Introduction to Micro/Nano Fabrication Techniques

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Dr. Yi-Chung Tung

Fabrication of Nanomaterials

- Top-Down Approach
  - Begin with bulk materials that are reduced into nano-scale materials
  - Ex: Traditional Machining
- Bottom-Up Approach
  - Begin with atoms and molecules that can grown into zero, one, two, and three-dimensional nanostructures
  - Ex: Chemical Synthesis
- Hybrid
  - Top-Down + Bottom-Up

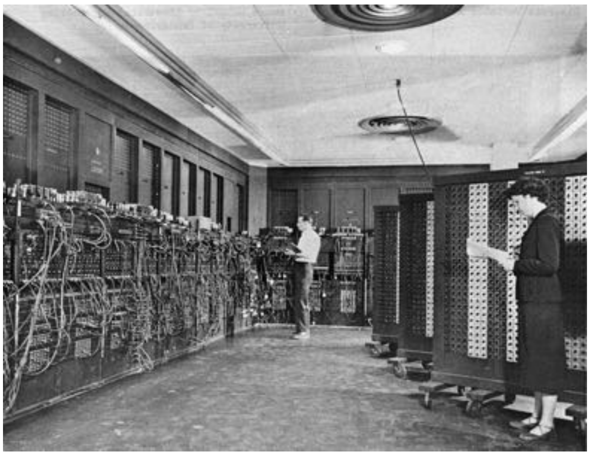
Top-Down Approach

- Mechanical energy
  - Ball milling, polishing, grinding
- Thermal
  - Annealing, evaporation, pyrolysis
- High energy
  - Arch, laser, ion milling, reactive ion etching
- Chemical
  - Chemical etching, CMP, electropolishing, anodizing
- Lithographic
  - Photo, e-beam, EUV, X-ray, μ-cp, NIL, Nanosphere
- Nature
  - Erosion, decomposition, digestion

Bottom-Up Approach

- Gas
  - Chemical vapor deposition, atomic layer deposition, MOCVD, MBE, ion implantation
- Liquid
  - Self-assembly, supermolecule, reduction, template synthesis
- Lithographic
  - Dip-pen, block co-polymer, STM writing
- Biological
  - Protein, nuclear acidcrystal formation

Building a Computer

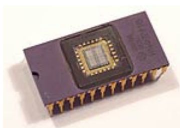


ENIAC: Electronic Numerical Integrator And Computer, 1946.

First Integrated Circuit

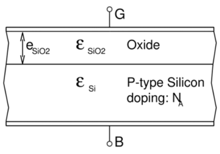
"What we didn't realize then was that the integrated circuit would reduce the cost of electronic functions by a factor of a million to one, nothing had ever done that for anything before" - Jack Kilby 2000 Nobel Prize

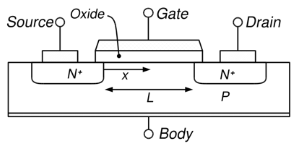
1958 Texas Instruments

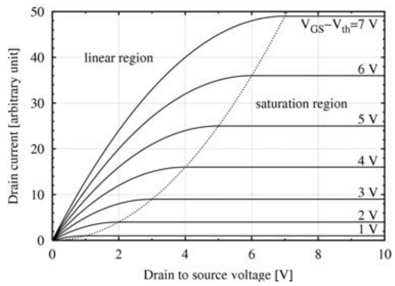


MOSFET

- Metal-Oxide-Semiconductor Field-Effect Transistor

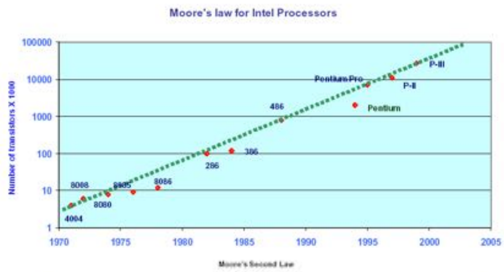


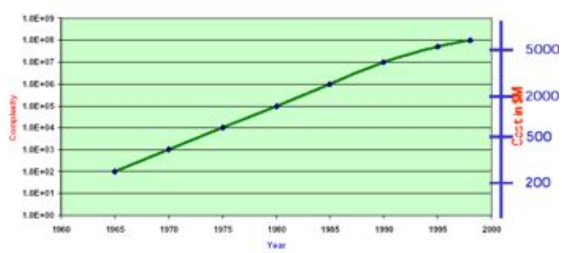




- Small Print
- Low Power Dissipation
- Batch Process
- Fast Response
- Pure Electrical Switch, No Moving Parts

Moore's Law





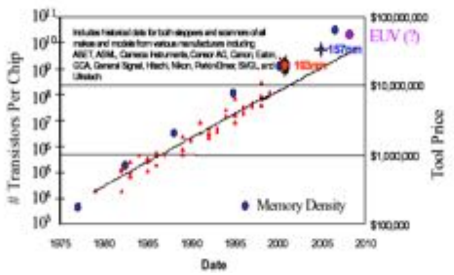
Moore's Laws

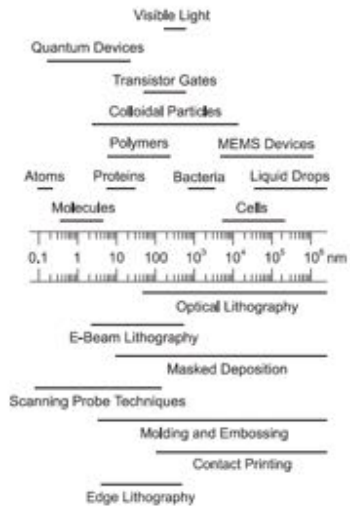
First Law: Number of components in a chip (IC) will double roughly every 18 months (1965, in *Electronics*). This has held true more or less since then.

Second Law: Facility costs increase on a semilog scale (terminology due to Eugene Meieran, Intel Fellow). Fab costs double approximately every four years.

