Nanometer Scale Patterning and Processing

Spring 2016

Lecture 2

Overview of Lithography

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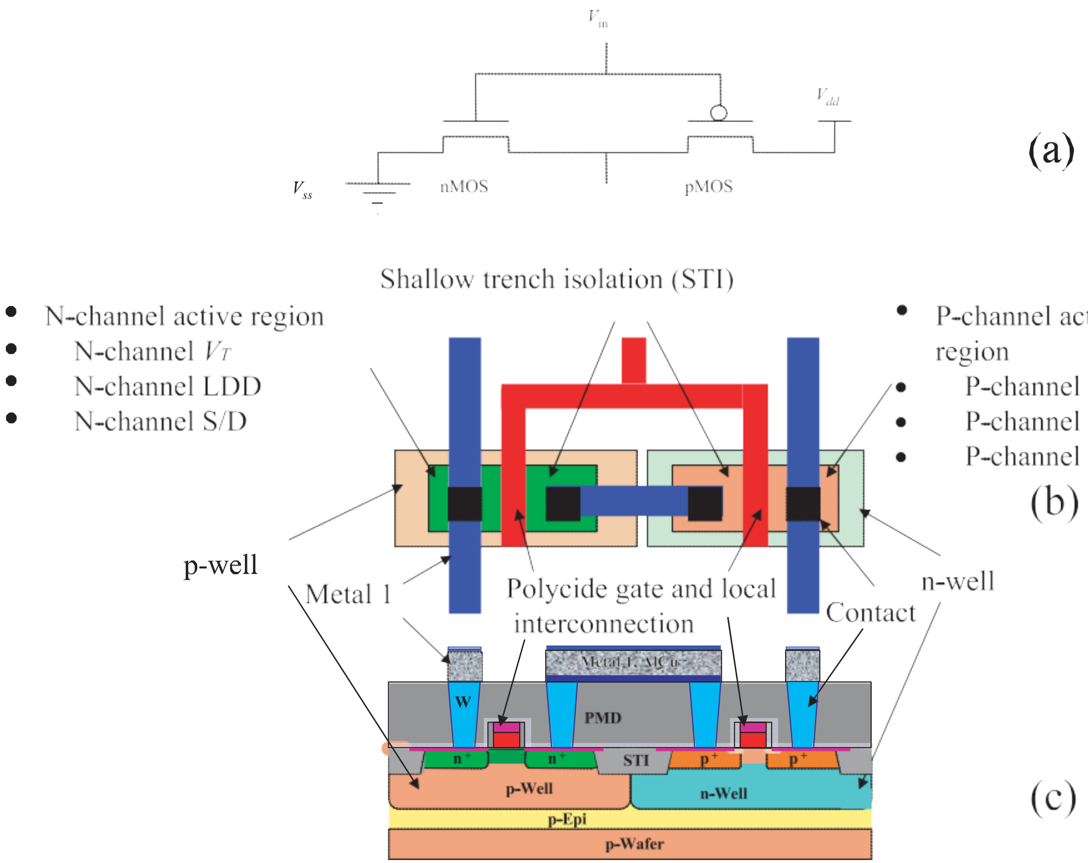
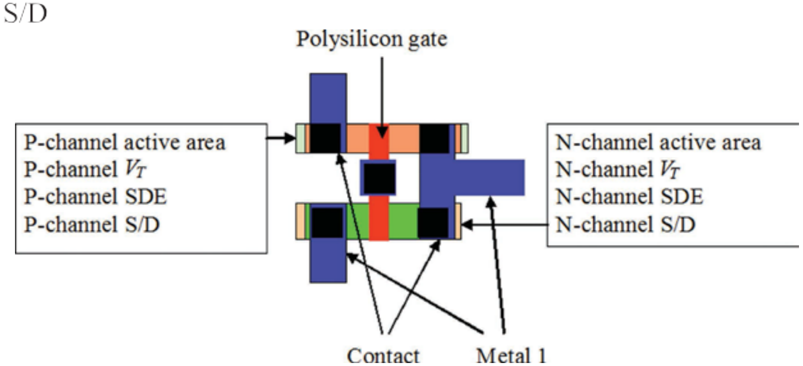
Anatomy of a CMOS Transistor

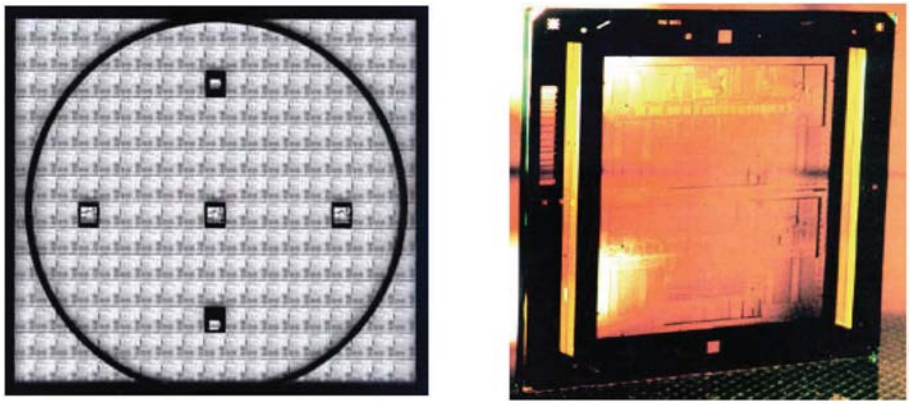




(Xiao 2012) Figure 1.14 (a) The circuit of a CMOS inverter, (b) an example of a textbook-style design layout of a CMOS inverter, and (c) the cross section of the textbook layout.

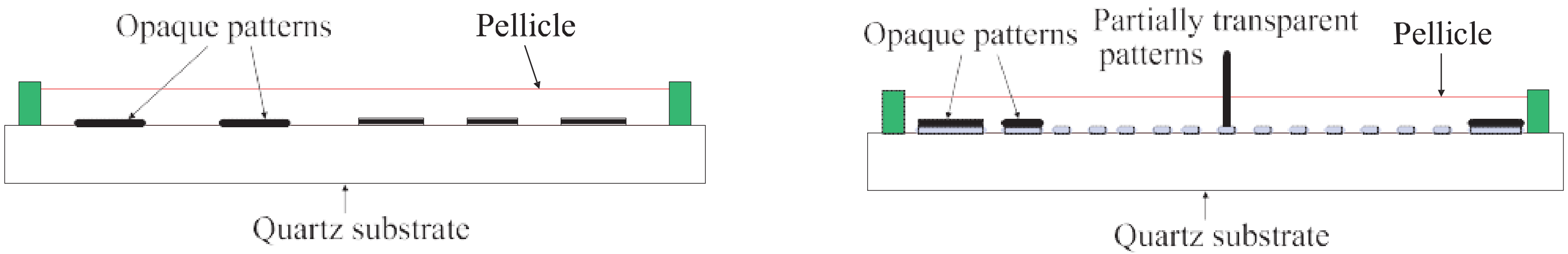
(Xiao 2012) Figure 1.15 CMOS inverter in a real-life IC layout.

Masks: Where Designs are Transferred to Silicon



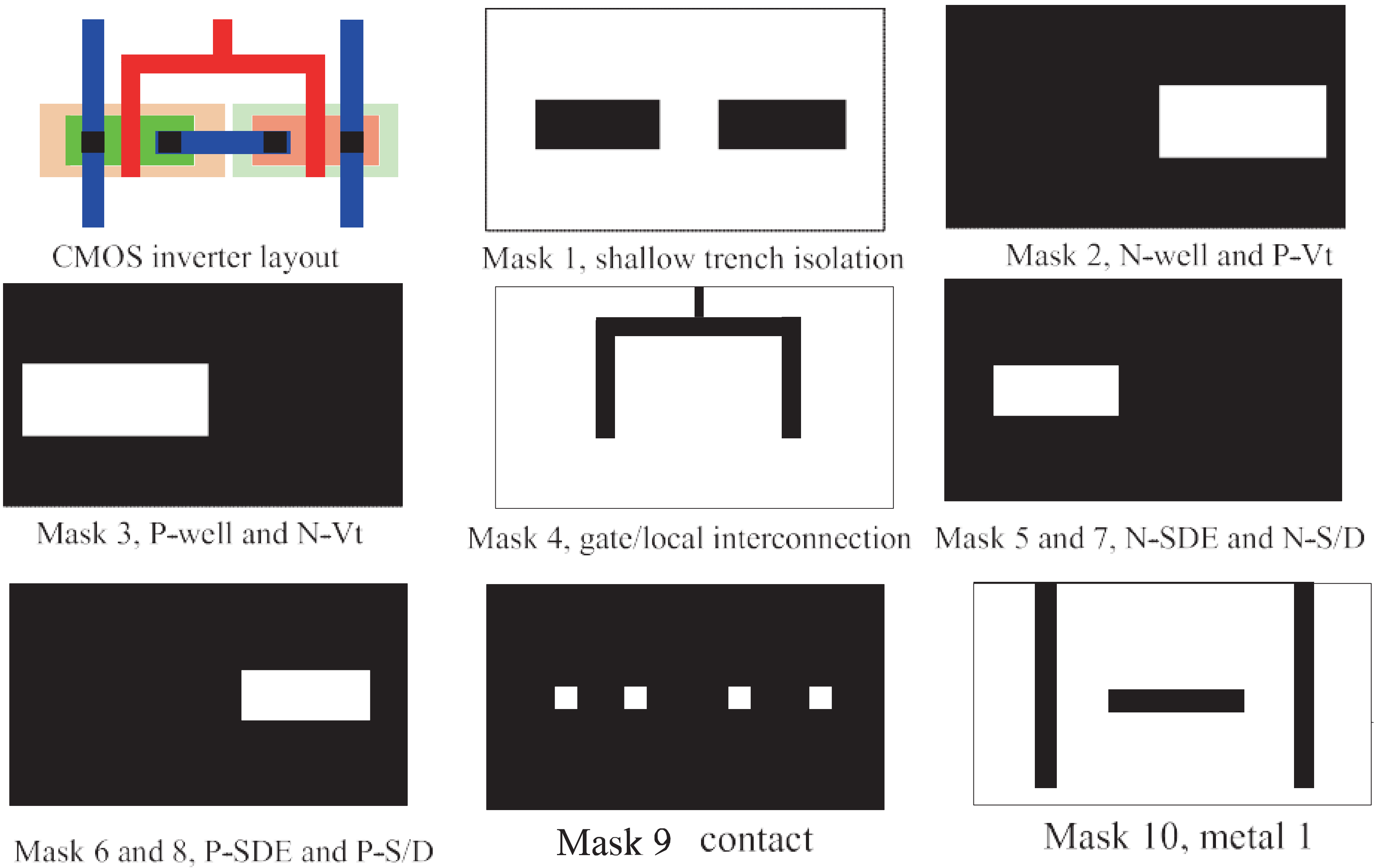
(a) (b)

(Xiao 2012) Figure 1.18 (a) A mask and (b) reticle. (SGS Thompson).



