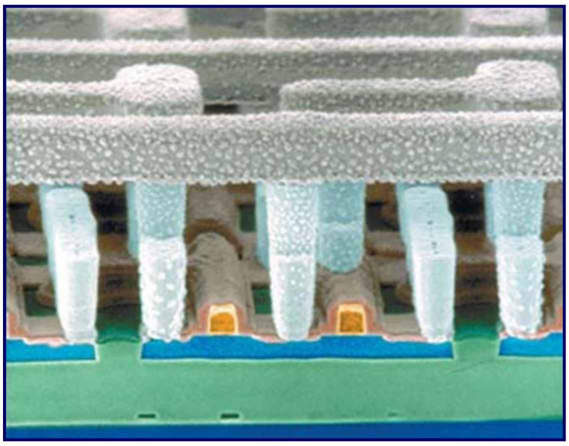
Introduction to Lithography



G. D. Hutcheson, *et al.*, *Scientific American*, **290**, 76 (2004).

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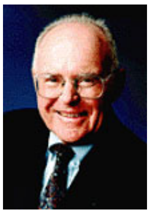
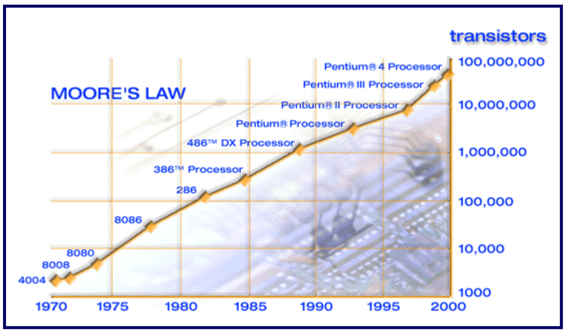
Moore's Law



Intel Co-Founder Gordon E. Moore



"Cramming More Components Onto Integrated Circuits"
Author: Gordon E. Moore
Publication: Electronics, April 19, 1965

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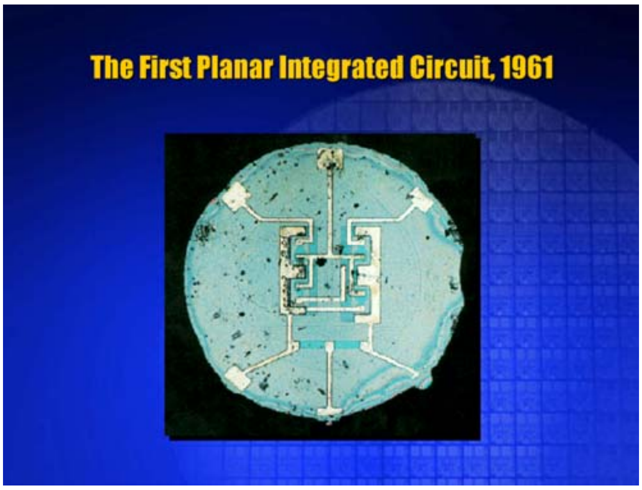

"No Exponential is Forever … but We Can Delay 'Forever',"
Gordon E. Moore, International Solid State Circuits Conference, Feb. 10, 2003.

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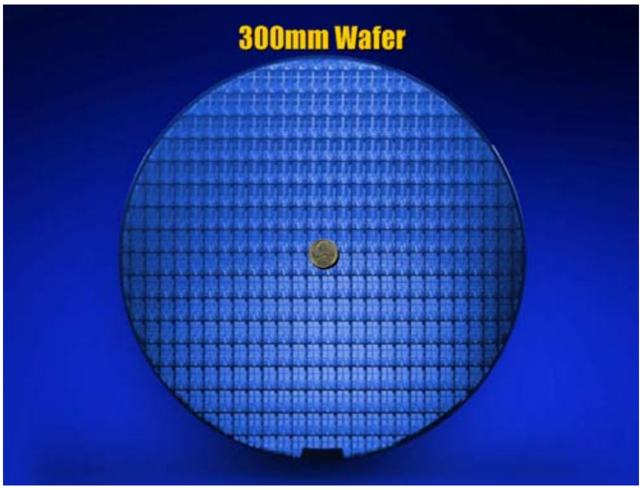