Tool Cost

- Why does the tool cost increase so fast?
- What is the bottleneck?

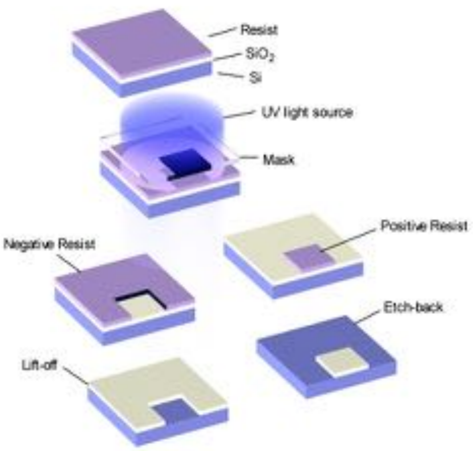




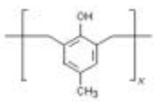
Industrial Process

- Lithography
- Deposition
- Etching
- Planization
- Packaging

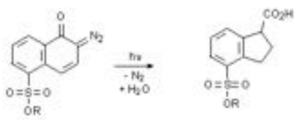
Photolithography



Photoresist

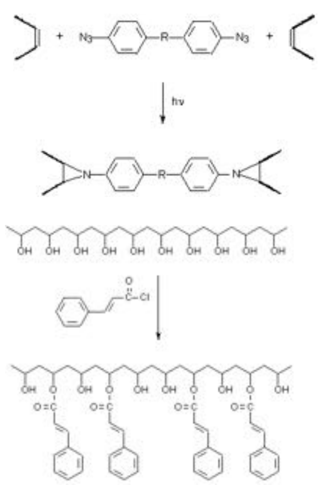


Novolak



Diazonaphthaquinone additive

Positive tone



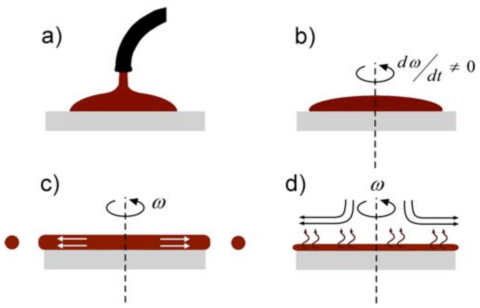
Negative tone

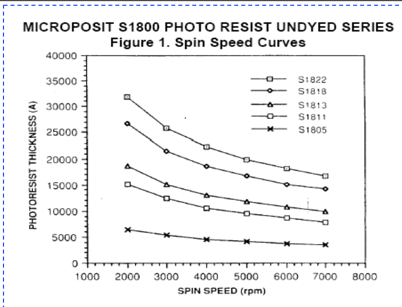
STEP I: Cleaning

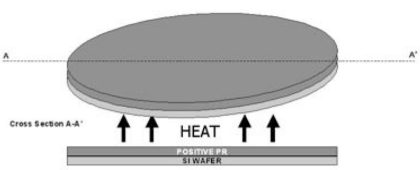
RCA Cleaning (By Radio Corporation of America in 1965)

Chemicals	Volume ratio	Procedure Time (min)	Operation Temperature	Function
Trichlorothane		5	Room T	Dissolve Organic
Acetone		5	Room T	Dissolve Organic
DI Water		5	Room T	Washing
H_2SO_4 (98%)-H_2O_2 (30%) (Piranha Solution)	3:1	10-20	~90℃	Oxide and Dissolve Organic and Metals
DI Water		5	Room T	Washing
HF(49 wt %)-H_2O	~2:100	10-20	Room T	Dissolve surface SiO_2
NH_4OH(29%)-H_2O_2(30%)-H_2O	1:1:5	10-20	~90℃	Oxide and Dissolve Metals
DI Water		5	Room T	Washing
HCl(37%)- H_2O_2(30%)-H_2O	1:1:5	10-20	~90℃	Oxide and Dissolve Metals
DI Water		5	Room T	Washing
Spin Dry (In lad – N_2 blow)				

