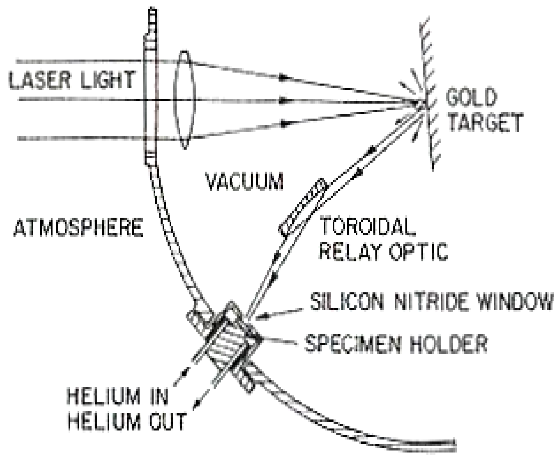
One in every home…

X-Ray lithography

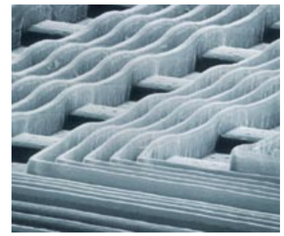


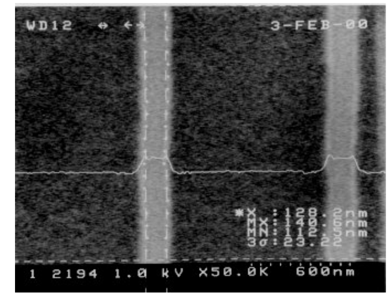
- **Diffraction limits lithography resolution to λ/2**
- **Obvious solution: use lower wavelengths sources**
- **DUV and EUV approaching standardization**
- **X-Ray lithography still at "exploratory" stage**

Plasma X-Ray source



Structures produced with X-ray litho. (ctnd.)



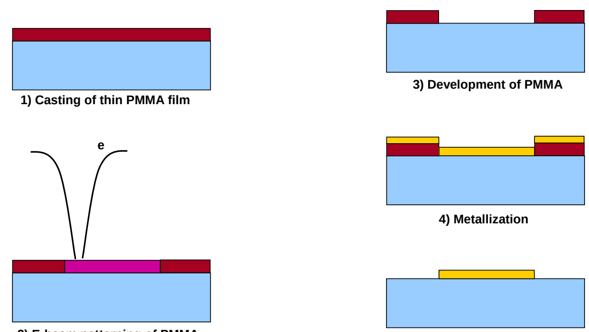


125 nm feature exposed with SAL

Source: SAL, Inc.

Chap. 1 : Nanolithography

Electron beam lithography

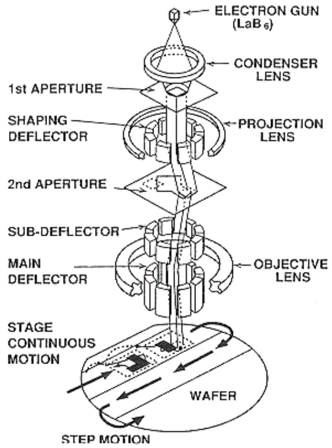


Employs a beam of electron instead of photons

Advantage: Fast turn-around time
Disadvantage: Slow throughput

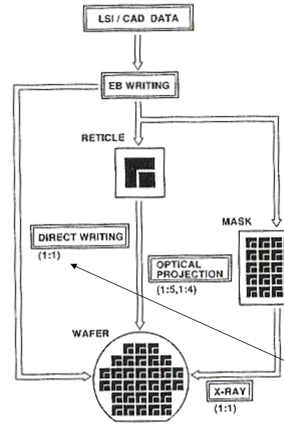
More ? Google it ! **Also, check out R.F.W. Pease, Stanford**