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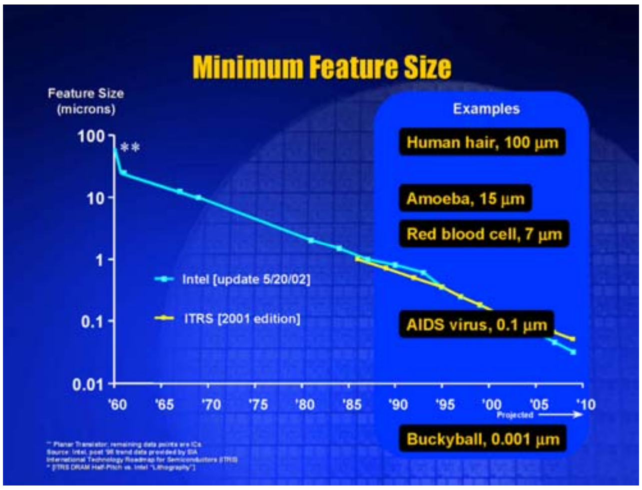

"No Exponential is Forever … but We Can Delay 'Forever',"
Gordon E. Moore, International Solid State Circuits Conference, Feb. 10, 2003.

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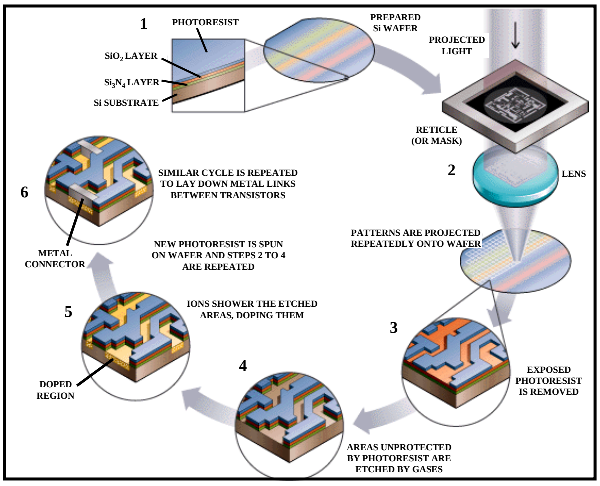
Typical Lithographic Process Flow



G. D. Hutcheson, *et al.*, *Scientific American*, **274**, 54 (1996).

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Lithography Yield

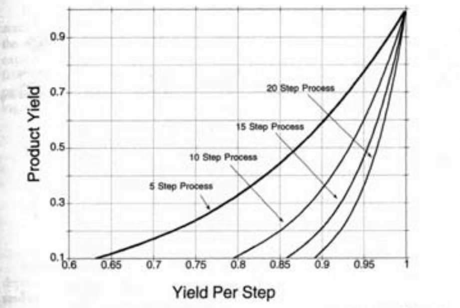

FIGURE 1. Plot of dependence of product yield on the average yield per lithography level shown for 5, 10, 15 and 20 step manufacturing processes.

NOTE: Typical fabrication facilities (fabs) have product yields > 95%
→ Lithography yield per step > 99%

Lithography is 90% of the production cost in modern day fabs

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Lithography Areal Throughput

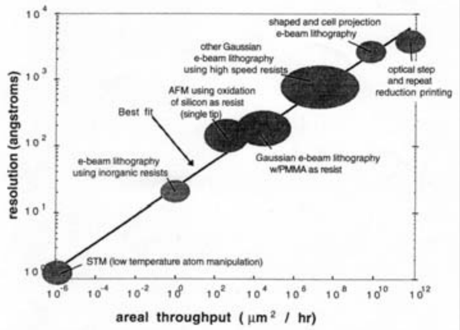

FIGURE 2. Plot showing areal throughput for 50% coverage (for example equal lines and spaces) at the plotted resolution for a wide range of lithographic methods which have been demonstrated to date. The solid line represents a phenomenological relationship between resolution and throughput given by the power law fit found in text.