STEP II: PR Spin Coating/Soft Bake

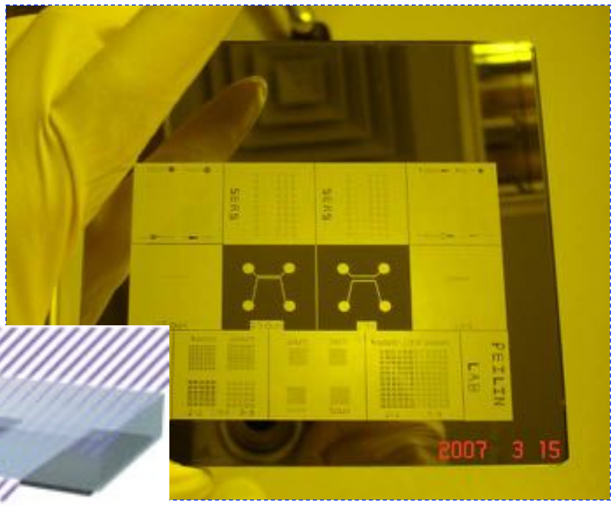


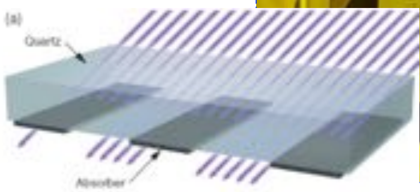




STEP III: Align and Exposure

- Mask: Quartz + Cr Patterns





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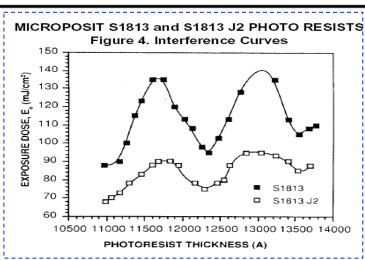
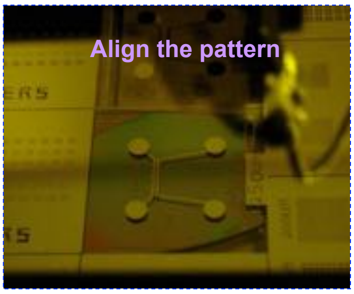
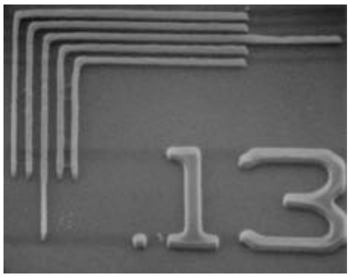
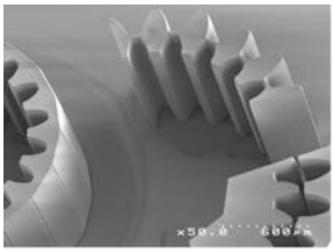


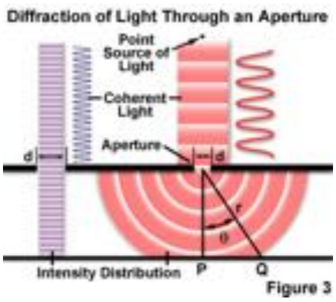


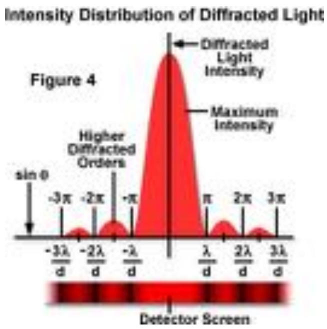
STEP IV: (PEB) and Develop





Limitation of Optical Lithography

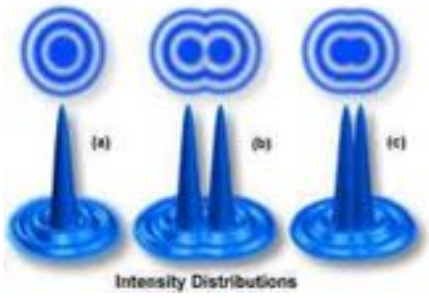




$r = 1.22 \times \lambda/(2 \times N.A.)$

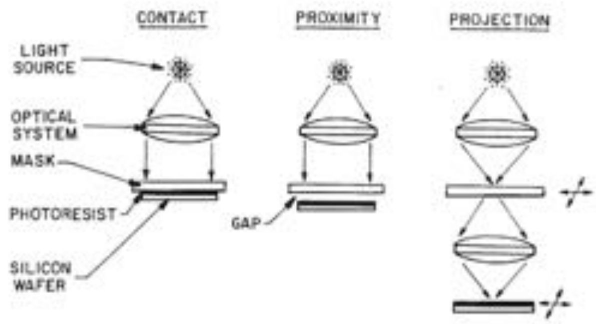
$N.A. = n \times \sin(\theta)$

Diffraction Limit



Resolution = K x λ/(N.A.)
Depth of Focus = λ/(N.A.)²
K = 0.61

Photolithogrpahy Types

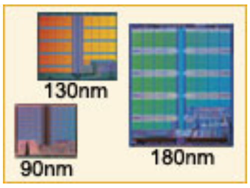


$W_{min} = k_1 \, sqrt(\lambda d)$

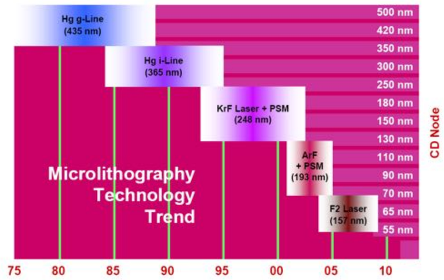
$W_{min} = k_1 \, \lambda/NA$

Photolithogrpahy Types

UV Wavelength (nm)	Wavelength Name	UV Emission Source
436	g-line	Mercury arc lamp
405	h-line	Mercury arc lamp
365	i-line	Mercury arc lamp
248	Deep UV (DUV)	Mercury arc lamp or Krypton Fluoride (KrF) excimer laser
193	Deep UV (DUV)	Argon Fluoride (ArF) excimer laser
157	Vacuum UV (VUV)	Fluorine (F_2) excimer laser



Year	Linewidth (nm)	Wavelength (nm)
1986	1,200	436
1988	800	436/365
1991	500	365
1994	350	365/248
1997	250	248
1999	180	248
2001	130	248
2003	90	248/193
2005 (fcst)	65	193
2007 (fcst)	45	193



Water Immersion Lithography

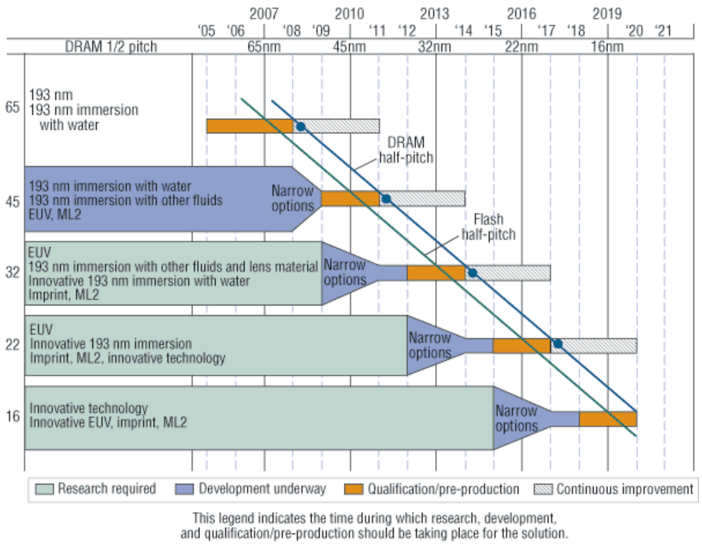
Year	Linewidth (nm)	Wavelength (nm)
1986	1200	436 g-line mercury lamp
1988	800	436/365
1991	500	365 i-line mercury lamp
1994	350	365/248
1997	250	248 KrF excimer laser
1999	180	248
2001	130	248
2003	90	248/193
2005	65	193 ArF excimer laser
2007	45	193/157