(Xiao 2012) Figure 1.16 (a) Binary mask and (b) an attenuated phase shift mask.

Example: Layout and Binary Masks for a CMOS Inverter (Xiao 2012) Figure 1.17



RIT's Advanced CMOS Process

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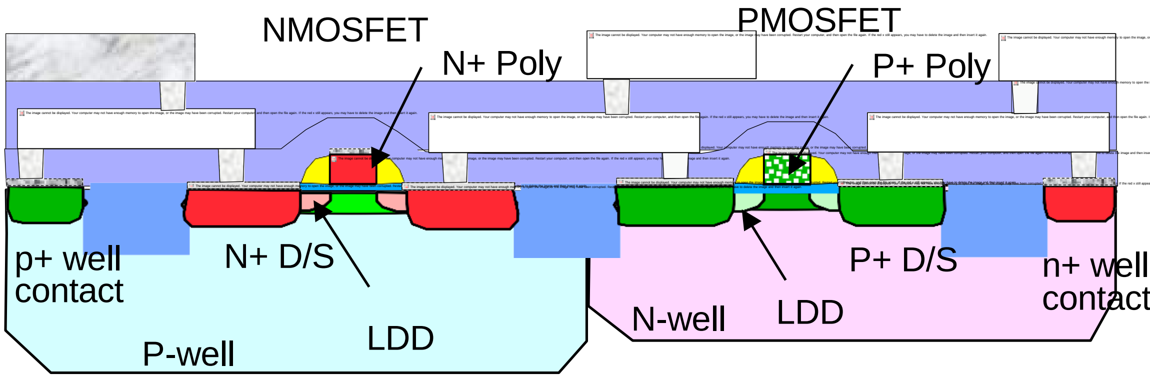
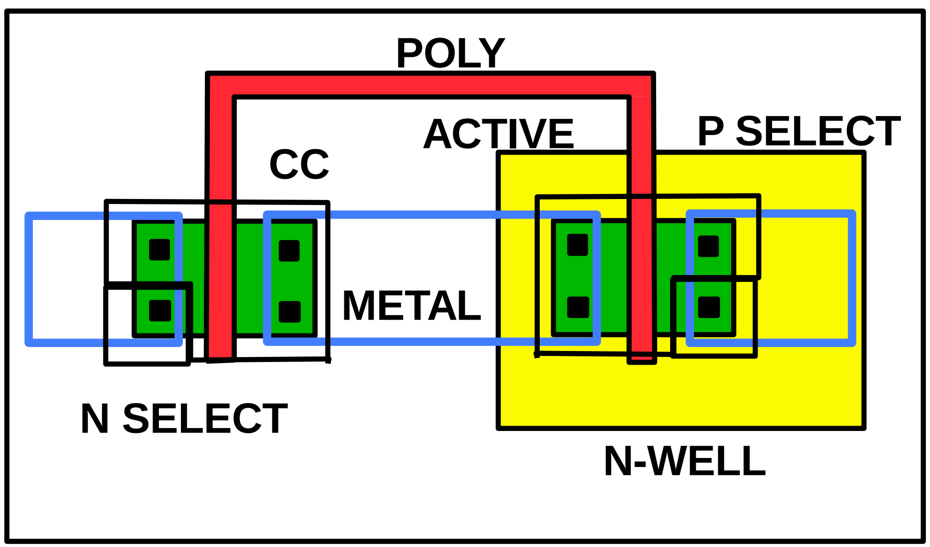
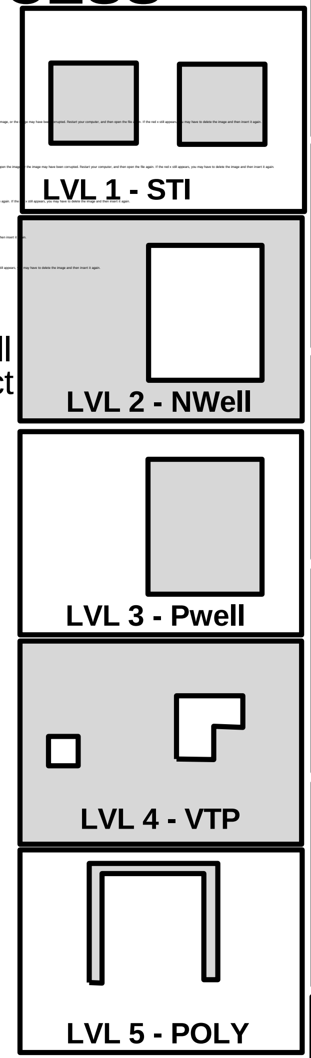
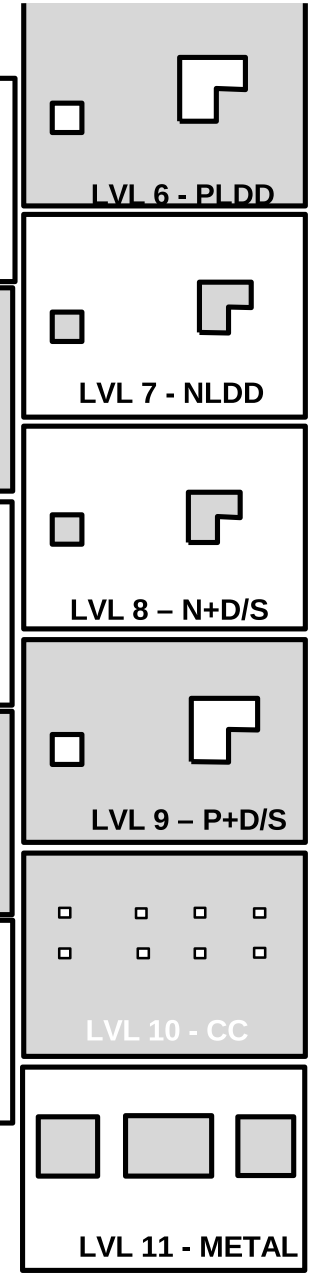
RIT ADVANCED CMOS PROCESS



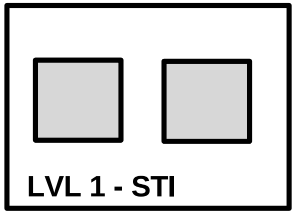




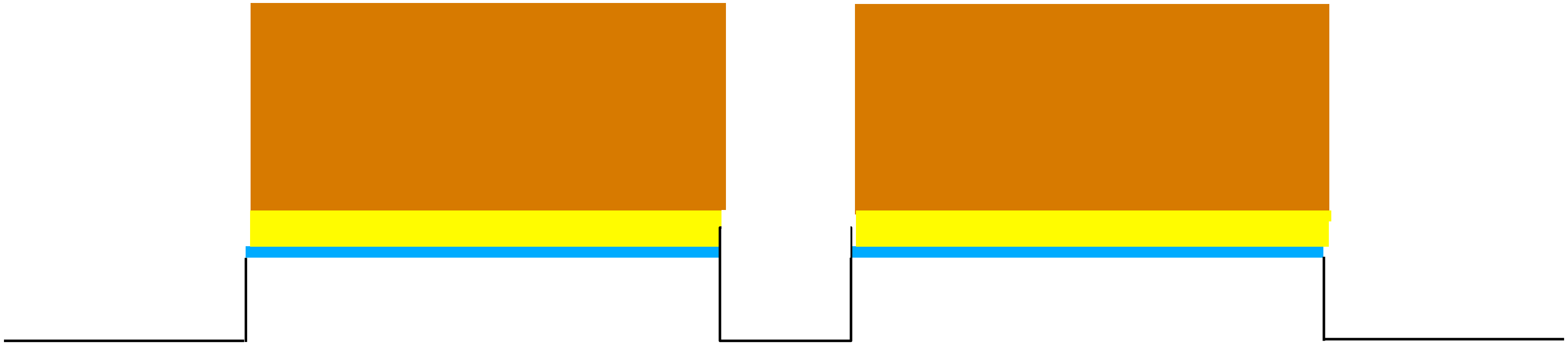


11 PHOTO LEVELS

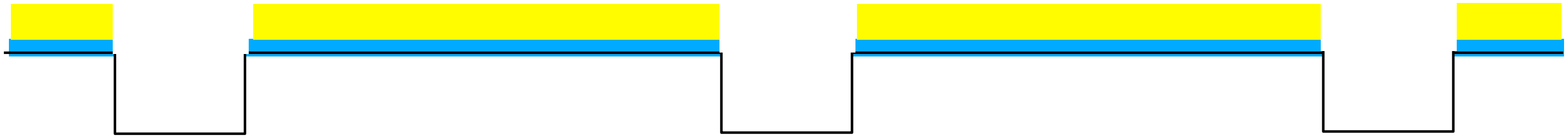
LEVEL 1 PHOTO – Shallow Trench Isolation



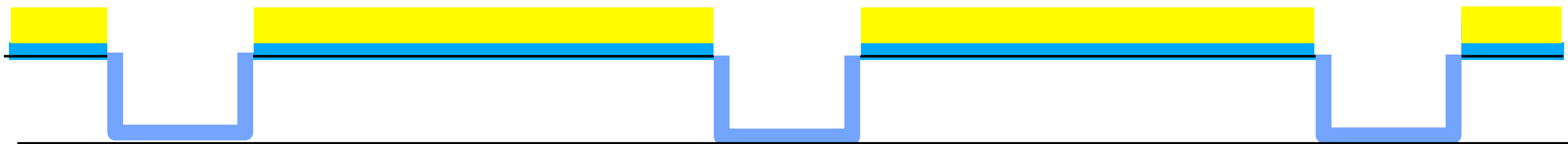
CONTINUE THE ETCH THRU PAD OXIDE AND INTO THE SILICON