Phenomenological Relationship:

Resolution (Å) ~ $23A_t^{0.2}$

(A_t = areal throughput in μm^2/hr)

This phenomenological relationship is essentially true over **18 orders of magnitude** in throughput!

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Requirements of a Lithography System

(1) Small dimensions (linewidth)
(2) Small variations in dimensions (linewidth control)
(3) Large depth of focus (tolerance of non-planar substrates and thick resists)
(4) Accurate alignment of subsequent patterns (registration)
(5) Low distortion of image and sample (high quality masks, projection systems)
(6) Low cost (high throughput)
(7) High reliability (high yield)
(8) Tolerance of contamination particles on mask and sample (clean room requirements)
(9) Uniformity over large areas (large wafers)

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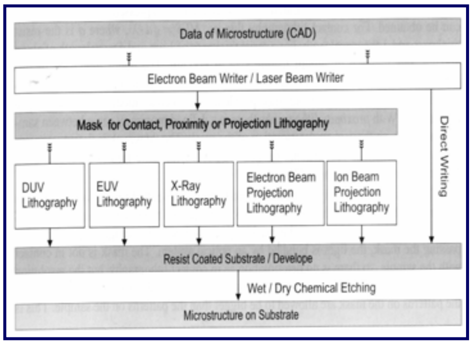
Lithography Pathways



Pathways from pattern design to pattern transfer:

(1) Can be direct (e.g., e-beam or ion beam lithography)

(2) Usually a 2 step process
 (A) Generation of mask
 (B) Transfer of its pattern to a large number of substrates

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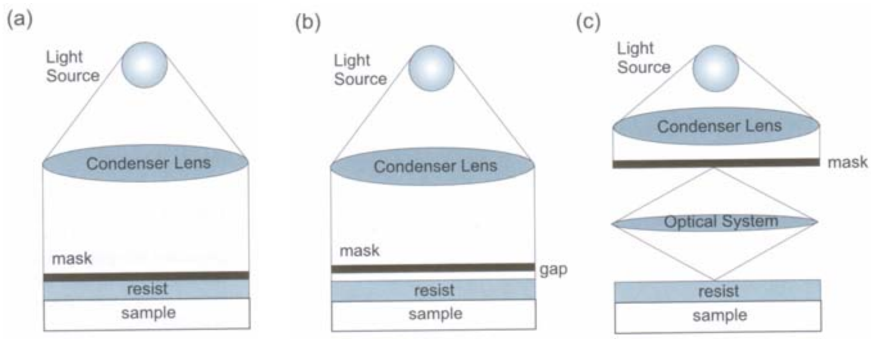
Masking Methods



Contact **Proximity** **Projection**

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Resists

Resists: (1) Positive → exposure degrades resist (dark field mask)
(2) Negative → exposure hardens resist (light field mask)

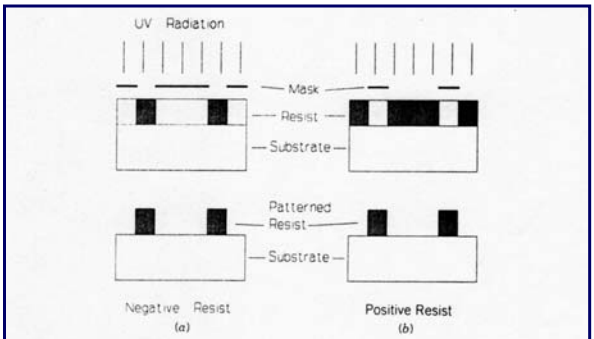

Fig. 10.2 Schematic of pattern transfer: (*a*) Negative resist and (*b*) positive resist.