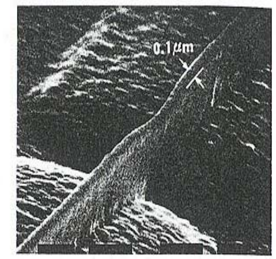
Electron beam lithography system



Throughput enhanced by variable beam shaping

Applications of electron beam lithography

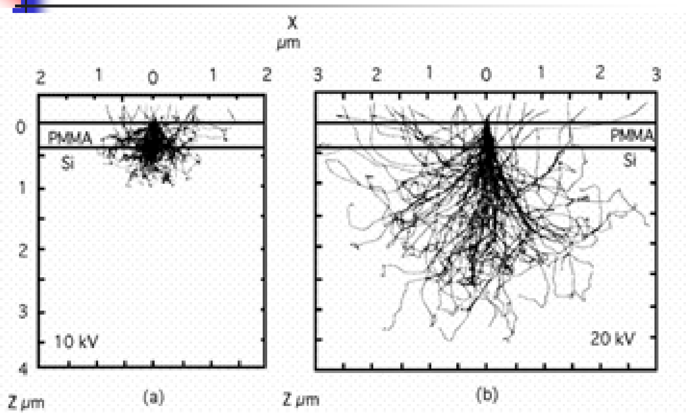




Mainly employed for the fabrication of photomasks

Also used to write patterns directly on wafer

Scattering phenomena in e-beam litho

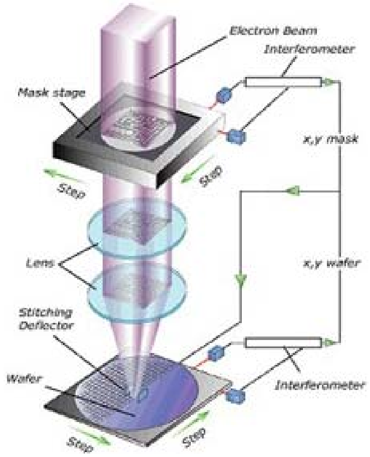


Scattering phenomena dictate resolution
Better resolution achieved at higher beam energies

E-beam fabricated nanostructures

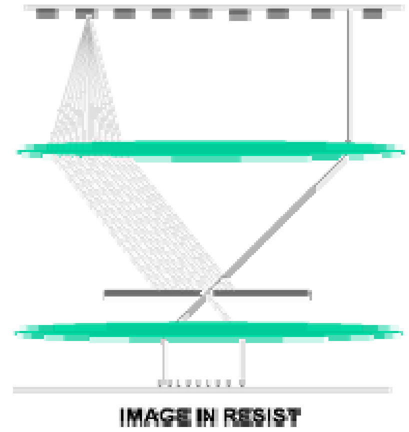
- 30 nm thick poly(methyl methacrylate) (PMMA) is spin-cast on Si substrate.
- Exposure to e-beam along vertical lines spaced 50 nm apart, breaks polymer bonds and increases solubility.
- 10 nm lines are dissolved away by a solvent.

Electron beam projection lithography (EPL)



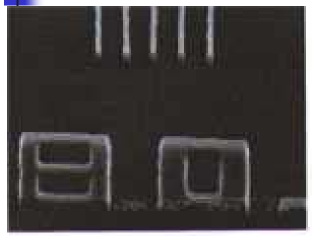
SCALPEL System (Lucent Technologies)

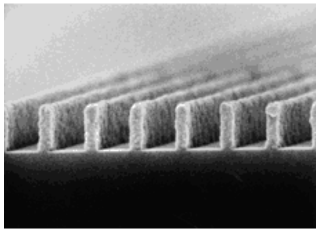
Electron beam projection lithography (ctnd.)

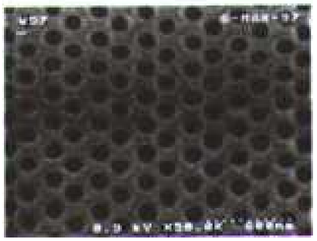


Principle of continuous membrane EPL

Structures produced by EPL







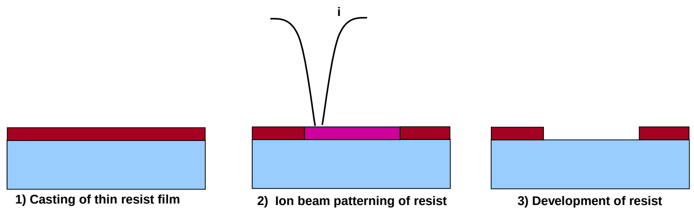
Technology was a serious contender for future sub-70 nm nodes