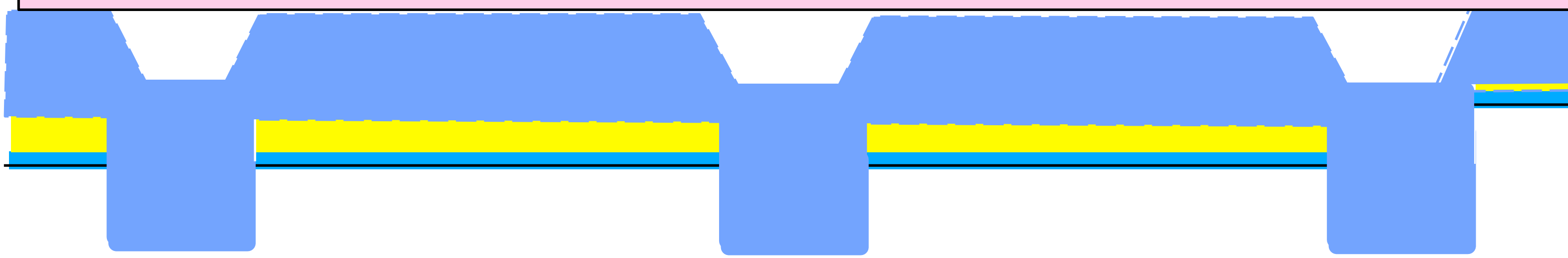
Remove Photoresist



GROW TRENCH LINER OXIDE

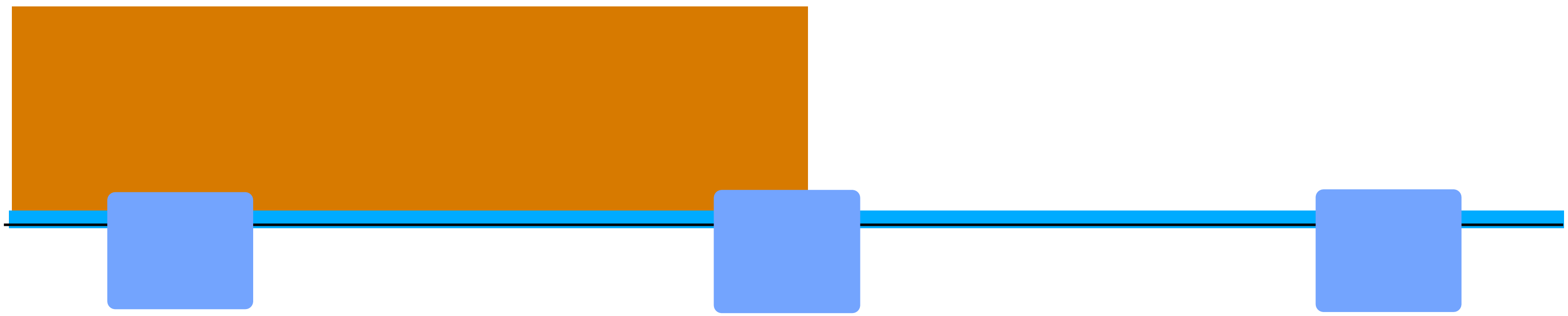


DEPOSIT LTO TRENCH FILL

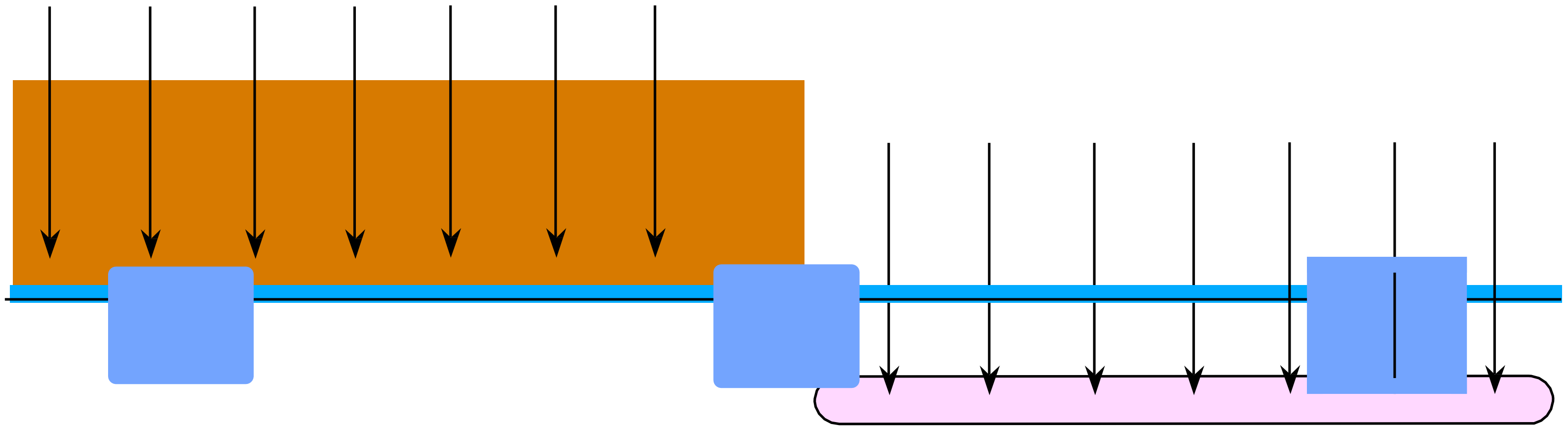


AFTER CMP

PHOTO 2 N-WELL



N-WELL IMPLANT



REFERENCES

1. Silicon Processing for the VLSI Era, Volume 1 – Process Technology, 2nd, S. Wolf and R.N. Tauber, Lattice Press.

2. The Science and Engineering of Microelectronic Fabrication, Stephen A. Campbell, Oxford University Press, 1996.

Applications of Nanotechnology

- Electronics and information processing
  - Integrated circuits
- Information storage and transmission
  - Hard disks (conventional)
  - Optical communication and information processing (photonics, e.g. Silicon photonics)
- Light sources (LEDs, etc.)
- Chemical and biological sensors, Catalysis
- Micro- and nanomechanical structures
  - Airbag sensors, gyroscopes, MEMS camera focusing lens
- Medical diagnostics, therapeutics, etc.
  - Microfluidics, biosensing and sorting
- Nanorobots ??
  - Fictions ☺
- Microscopy and metrology:
  - Observation at the nanoscale
  - Measurement with nanometer precision and accuracy
- 3D Printing

Contents courtesy of Prof. Bo Cui

Classification of Top-Down Nanofabrication

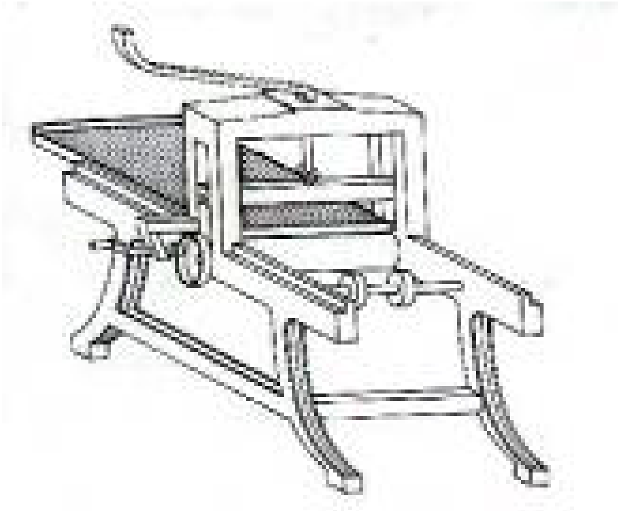
- **Additive Methods:**
  - **Thin film deposition**
  - Physical vapor deposition (PVD): sputtering, e-beam or thermal evaporation
  - Chemical vapor deposition (CVD): metal-organic CVD, plasma-enhanced CVD, low pressure CVD…
  - Epitaxy: molecular beam epitaxy (MBE), liquid-phase epitaxy…
  - Electrochemical deposition: electro- and electroless plating (of metals)
  - Oxidation (growth of thermal SiO_2)
  - Spin-on and spray-on film coating (resist coating)
  - **Printing techniques**: ink-jet, micro-contact printing, 3D printing
  - **Assembly**: wafer bonding, surface mount, wiring and bonding
- **Subtractive methods:**
  - Etching: wet chemical etching, reactive ion etching; ion beam sputter etching, focused ion beam etching.
  - Tool-assisted material removal: chemical-mechanical polishing, chipping, drilling, milling, sand blasting.
  - Radiative and thermal treatment: laser ablation, spark erosion.
- **Modifying methods:**
  - Radiative treatment: resist exposure, polymer hardening
  - Thermal annealing: crystallization, diffusion, change of phase
  - Ion beam treatment: implantation, amorphization
  - Mechanical modification: plastic forming and shaping, scanning probe manipulation

Contents courtesy of Prof. Bo Cui

What does ECE 695 specialize in?

- We study how to generate the structures of interest at nanometer length scale.
  - Lithography
  - Etching
  - Planarization
  - Deposition
- We do not focus on the material growth or properties
  - Material properties are important for all nanofabrication processes

History of Lithography

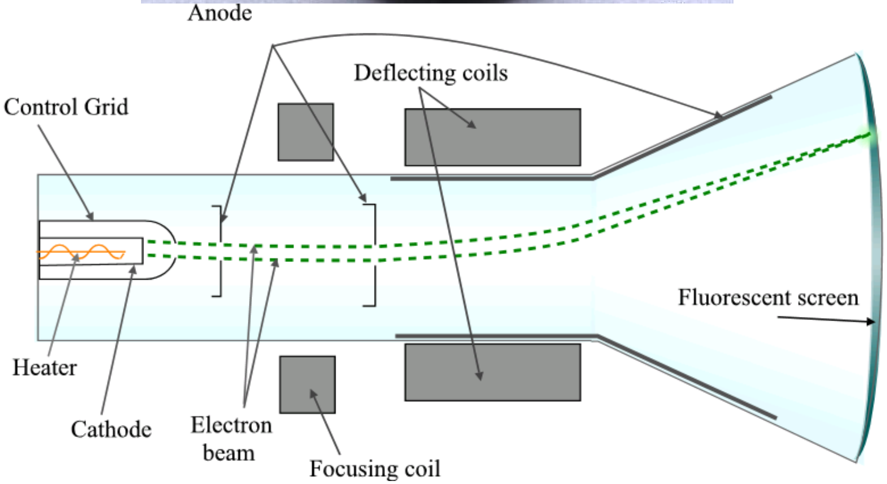


State-of-art lithography tool for IC industry

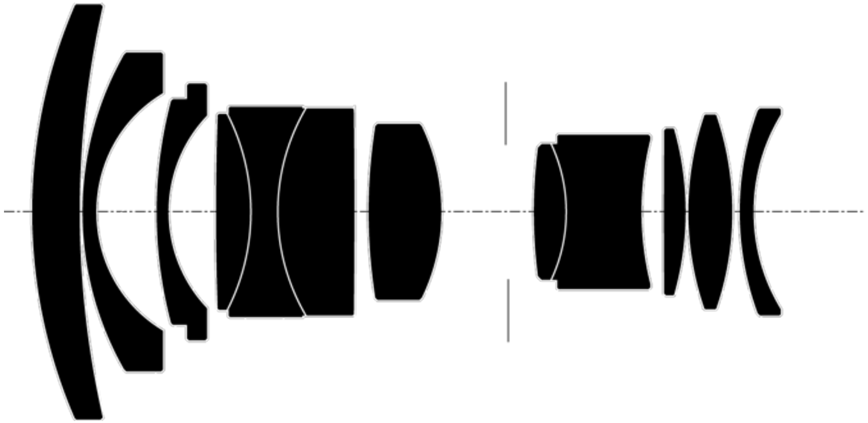
- **Lithography (Greek for "stone drawing"); based on repulsion of oil and water.**
- **Invented by Alois Senefelder in 1798.**
- **Used for book illustrations, artist's prints, packaging, posters, etc.**
- **In 1825, Goya produced a series of lithographs.**
- **In the 20th and 21st century, become an important technique with unique expressive capabilities in the art field.**
- **Nowadays used in semiconductor manufacturing (integrated circuit - IC).**