Resolution (R) = K x λ/(N.A.)
K = 0.25, NA ~1.4, λ = 193
R = 35 nm

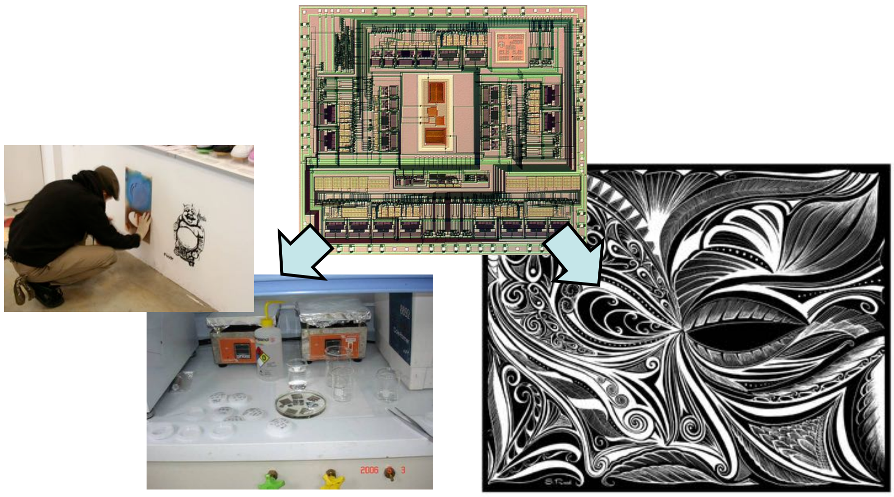
Air n= 1.0003
Water n = 1.437

The resolution is increased by a factor equal to the refractive index of the liquid. Current immersion lithography tools use highly purified water for this liquid, achieving feature sizes below 45 nanometers.

Trend of Lithography

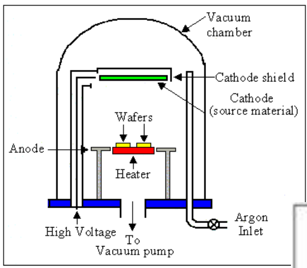


Nano/Micro Fabrication



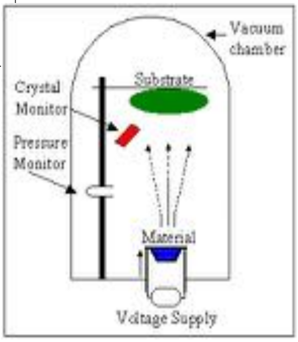
Lift-Off **Etching**

Thin Film Deposition

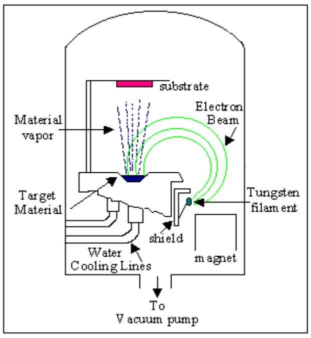


Sputter

Thermal Evaporator

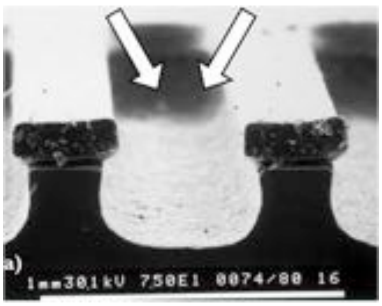


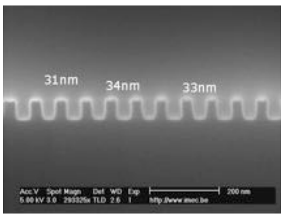
E-Beam Evaporator

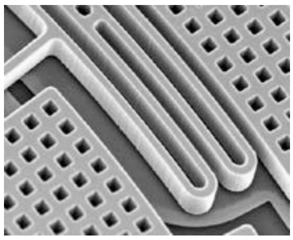


Etching (Wet and Dry)

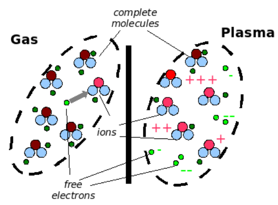
- Wet Etching: Chemical Reactions
- Dry Etching: Physical (and Chemical) Reaction

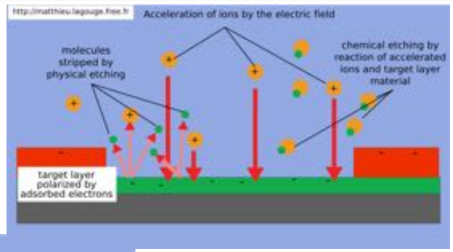


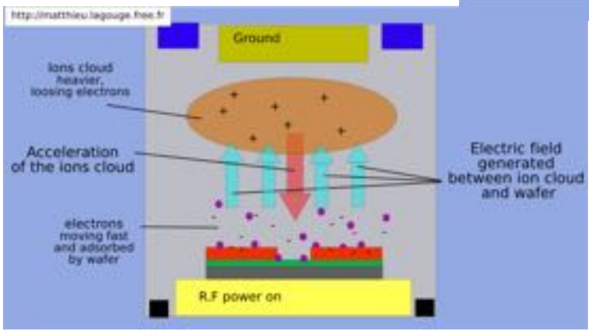


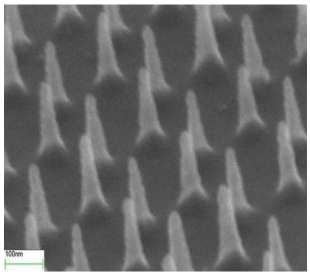


Reactive Ion Etching (RIE)









Inductively Coupled Plasma (ICP)

An ICP is different than an RIE because it uses two power supplies to generate plasma. One power source is used to generate a dense plasma (~10x more reactive species than RIE), while the second power source accelerates the ions towards the etching surface. This combination increases the anisotropy of the etched feature as compared to conventional RIE.