Relatively low throughput and high cost of mask precluded its viability

Eventually abandoned (~2001) in favor of EUV (λ = 13.5 nm) optical systems

Chap. 1 : Nanolithography

Ion beam lithography

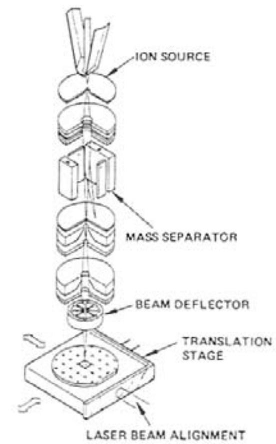


- **Advantages of ion beams:**
  - **Enhanced resists sensitivity**
  - **Can be focused to narrower linewidth**
  - **Reduced scattering**
  - **Allows hybrid processes such as ion-induced etching and implantation**

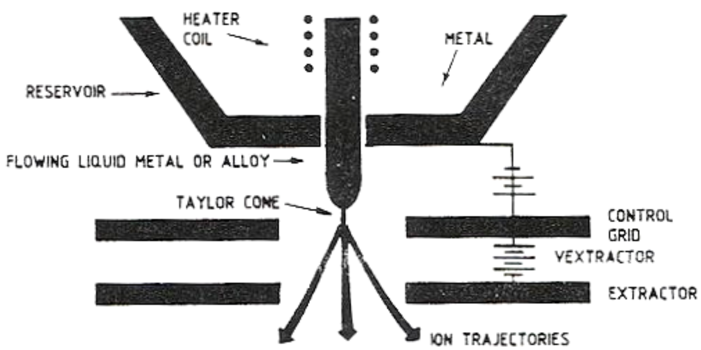
More ? Google it !

Focused ion beam lithography

- **FIBL components:**
  - **Ion source**
  - **Ion optics column**
  - **Sample displacement table**
- **Specifications:**
  - **Accelerating voltage 3-200 kV.**
  - **Current density up to 10 A/cm^2 .**
  - **Beam diameter 0.5-1.0 μm.**
  - **Ions: Ga^+ , Au^+ ,Si^+ ,Be^+ etc.**

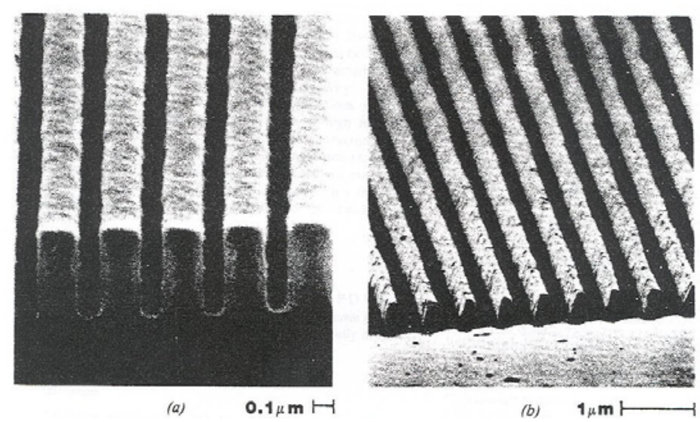


Liquid metal ion sources



Provides sub-micrometer beam with good current density (1-5 A/cm^2) for metals with a relatively low melting temp and vapor pressure (ie. Ga, In, Sn etc).

FIB fabricated nanostructures



Issues in FIBL

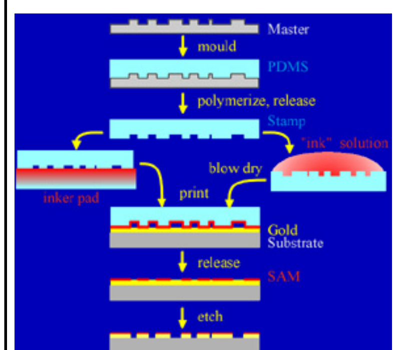
- **Effects of the ion beam on the substrate:**
  - **Displacement of atoms.**
  - **Emission of electrons.**
  - **Chemical effect like change of solubility of the resist.**
  - **Sputtering of substrate atoms by low energy ions.**
- **May result in resist heating as high as 1500º C**