Two Aspects of Lithography:

Pattern Generation

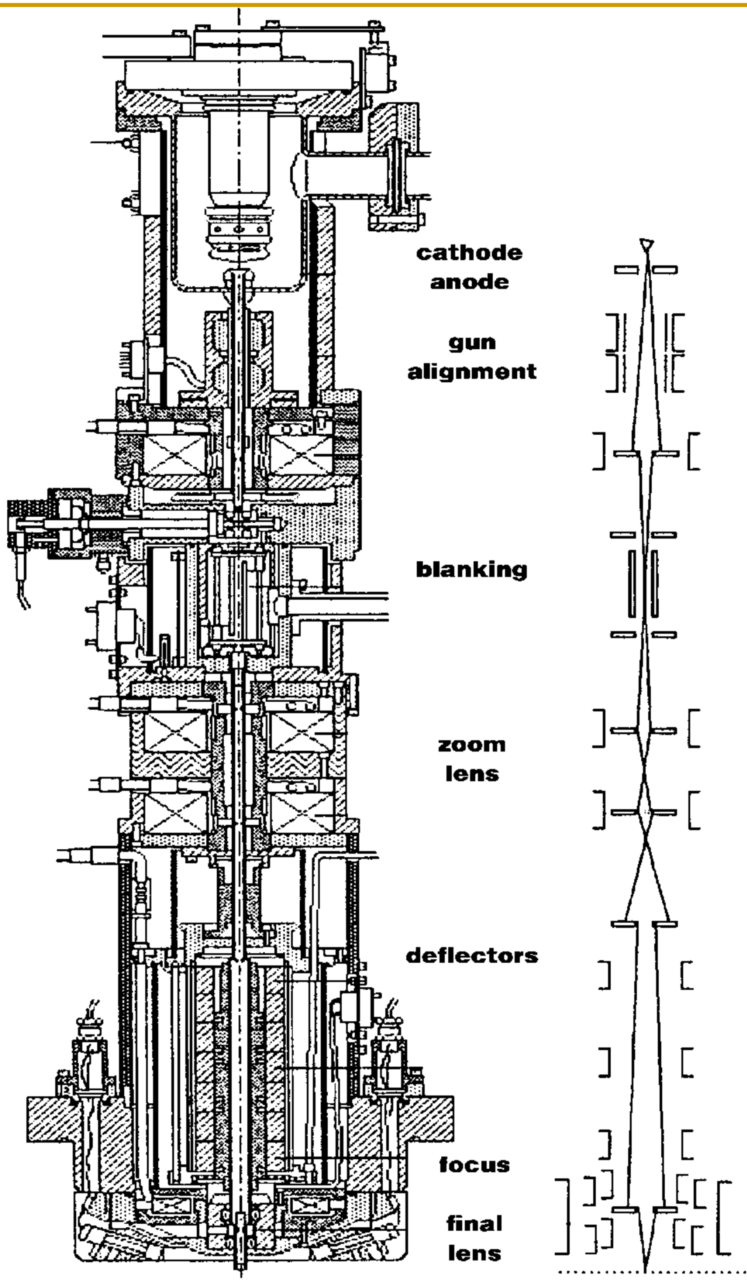


Pattern Replication



Resolution, uniformity, overlay, throughput

How are patterns generated from design: electron-beam lithography



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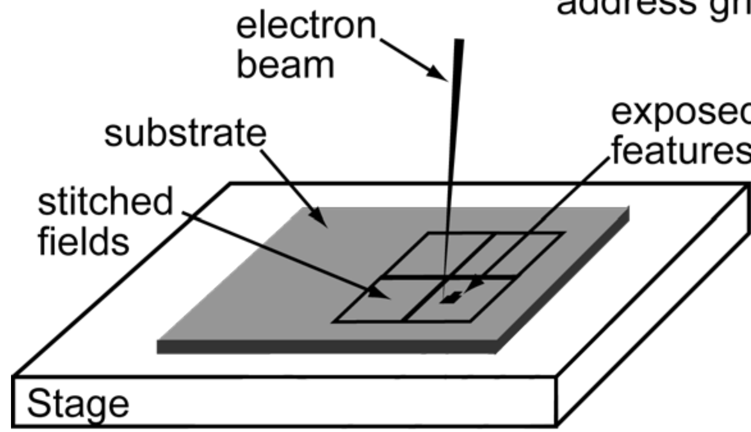
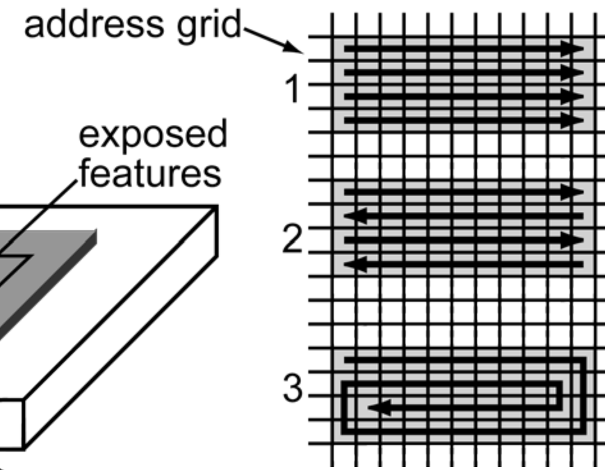
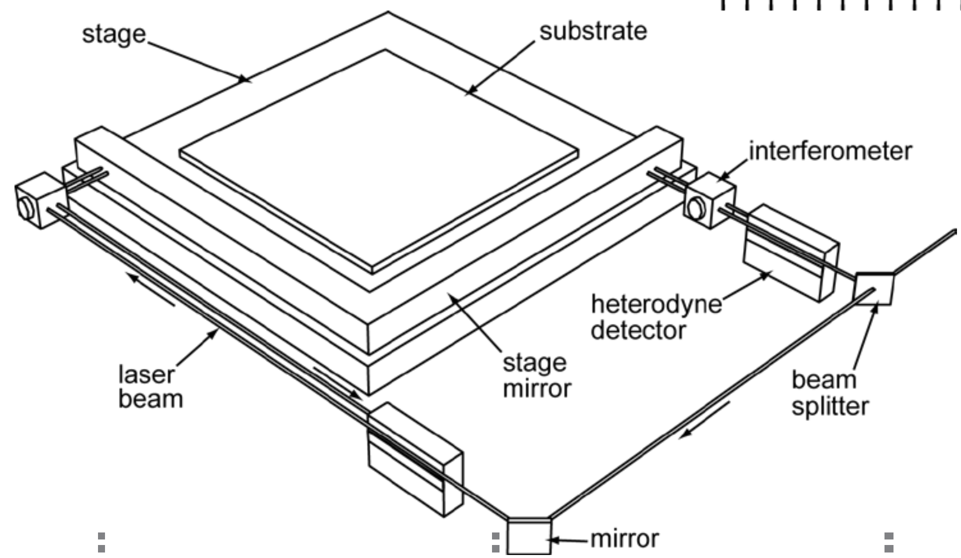
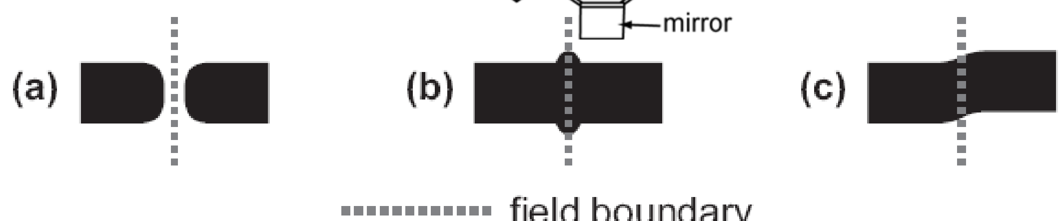
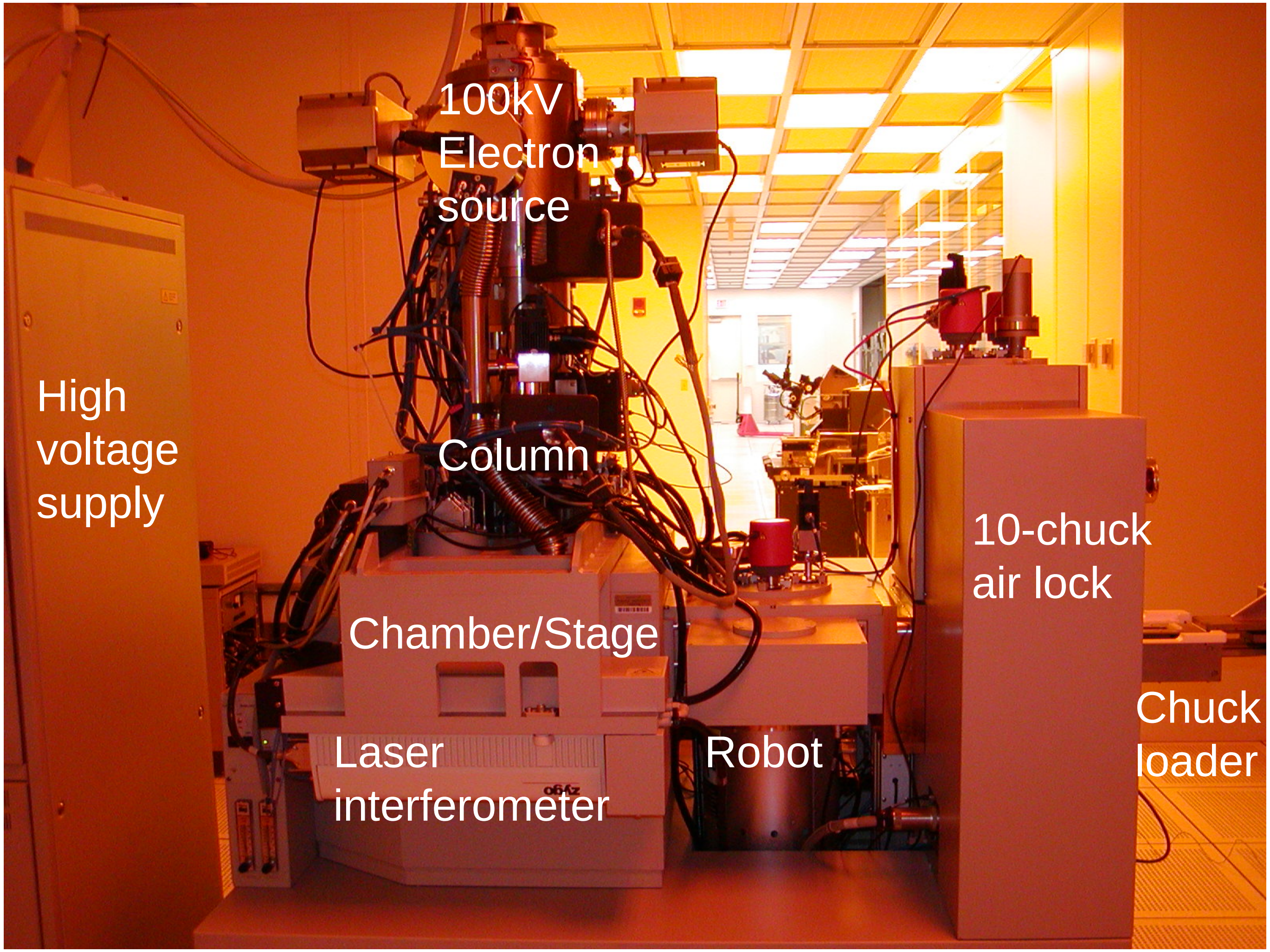