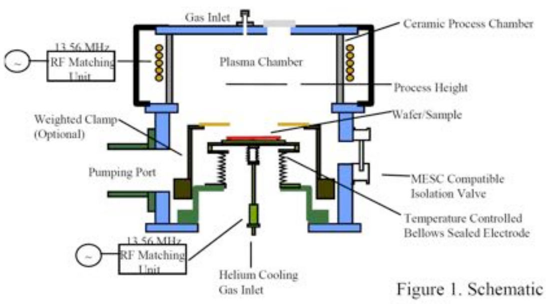
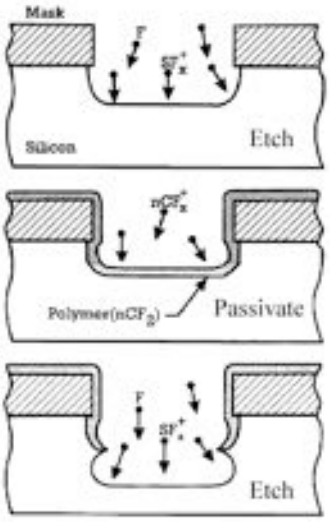
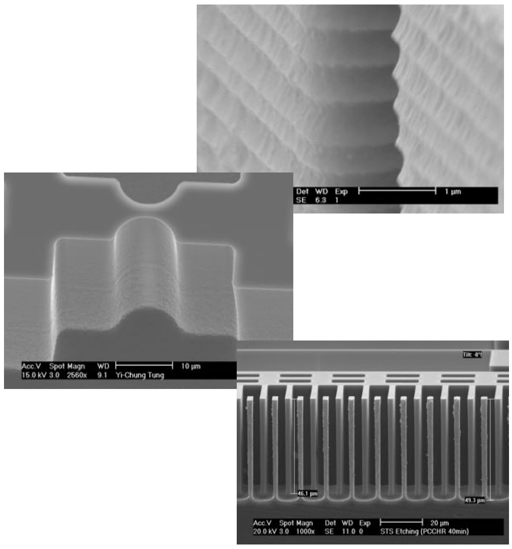


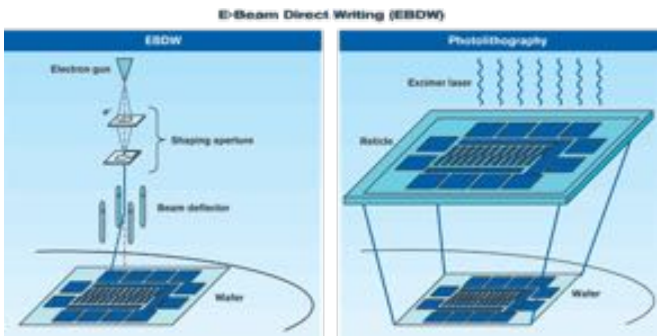
Figure 1. Schematic of STS ICP system.

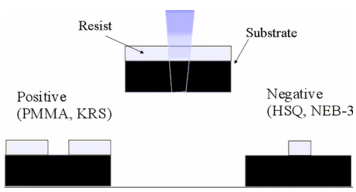
ICP and Bosch Process





E-Beam Lithography





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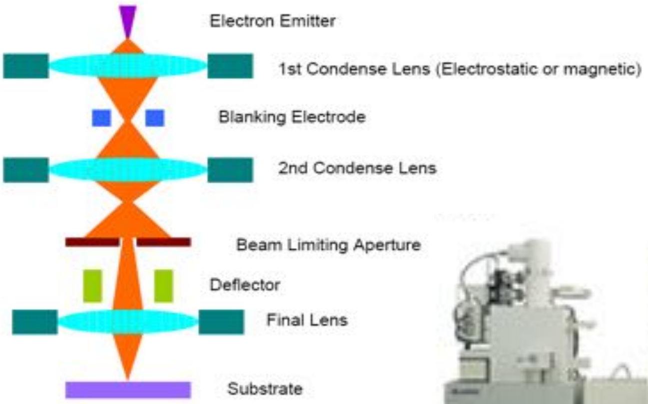

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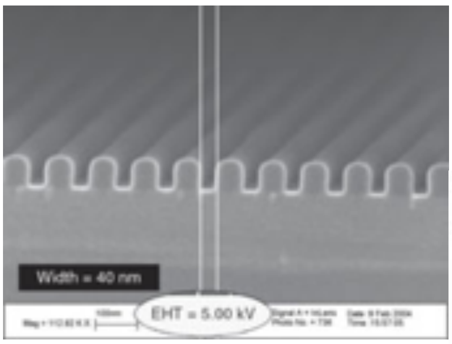
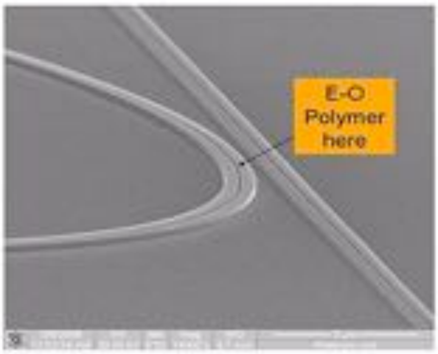
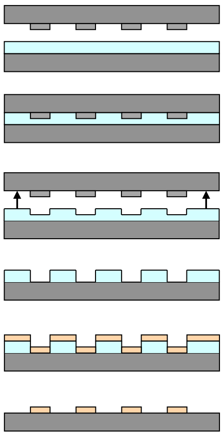
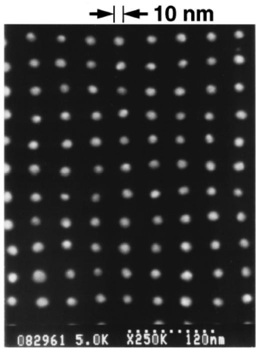