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Requirements of a Resist

(1) High sensitivity → less exposure time → lower cost

(2) Contrast (only brightly illuminated areas are affected)

(3) Adhesion to substrate

(4) Etch resistance (enables subsequent processing)

(5) Resist profile control (flexibility for lift-off)

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Optical Lithography Process

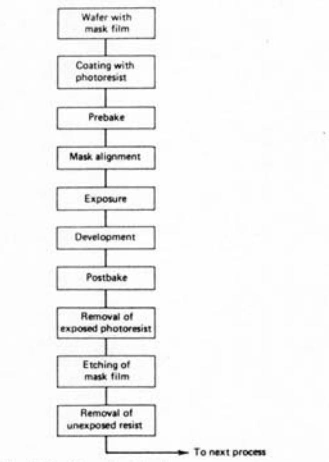

Fig. 10.5 Flow chart for the pattern transfer process.

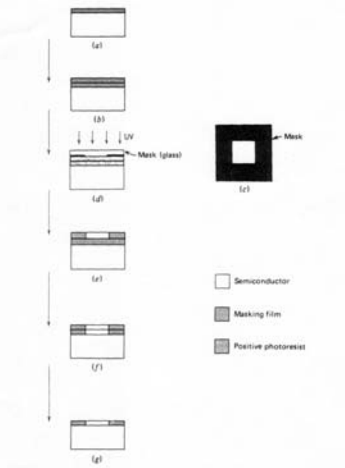

Fig. 10.6 Steps in opening a window in a masking film, using positive photoresist.

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Etching versus Lift-off

Etching: (a) Develop resist on top of deposited layer
(b) Underlying material is removed by etching through openings in the mask

Lift-off: (a) Deposit material on top of developed resist
(b) Material is lifted-off when resist is removed

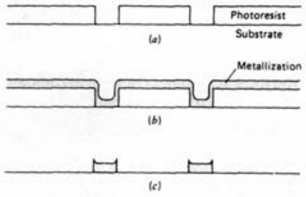

Fig. 10.9 The lift-off process.

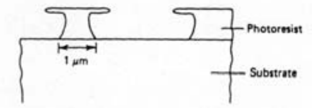

Fig. 10.10 Profile of photoresist using a chlorobenzene modification step prior to development. Adapted from Hatzakis et al [29].

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Limitations of Optical Lithography

Minimum feature size = $k\lambda$/NA

where k = proportionality factor
(typically 0.5 for diffraction limited systems)
λ = wavelength
NA = numerical aperture = sin α
(2α = acceptance angle of lens at point of focus)
→ measure of light gathering power of lens

However, depth of focus = $\lambda/(\text{NA})^2$
→ important because wafers are not flat

Increasing NA is not the answer → reduce λ to reduce feature size

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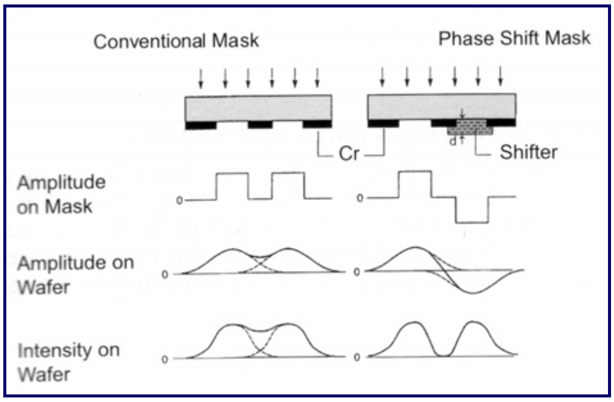
Deep Ultra-Violet Lithography

Deep UV → Excimer Laser Sources:

XeF → 351 nm
XeCl → 308 nm
KrF → 248 nm
} Fused silica / quartz optics

ArF → 193 nm
F_2 → 157 nm
} CaF optics → difficult to grind and polish due to hygroscopic (water-absorbing) properties

Phase Shifting Masks



→ Minimizes diffraction effects but complicates mask making

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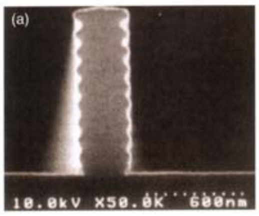
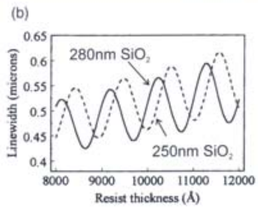
Influence of Substrate Reflections



Interference between incident and reflected photon beams can lead to a standing wave pattern in the resist.