The Vistec VB6 UHR-EWF electron-beam lithography tool



Classification of Lithography

Lithography with particles or waves
•Photons: photolithography
•X-rays: from synchrotron, x-ray lithography
•Electrons: electron beam lithography (EBL)
•Ions: focused ion beam (FIB) lithography

Imprint lithography (molding)
•Soft Lithography: micro-contact-printing…
•Hot embossing
•UV-curable imprinting

SPM-lithography
•AFM
•STM
•DPN (dip-pen nanolithography)

Pattern replication: parallel
(masks/molds necessary)
High throughput, but not easy to change pattern
•Optical lithography
•X-ray lithography
•Imprint lithography
•Stencil mask lithography

Pattern generation: serial
(Slow, for mask/mold making)
•E-beam lithography (EBL)
•Ion beam lithography (FIB)
•SPM-lithography
- AFM, STM, DPN

Multiple serial (array)
•Electron-beam micro-column array (arrayed EBL)
•Zone plate array lithography
•Scanning probe array

Lithography on surfaces
•Optical/UV lithography
•E-beam lithography
•FIB lithography
•X-ray lithography
•Spm-lithography
- AFM
- STM
- DPN (dip-pen nanolithography)

•Imprint lithography
- Soft lithography
- Hot embossing
- UV imprinting

•Stencil mask lithography

3D Lithography
•Two photon absorption
•Stereo-lithography

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List of Lithography Techniques (I)

- High resolution photon-based lithography.
  - Deep UV lithography with high NA and/or low k1 factor.
  - Extreme UV lithography, why selected as next generation lithography by industry.
  - X-ray lithography, X-ray optics, mask, LIGA process.
- Electron beam lithography.
  - Electron optics, e-beam sources, instrumentation.
  - Electron-matter interaction, proximity effect, pattern design, alignment.
  - Resists and developers, resolution limits, contrast, sensitivity, etching selectivity.
  - CAD tool, fraction tool (CATS, Cview, etc)
- Nano-patterning by focused ion beam.
  - Ion source, ion optics, instrumentation.
  - Ion-matter interaction, focused ion beam etching and lithography.
  - Focused ion beam induced deposition, mechanism and applications.
  - Focused electron beam induced deposition.
- Nanoimprint lithography (NIL).
  - Thermal NIL, resist, thermoplastic properties of polymers, tools.
  - UV-curable NIL, resist, whole wafer vs. step-and-flash imprint, tools.
  - Alignment, mold fabrication, defects, limits.
  - Reverse NIL, NIL using thermal-set resist, pulsed laser assistant NIL of metals.

Contents courtesy of Prof. Bo Cui

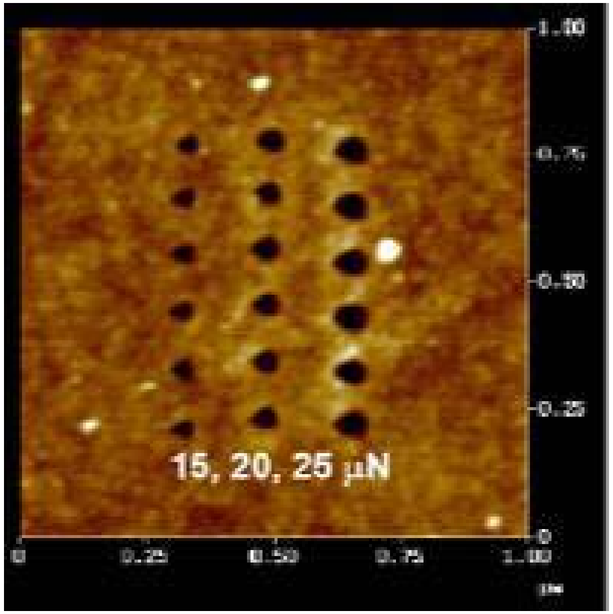
List of Lithography Techniques (II)

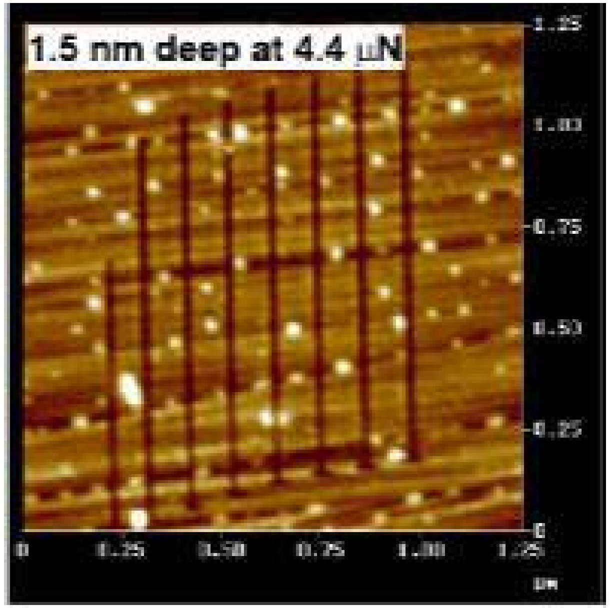
- Nano-patterning by scanning probes.
  - AFM-based, local oxidation and dip-pen lithography.
  - NSOM-based, near field optics, exposure of resist.
  - STM-based, manipulation of atoms and exposure of resist.
- Soft lithography.
  - Micro-contact printing of chemical patterns, capabilities and resolution limits.
  - Nano-transfer printing.
- Other top-down patterning techniques.
  - Focused proton beam lithography.
  - Pattern transfer by stencil mask.
- Nano-patterning by self assembly.
  - Anodized aluminum oxide, application as template for nano-wire growth.
  - Nano-sphere lithography, fabrication of nanostructure of various shapes.
  - Block copolymer self assembly, how to achieve long-range ordering.

Contents courtesy of Prof. Bo Cui

AFM lithography – scratching (simplest, mechanical lithography)

- Material is removed from the substrate leaving deep trenches with the characteristic shape of the tip used.
- The advantages of nano-scratching for lithography
  - Precision of alignment, see using AFM imaging, then pattern wherever wanted.
  - The absence of additional processing steps, such as etching the substrate.
- But it is not a clean process (debris on wafer), and the AFM tip cannot last long.

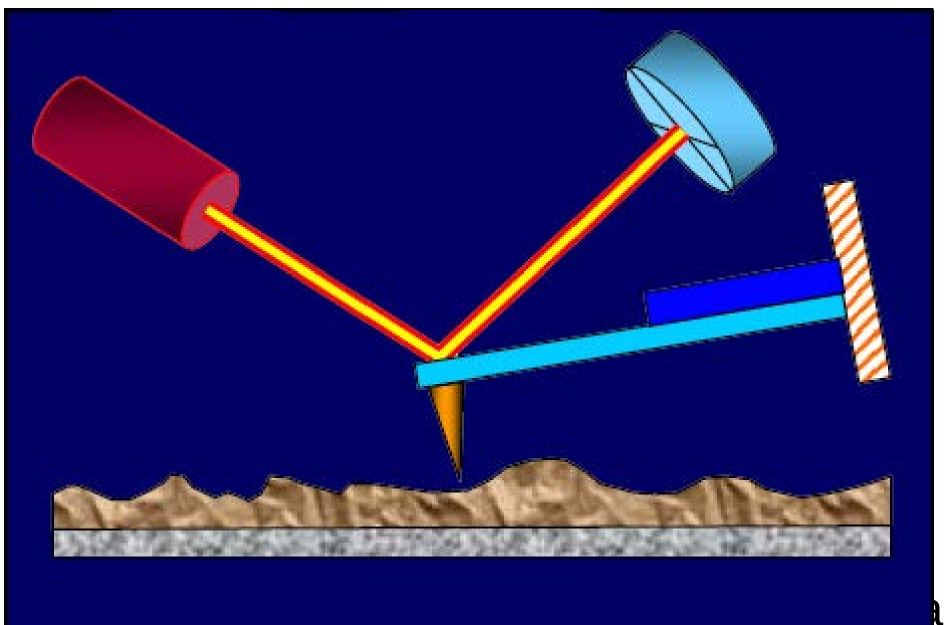


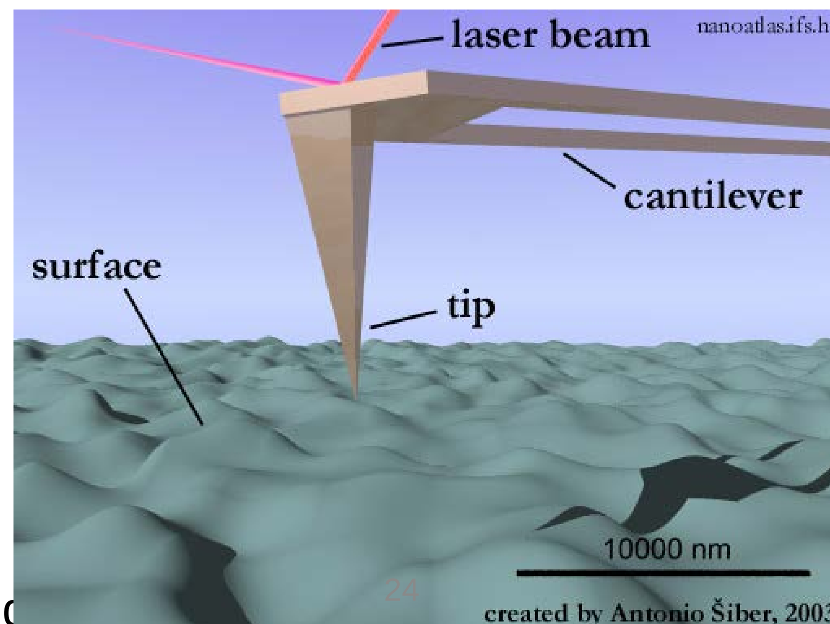


Scanning probe lithography (SPL)