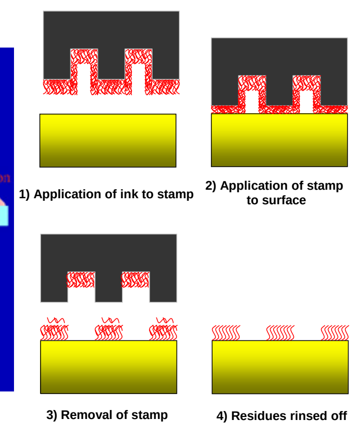
Chap. 1 : Nanolithography

Alternate Nanolithography Techniques

- **Micro-contact Printing**
- **Nanoimprint Lithography**
- **Scanned Probe Lithography**
- **Dip-pen Lithography**

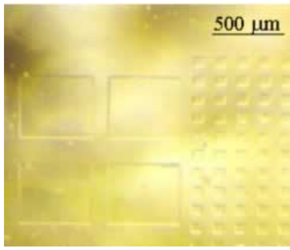
Micro-contact printing





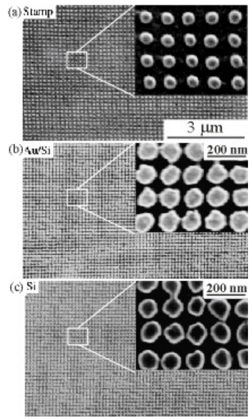
Source: IBM Zurich

Micro-contact printing



Printing of PDMS

Source: Winograd Group, Penn State



High resolution µCP of 60 nm dots

Source: IBM Zurich

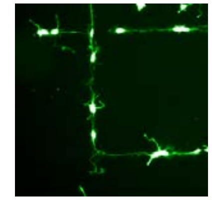
Selective growth of neurons on printed surfaces

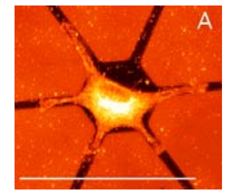
Biological interactions that underlie neuron cell attachment and growth are being employed to produce defined networks of neurons.

Microcontact printing has been used to place chemical, biochemical, and/or topographical cues at designated locations.

Important potential for the interfacing of solid state electronics with nerve cell biology, and for the fundamental electrical studies of single nerve cells.

Source: Craighead Group, Cornell



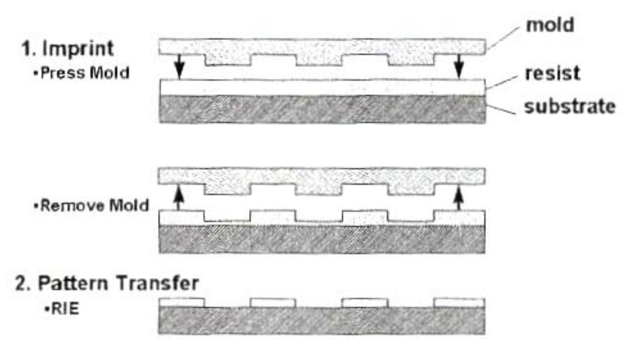


Selective growth of neurons on chemically patterned Si (C. D. James *et al.)*

Alternate Nanolithography Techniques

- Micro-contact Printing
- **Nanoimprint Lithography**
- Scanned Probe Lithography
- Dip-pen Lithography

Nanoimprint Lithography

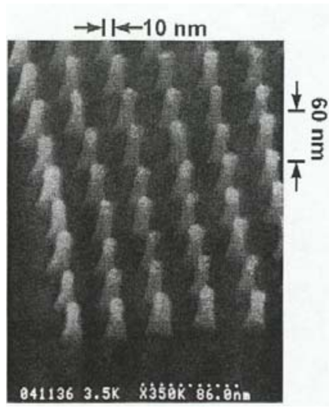


Consists of pressing a mold onto the resist above its glass transition temperature T_g

More ? Check out S. Y. Chou, Princeton

NIL master

- SiO_2 pillars with 10 nm diameter, 40 nm spacing, and 60 nm height fabricated by e-beam lithography.
- Master can be used tens of times without degradation

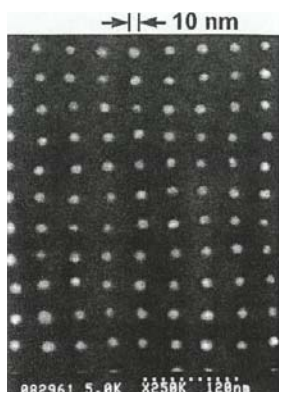


NIL pattern in PMMA

- Mask is pressed into 80 nm thick layer of PMMA on Si substrate at 175° C (T_g=105 ° C), P= 4.4 MPa.
- PMMA conforms to master patterng, resulting in ~10 nm range holes