Reflections can also occur at buried interfaces, thus leading to a dependence of linewidth on buried layer thicknesses.

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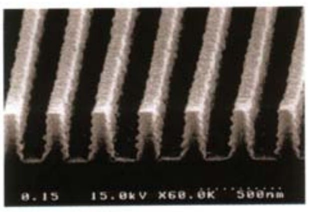
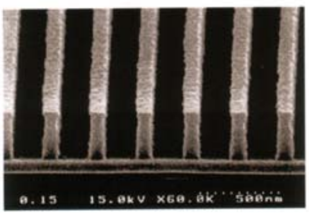
Effect of Anti-Reflective Coatings



Without Anti-Reflective Coating



With Anti-Reflective Coating

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Extreme Ultra-violet Lithography

(a.k.a., soft x-ray lithography)

- Developed at Sandia National Laboratory in 1996
- EUV source based on a plasma created when a laser is focused on a beam of Xe gas clusters expanding at supersonic speeds
- $\lambda \sim 10$ nm

NOTE: At short λ, optical materials are highly absorptive

→ Reflective optics (e.g., Bragg reflectors)
→ Thin, defect-free masks

e.g., at $\lambda = 13$ nm, reflector consists of 40 layer pairs of Mo and Si with 7 nm periodicity per layer pair

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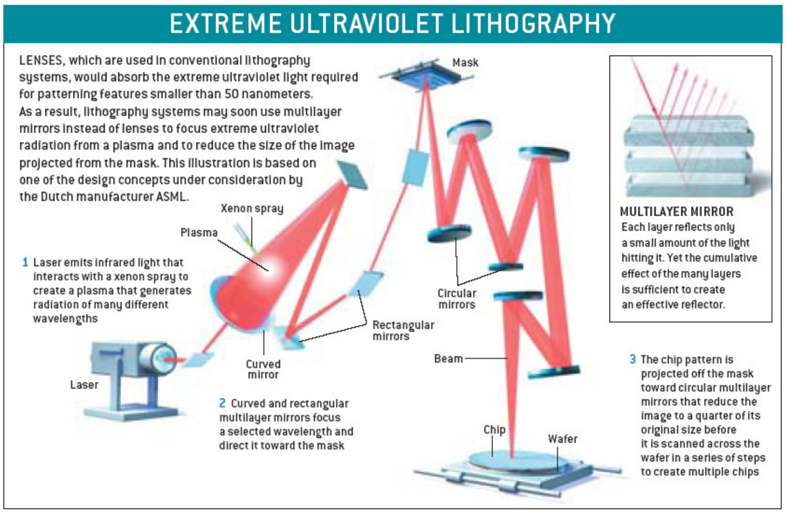
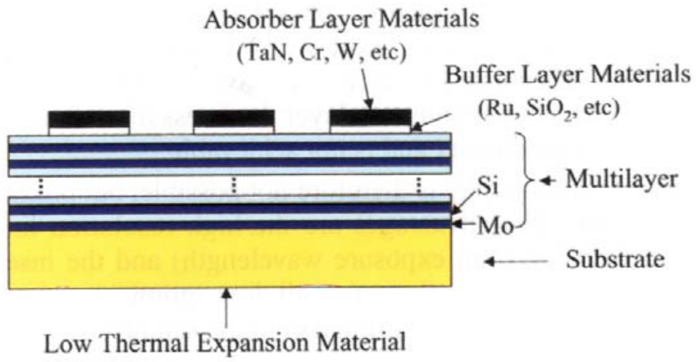


G. D. Hutcheson, *et al.*, *Scientific American*, **290**, 76 (2004).

Typical EUV Mask



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Depth of focus is less of an issue at short wavelengths
→ high aspect ratio resist profiles are possible with EUV