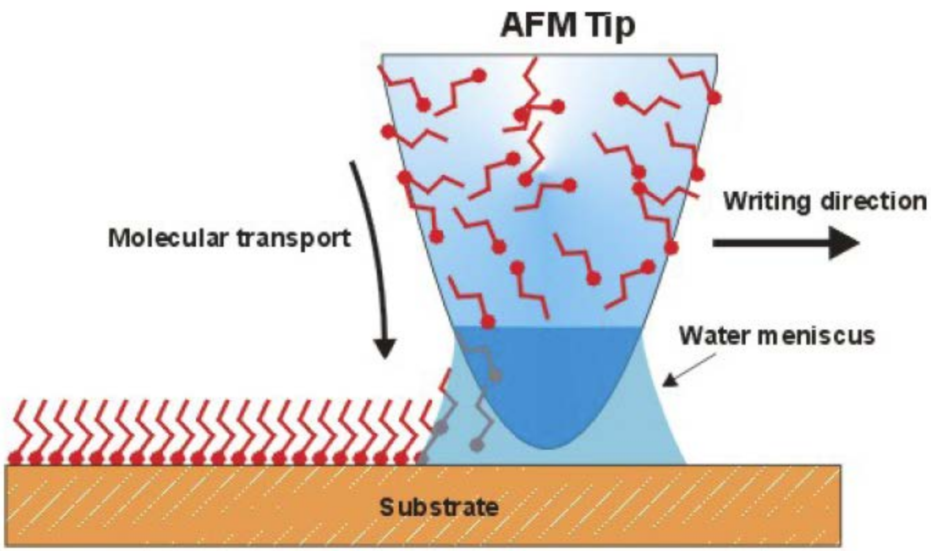
- Mechanical patterning: scratching, nano-indentation
- Chemical and molecular patterning (dip-pen nanolithography, DPN)
- Voltage bias application
    - o Field enhanced oxidation (of silicon or metals)
    - o Electron exposure of resist materials
- Manipulation of atoms/molecules by STM, or nanostructures by AFM

AFM: atomic force microscopy (X-Y positioning by piezo; Z deflection by optical measurement)

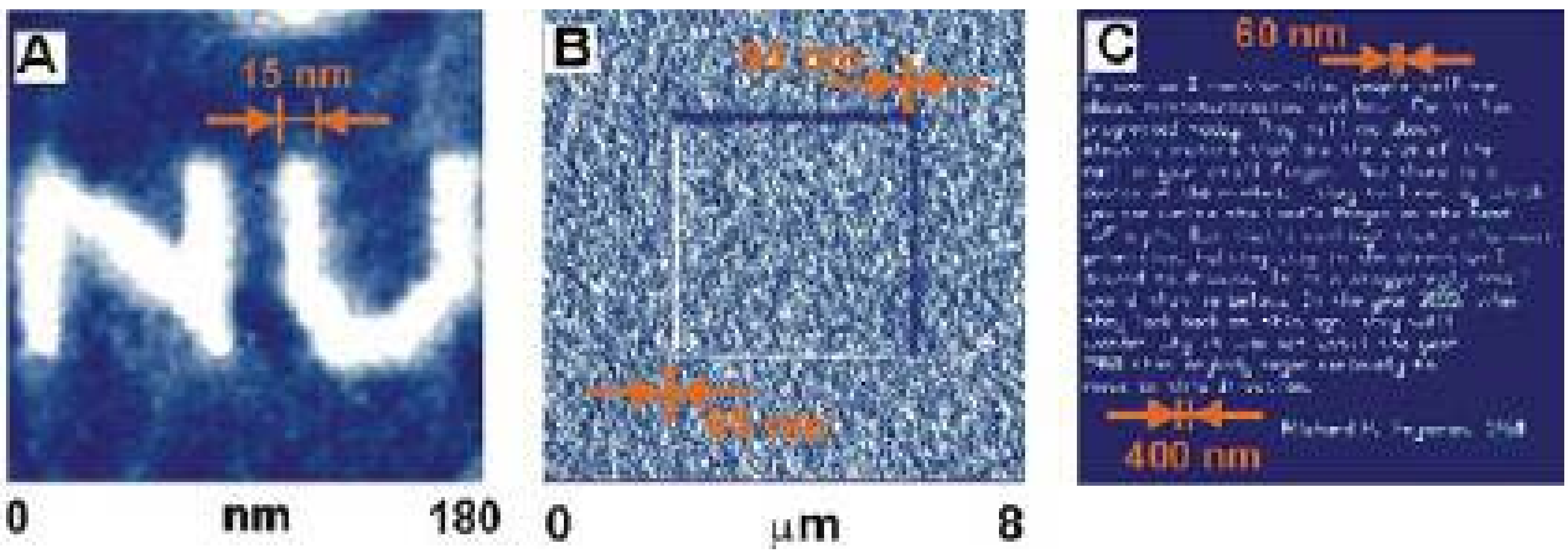




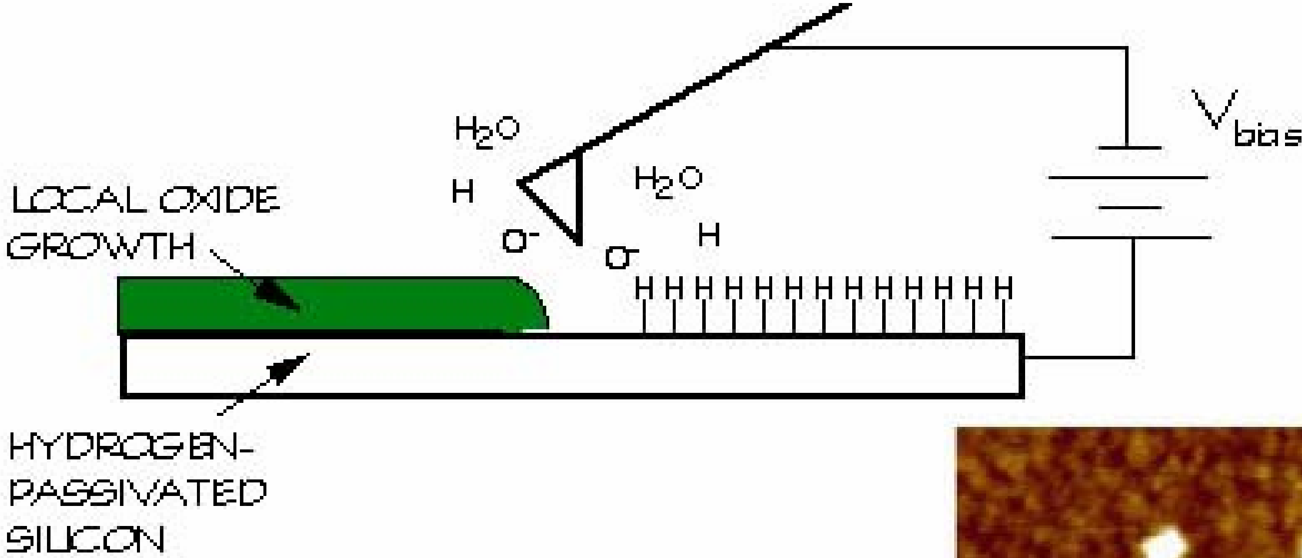
Dip-pen nanolithography (DPN)

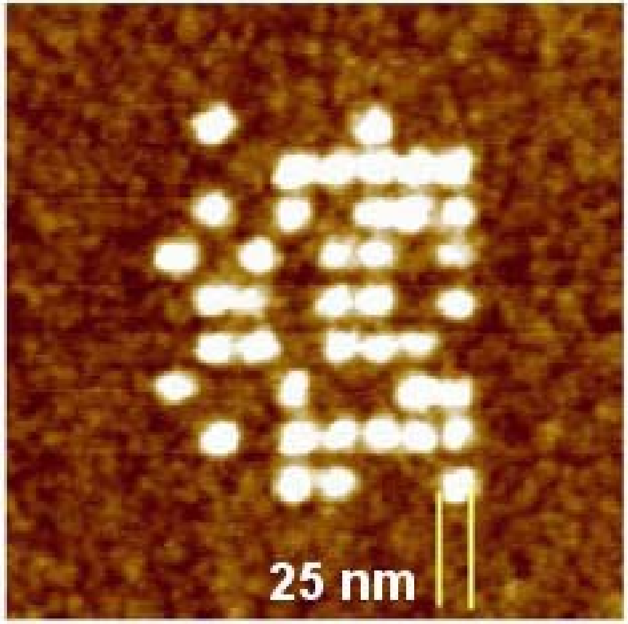


- Similar to micro-contact printing, and writing using a fountain pen.
- AFM tip is “inked” with material to be deposited
- Material is adsorbed on target
- <15nm features
- Multiple DPN tip arrays for higher throughput production



AFM lithography: oxidation (local electrochemical anodization)





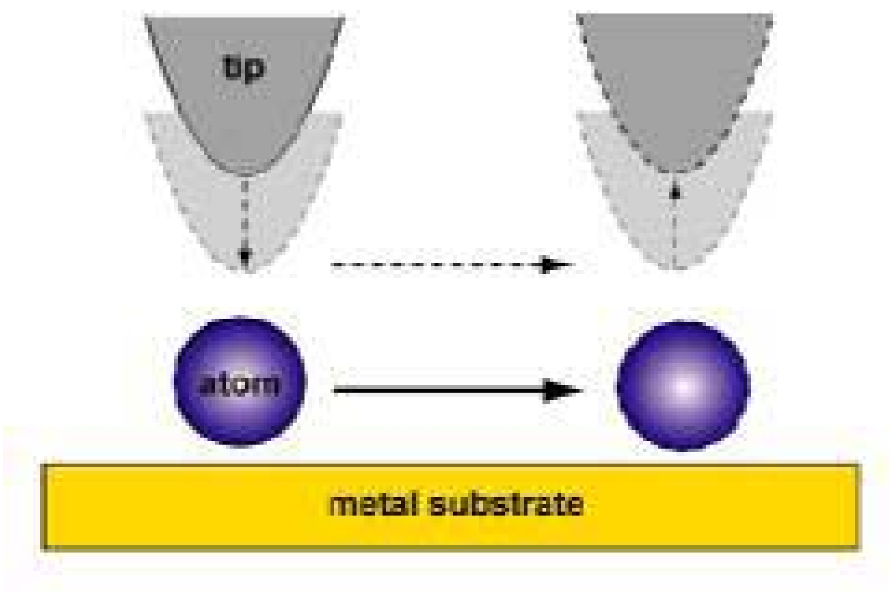
- Resulting oxide affected by experimental parameters
  - Voltage (typically from 5-10V)
  - Tip scan speed (stationary to tens of µm/s)
  - Humidity (20% to 80%)
- Detected current can be used for process control
- Changes in translational velocity influence current flow

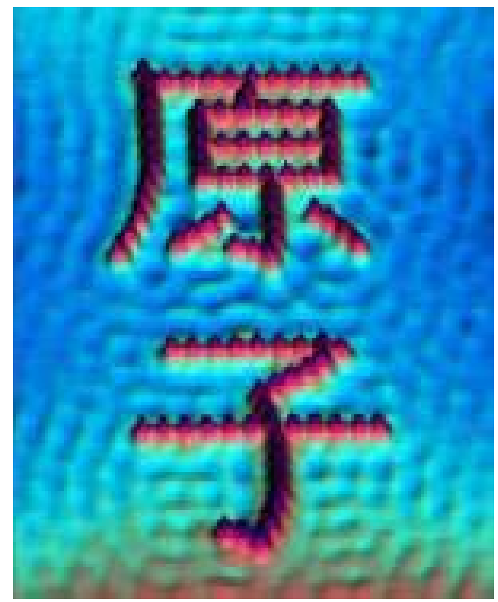
STM lithography (STM: scanning tunneling microscopy)

By applying a voltage between tip and substrate it is possible to deposit or remove atoms or molecules.
Van der Waals force used to drag atoms/molecules.