Nanoimprint Lithography (NIL)





Stephen Chou

Joseph C. Elgin Professor of Engineering
Professor of Electrical Engineering

Ph.D., Massachusetts Institute of Technology, 1986
M.A., Physics, State University of New York at Stony Brook, 1982
B.S., Physics, University of Science and Technology of China, 1978

Room: B412 Engineering Quadrangle
Phone: 609-258-4416
Email: chou@princeton.edu

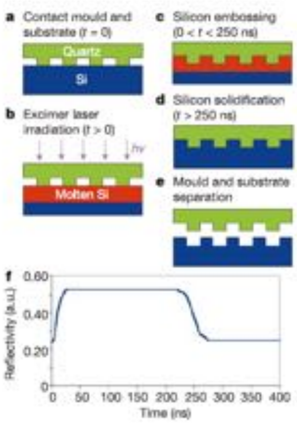
Webpage: Chou's Lab

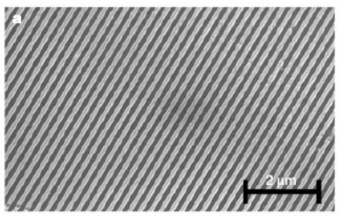
Nanoimprint Lithography (NIL)

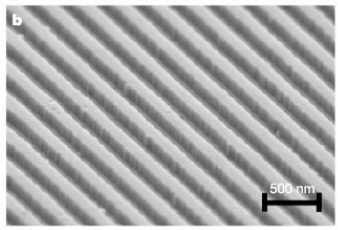
Ultrafast and direct imprint of nanostructures in silicon

NATURE | VOL 417 | 20 JUNE 2002 |

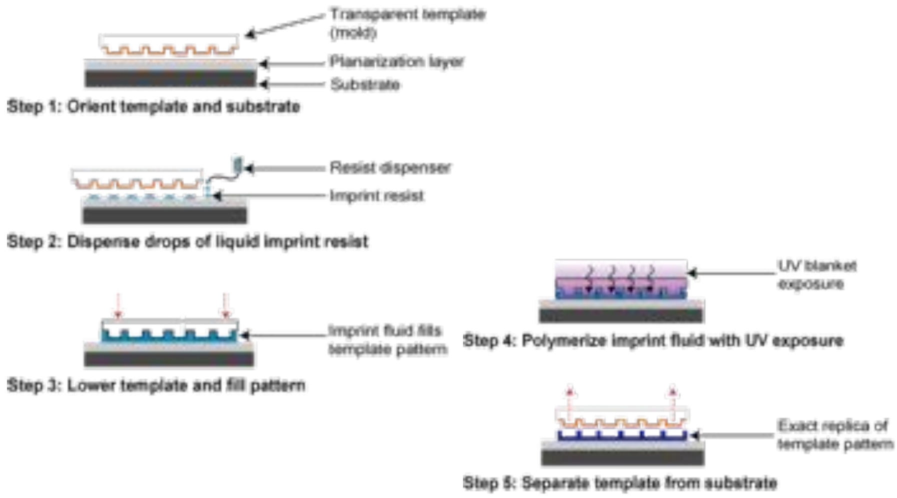
Stephen Y. Chou*, Chris Keimel & Jian Gu







Step and Flash Imprint Lithography



Nanoimprinter

NX-2000, Nanoimprintor, Nanonex

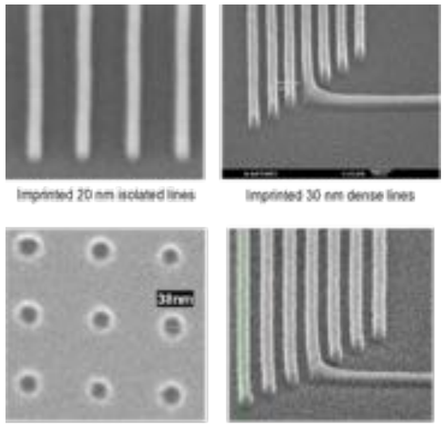
IMPRIO 100

Molecular Imprints, Inc.

- Resolution: Sub-50 nanometers, imprint template (mold) limited.
- Alignment: < 500 nm, 3σ (X, Y, and Rotation).
- Flexibility: Handles up to 8 inch wafers, including fragile substrates.
- Field size: 25 x 25 mm full active print area, 100 μm street width.