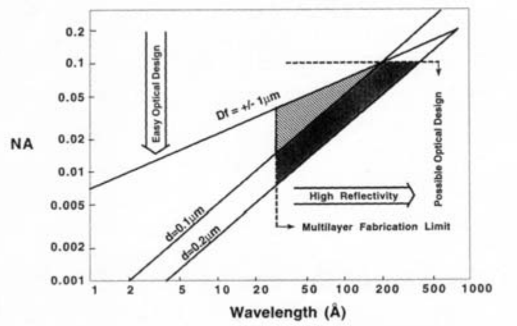

FIGURE 16. Sets of numerical aperture and EUV wavelengths capable of meeting the diffraction limited resolution and depth of focus requirements of a projection camera design. The shaded regions correspond to a bound of ± 1 μm of DOF and two different resolutions, $d = 0.2$ and $d = 0.1$ μm[70].

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Example of resist patterned with EUV lithography:

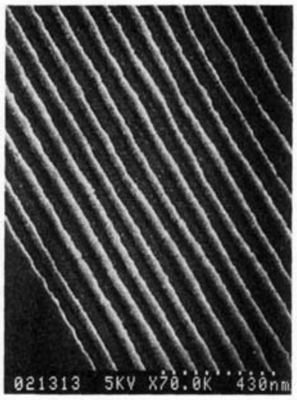

FIGURE 17. A 50 nm line and space pattern in PMMA resist, patterned by reduction EUV lithography[71].

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X-Ray Lithography

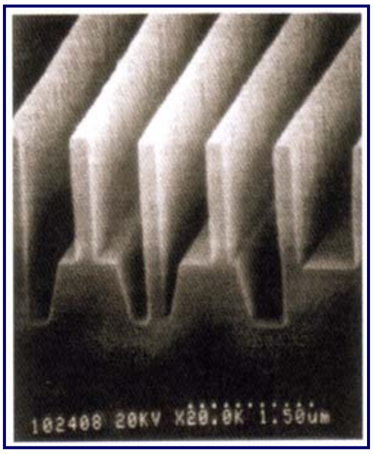
- λ = 1 nm BUT resolution = $k(\lambda g)^{1/2}$
  where g = size of gap between mask and substrate
  (tends to be 5 – 40 μm in production)

- Therefore, resolution = 0.07 – 0.2 μm for λ = 1 nm

- However, when contact printing is done in research environments, 30 nm resolution is achievable

- High aspect ratios are achieved in developed resists

Example of resist patterned with x-ray lithography:



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Established Advantages of X-Ray Lithography

(1) Large depth of focus

(2) Excellent resist profiles (pillars of resist)

(3) Large process latitude

(4) Linewidth independent of substrate topography or type

(5) Relatively immune to low atomic weight contaminants

Remaining Disadvantages of X-Ray Lithography

(1) 1X mask technology (gold on 1 – 2 μm thick silicon)
→ Defects, aspect ratio, bending, and heating are problems
(2) Source cost and/or complexity
(3) Alignment/registration is nontrivial

To become a commercial success, x-ray lithography needs:

(A) A mask → distortion free, inspectable, repairable
(B) A resist → presently acceptable but could be improved
(C) An alignment/registration system
(D) An x-ray source → acceptable cost and throughput

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Ion Beam Lithography

- Typically, liquid metal (e.g., gallium) ions are used
- Ion projection lithography developed in the late 1970's
- Advanced lithography group → consortium of industry, government, and universities
- ALG-1000 → 20 μm by 20 μm fields at 3X reduction using 150 keV hydrogen ions → 0.1 μm resolution

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Advantages of Ion Beam Lithography

(1) Less long range scattering than electrons

(2) Ion beams stay near initial trajectory
→ no dose adjustment for different patterns or substrates

(3) Can directly write metal lines (focused ion beam)
→ suitable for mask repair

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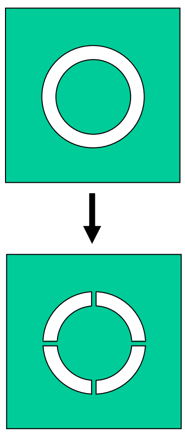
Disadvantages of Ion Beam Lithography