Advantages of STM Lithography

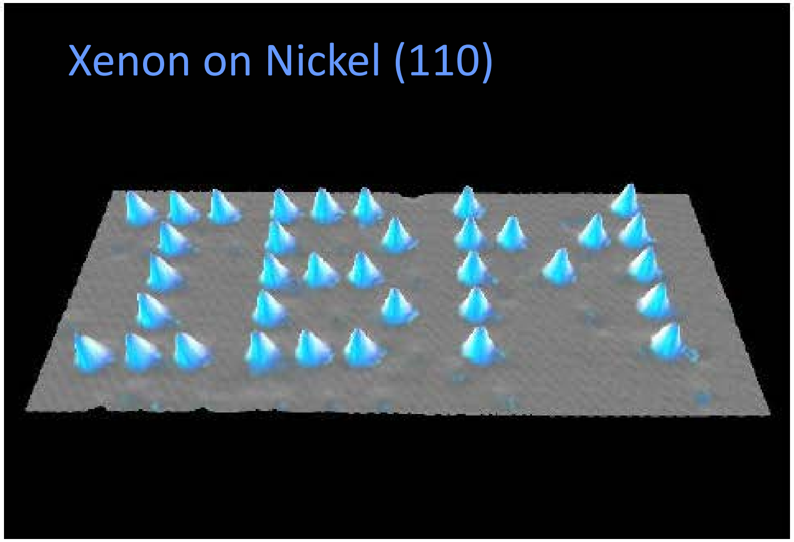
- Information storage devices (one atom per bit, highest storage density).
- Nanometer patterning technique (highest resolution, ~Å).
- Manipulations of big molecules and individual atoms.

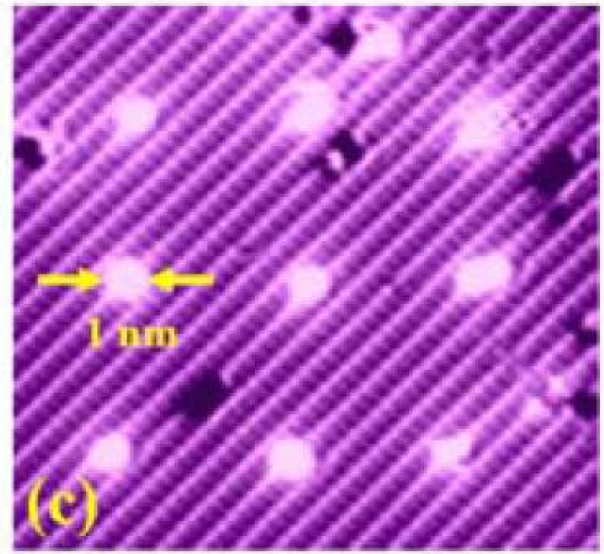


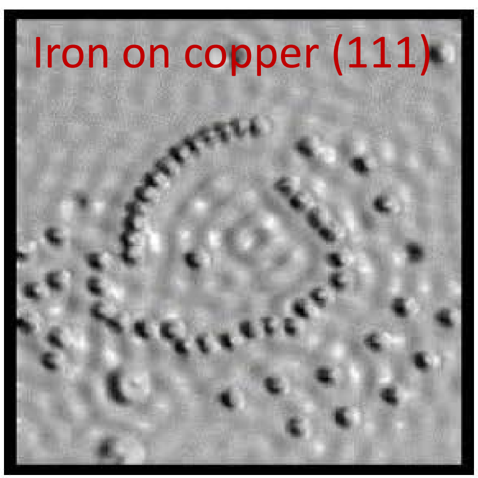


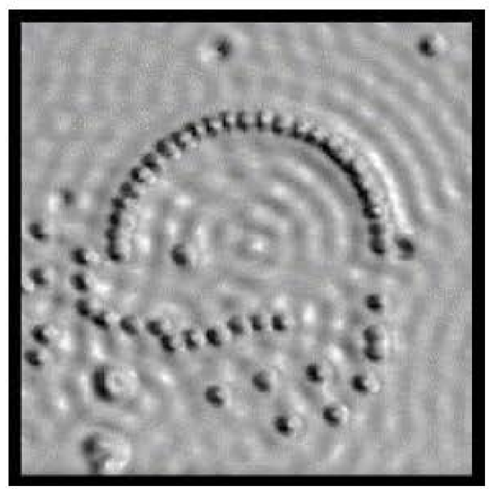
Iron on copper (111)

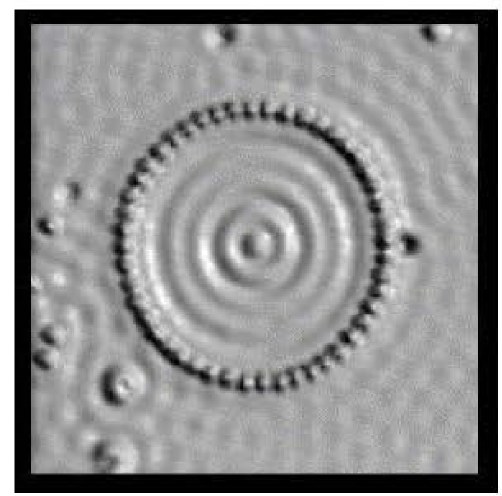
Scanning probe lithography (STM)







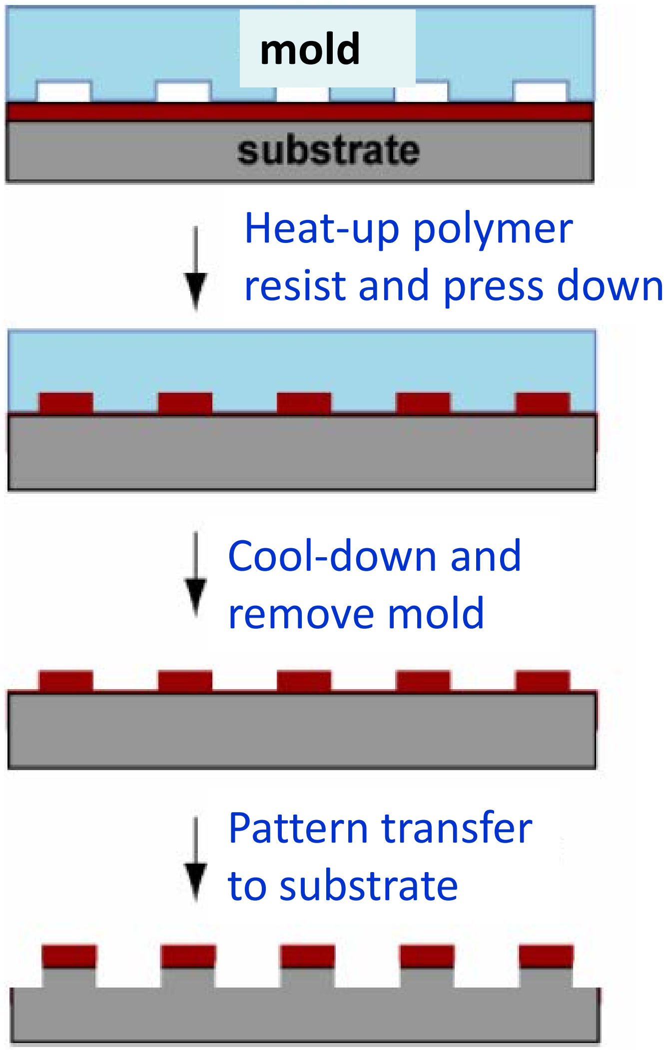




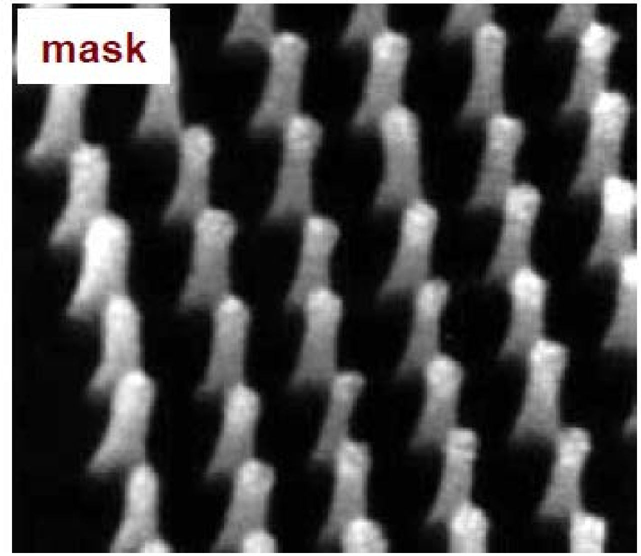
STM manipulation of atoms/molecules

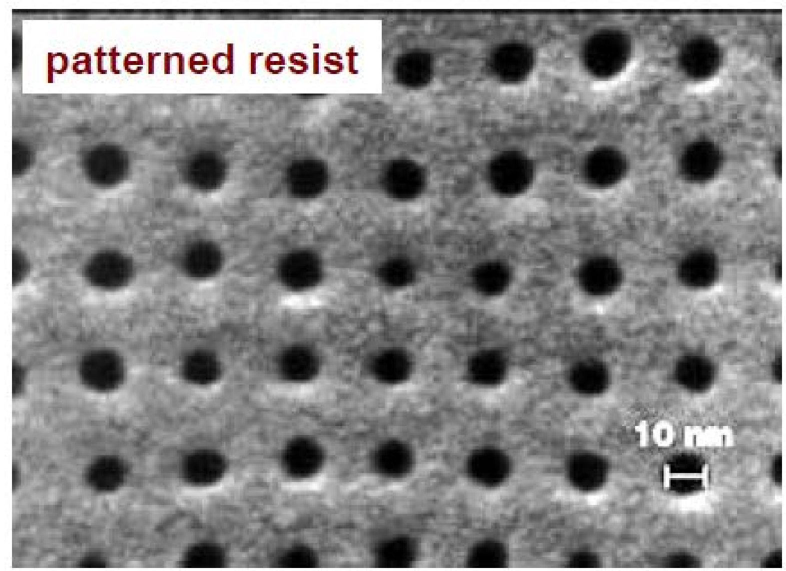
M.F. Crommie, C.P. Lutz, D.M. Eigler. Science 262, 218-220 (1993)

Lithography by molding/material transferring II: nanoimprint lithography (thermal/hot embossing)