Metal dots by NIL

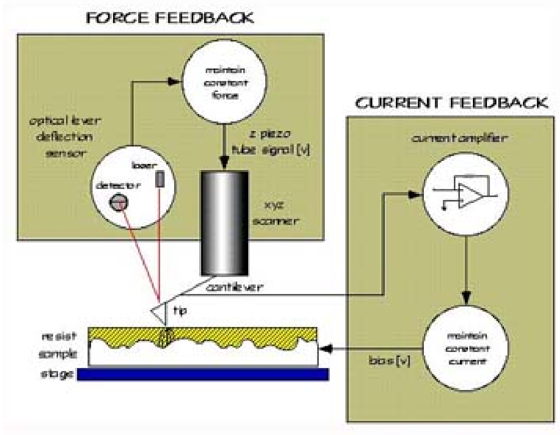
- Reactive ion etching is used to cut down resist thickness until shallow regions are completely removed
- Ti/Au is deposited onto resist.
- Resist and metal-coating is removed by solvent leaving behind metal dots where resist had been removed.



Alternate Nanolithography Techniques

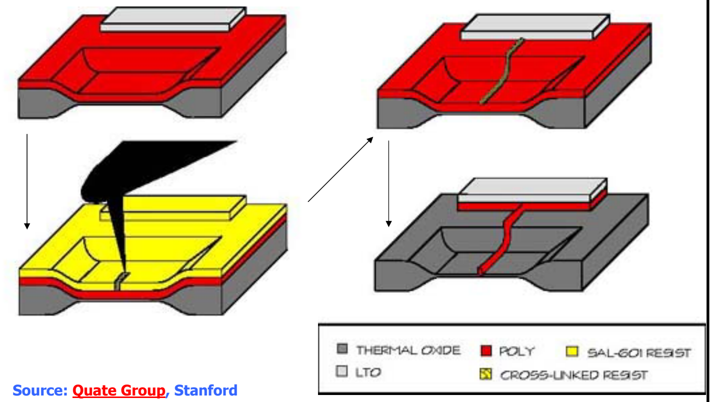
- Micro-contact Printing
- Nanoimprint Lithography
- **Scanned Probe Lithography**
- Dip-pen Lithography

Scanned Probe Lithography



Source: Quate Group, Stanford

Fabrication of CMOS gate using SPM lithography

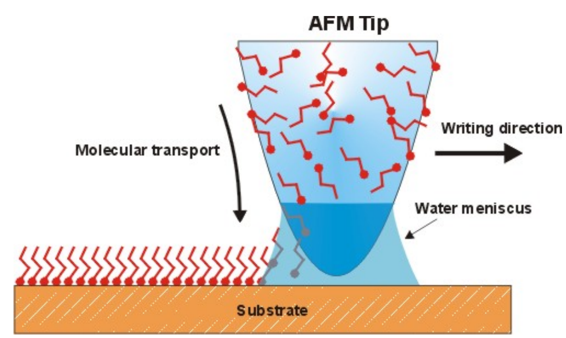


Source: Quate Group, Stanford

Alternate Nanolithography Techniques

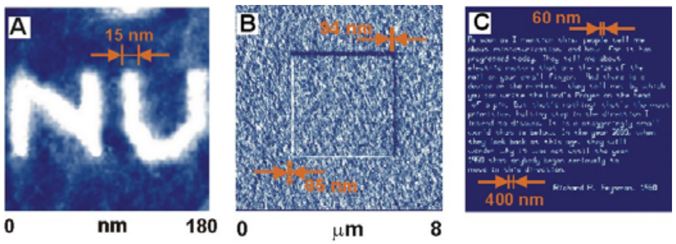
- Micro-contact Printing
- Nanoimprint Lithography
- Scanned Probe Lithography
- **Dip-pen Lithography**

Dip-pen lithography



Source: Mirkin Group, NWU

Dip-pen lithography



A) Ultra-high resolution pattern of mercaptohexadecanoic acid on atomically-flat gold surface. **B)** DPN generated multi-component nanostructure with two aligned alkanethiol patterns. **C)** Richard Feynmann's historic speech written using the DPN nanoplotter

Source: Mirkin Group, NWU