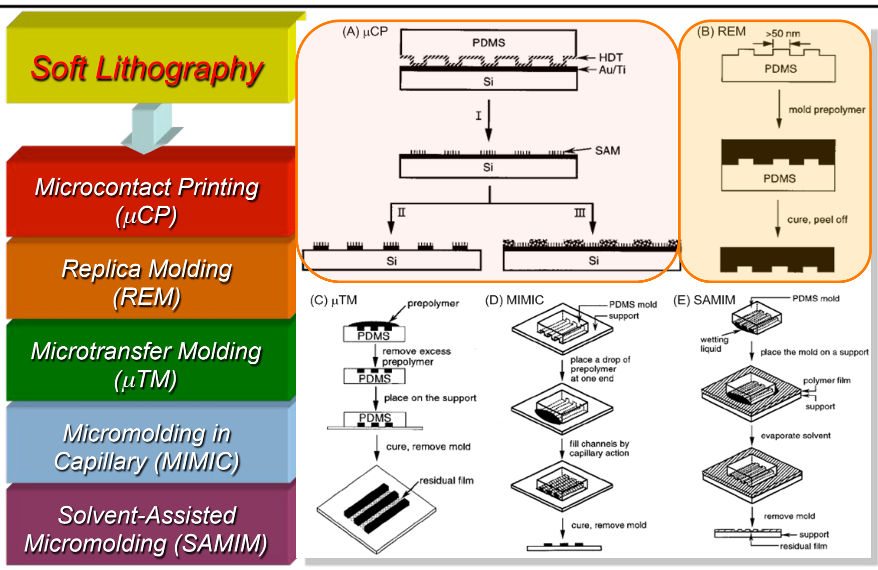
Nanoimprint Results and Challenge

- Mask Fabrication (1:1)
- Lift-off process
- Resist
- Mask Design



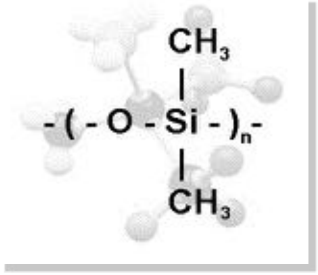
Imprinted 20 nm isolated lines
Imprinted 30 nm dense lines
Imprinted sub-40 nm contacts
Imprinted 50 nm dense lines

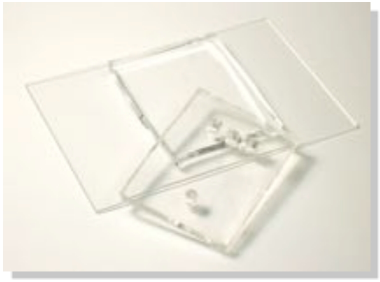
Soft Lithography



Soft Lithography - PDMS

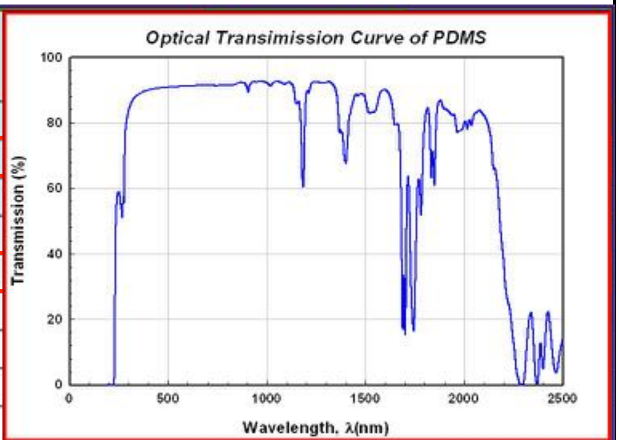
- PDMS (Polydimethylsiloxane)
  - PDMS is durable, optically transparent, and inexpensive
  - PDMS can be patterned by *Soft Lithography*





PDMS Material Properties

Density			
Young's Modulus			
Poisson's Ratio			
Tensile Strength			
Maximum Strain			
Thermal Expansion Ratio			
Thermal Conductivity			
Permittivity			
Resistivity			
Transparency (Visible Light)	Very Good	Excellent	Opaque

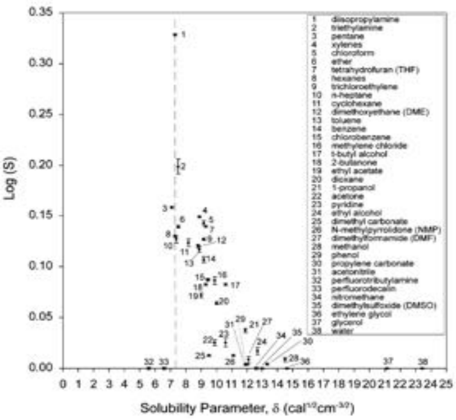


PDMS

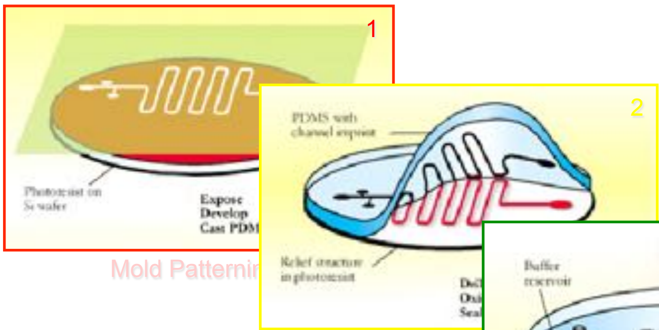
Solvent Compatibility of Poly(dimethylsiloxane)-Based Microfluidic Devices