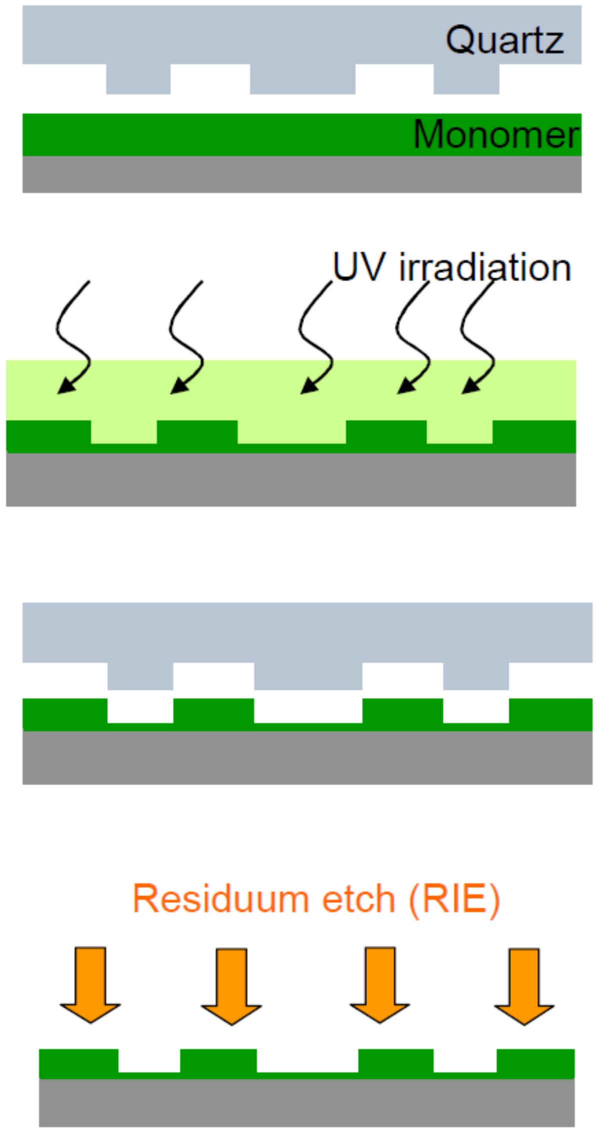


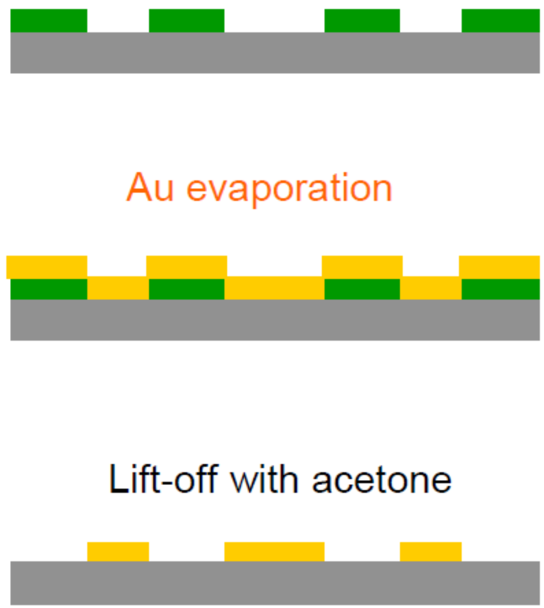
Mold = mask = template = stamp





UV-curable nanoimprint lithography (Au patterning by liftoff as an example)





- Liquid resist, soft and deformable by mold.
- Hardened by UV-curing (polymerization).
- Molds must be transparent (PDMS, Quartz).
- No temperature (thermal cycle) necessary.
- Thus a very gentle process, and thermal expansion mismatch no longer an issue.
- Many UV-curable resists are sensitive to oxygen – exposure under inert conditions.

Lithography by molding/material transferring (II): soft lithography (pattern duplication)

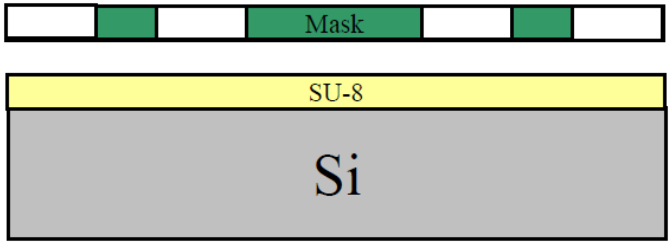
- A master mold is made by lithographic techniques and a stamp is cast from this master.
- Poly di-methyl siloxane (PDMS) is most popular material for stamps.
- Image reversal: fill PDMS stamp with PDMS pre-polymer, then peeled from PDMS stamp.

Stamp (mold) production

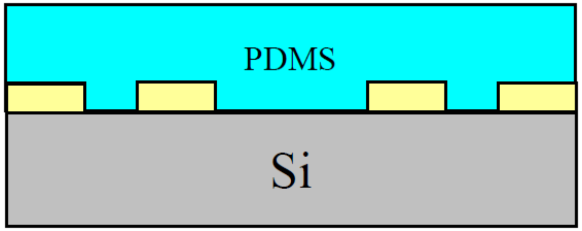
PDMS properties:

- Soft and flexible.
- Can be cured to create a robust PDMS stamp.
- Chemically inert, non-hygroscopic, good thermal stability.
- Can be bonded to a glass slide to create micro-fluidic components.

(hygroscopic: readily taking up and retaining moisture)



Photolithography pattern SU-8

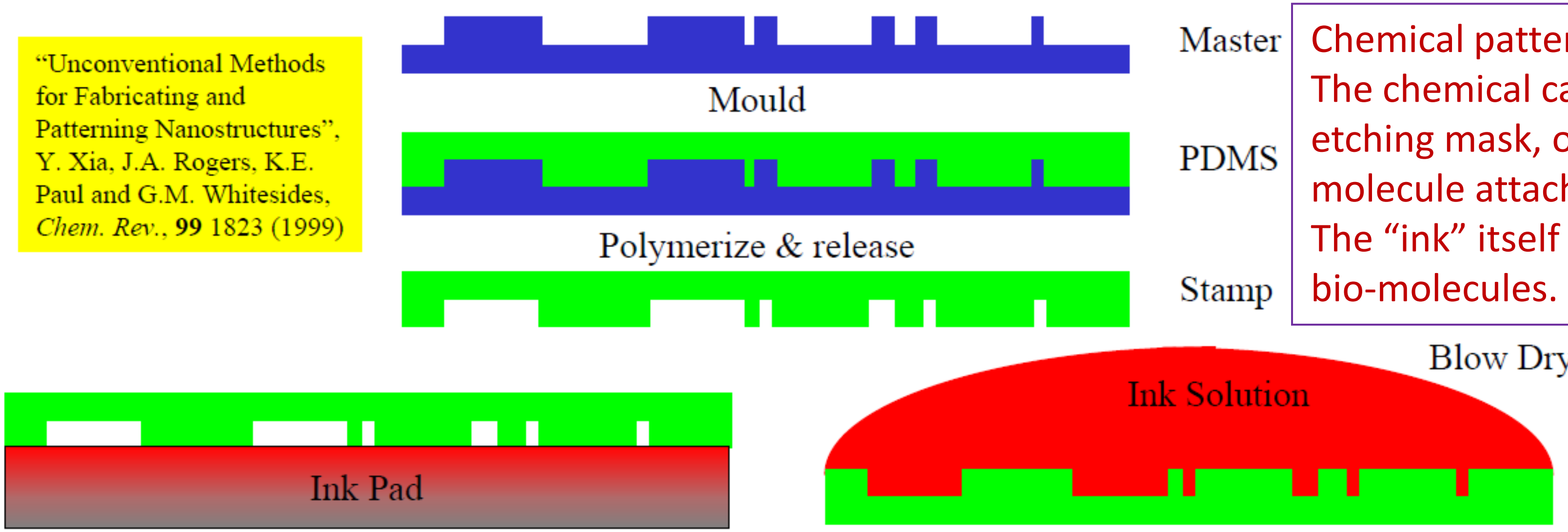


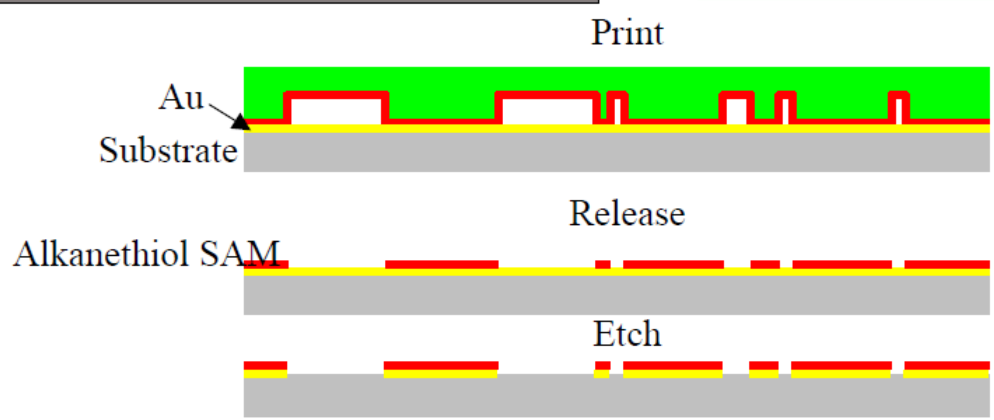
Cast PDMS pre-polymer and cure

PDMS stamp (mold) after peel off from SU-8 master

Soft-lithography I: micro-contact printing (µCP)

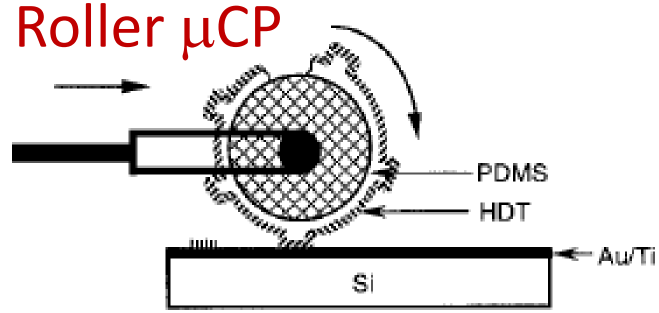
"Unconventional Methods for Fabricating and Patterning Nanostructures", Y. Xia, J.A. Rogers, K.E. Paul and G.M. Whitesides, *Chem. Rev.*, **99** 1823 (1999)





Chemical patterning.
The chemical can be used as etching mask, or for bio-molecule attachment.
The "ink" itself can also be bio-molecules.

Roller µCP



- Minimum resolution affected by diffusion of molecules, can reach sub-50nm.
- PDMS is deformable – can accommodate rough surfaces or spherical substrates.
- Self assembled mono-layers (SAM) are efficient barriers against chemical etches.
- For example, SAM monolayer can be used as etching mask to pattern Au using wet-etch.