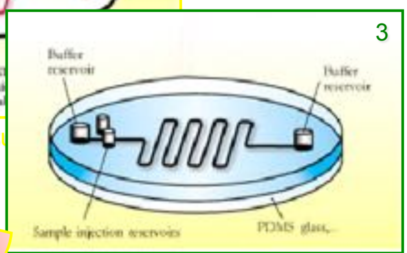
Anal. Chem. **2003**, *75*, 6544–6554

solvent	δ^a	S^b	μ (D)
perfluorotributylamine	5.6	1.00	0.0
perfluorodecalin	6.6	1.00	0.0
pentane	7.1	1.44	0.0
poly(dimethylsiloxane)	7.3	–	0.6–0.9
diisopropylamine	7.3	2.13	1.2
hexanes	7.3	1.35	0.0
n-heptane	7.4	1.34	0.0
triethylamine	7.5	1.58	0.7
ether	7.5	1.38	1.1
cyclohexane	8.2	1.33	0.0
trichloroethylene	9.2	1.34	0.9
dimethoxyethane (DME)	8.8	1.32	1.6
xylenes	8.9	1.41	0.3
toluene	8.9	1.31	0.4
ethyl acetate	9.0	1.18	1.8
benzene	9.2	1.28	0.0
chloroform	9.2	1.39	1.0
2-butanone	9.3	1.21	2.8
tetrahydrofuran (THF)	9.3	1.38	1.7
dimethyl carbonate	9.5	1.03	0.9
chlorobenzene	9.5	1.22	1.7
methylene chloride	9.9	1.22	1.6
acetone	9.9	1.06	2.9
dioxane	10.0	1.16	0.5
pyridine	10.6	1.06	2.2
N-methylpyrrolidone (NMP)	11.1	1.03	3.8
tert-butyl alcohol	10.6	1.21	1.6
acetonitrile	11.9	1.01	4.0
1-propanol	11.9	1.09	1.6
phenol	12.0	1.01	1.2
dimethylformamide (DMF)	12.1	1.02	3.8
nitromethane	12.6	1.00	3.5
ethyl alcohol	12.7	1.04	1.7
dimethyl sulfoxide (DMSO)	13.0	1.00	4.0
propylene carbonate	13.3	1.01	4.8
methanol	14.5	1.02	1.7
ethylene glycol	14.6	1.00	2.3
glycerol	21.1	1.00	2.6
water	23.4	1.00	1.9

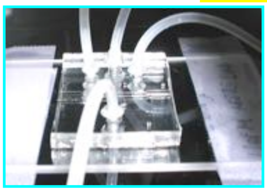


Replica Molding (REM)



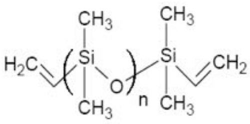


Bonding and Interconnecting

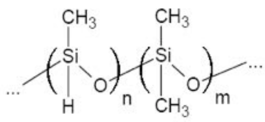


PDMS Curing and Bonding

- Curing of PDMS



1

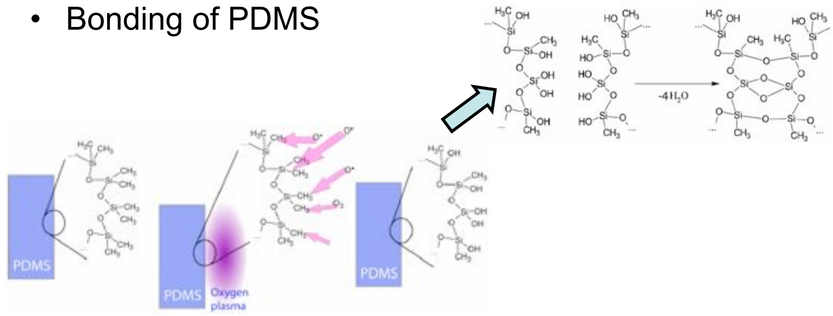


2

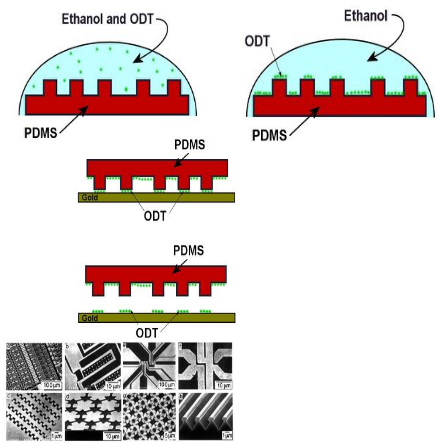
H_2PtCl_6

3

- Bonding of PDMS



Micro Contact Printing (μCP)



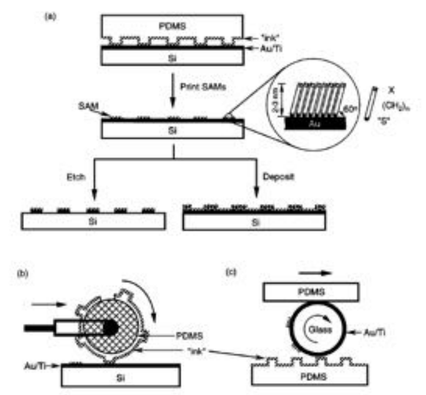
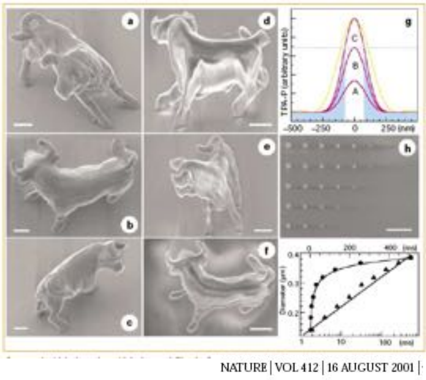


Figure 2 Schematic procedures for μCP of hexadecanethiol (HDT) on the surface of gold: (*a*) printing on a planar surface with a planar stamp (21), (*b*) printing on a planar surface over large areas with a rolling stamp (128), and (*c*) printing on a nonplanar surface with a planar stamp (174).

Others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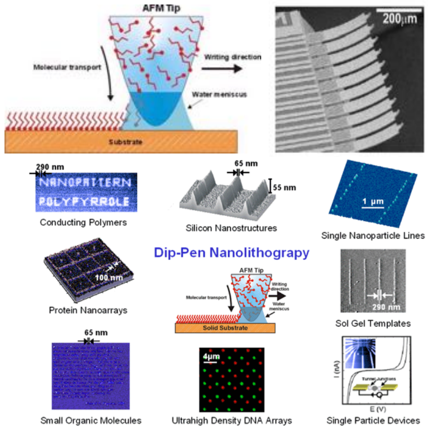
AFM Tip
Molecular transport
Writing direction
Water meniscus
Substrate
200μm
290 nm
Conducting Polymers
65 nm
55 nm
Silicon Nanostructures
1 μm
Single Nanoparticle Lines
Dip-Pen Nanolithography
100 nm
Protein Nanoarrays
Solid Substrate
290 nm
Sol Gel Templates
65 nm
Small Organic Molecules
4μm
Ultrahigh Density DNA Arrays
Single Particle Devices