(1) Ions interact strongly with target causing:
- (A) Ion mixing
- (B) Amorphizing crystals
- (C) Altered optical properties
- (D) Implanted dopants
- (E) Sputter etching

(2) Ions are highly absorbed (typically within 10 nm)
→ Stencil type masks
→ The center of a ring falls out unless sub-resolution supports are used



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Electron Beam Lithography

- Very popular in research environments
- Used for mask making commercially
- $\lambda = h/(2mE)^{1/2} \rightarrow \lambda = 7.7$ pm @ 25 keV
- Typically, EBL is direct write → serial (slow) process
- Projection EBL systems have been developed
  → e.g., SCALPEL

(SCALPEL = Scattering with Angular Limitation Projection Electron-beam Lithography)

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Advantages of Electron Beam Lithography

(1) High resolution → down to 5 nm
(2) Useful design tool → direct write allows for quick pattern changes (no masks are needed)

Disadvantages of Electron Beam Lithography

(1) Cost (up to $6 – 10 million for hardware)
(2) Direct write has low throughput → slow and expensive

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Projection Electron Beam Lithography

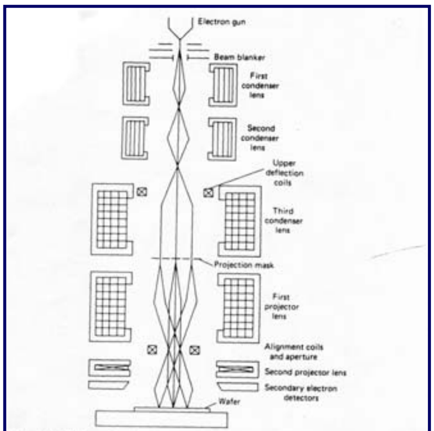

Fig. 10.16 Schematic of a demagnifying electron projection printing system. From Thornton [13]. Reprinted with permission from *Advances in Electronics and Electron Physics*.

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"Moore's Law" for Lithography Cost

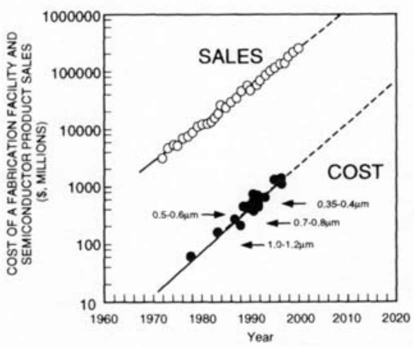

FIGURE 3. A compilation of estimates of the required capital investment for a large semiconductor fabrication line taken from the SEMATECH[165] and the estimated world-wide semiconductor electronics (IC) sales taken from DataQuest, Makimoto[10] and Bois[11]. The year for introduction of a particular technology, denoted by the design rule, e.g. 0.35 μm, is plotted versus millions of U.S. dollars.

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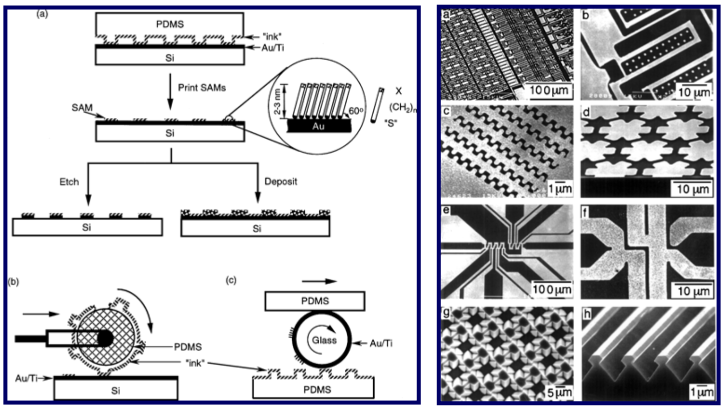
Microcontact Printing



- Use a stamp to transfer "ink" to surface.
- Can be rolled onto curved surfaces.

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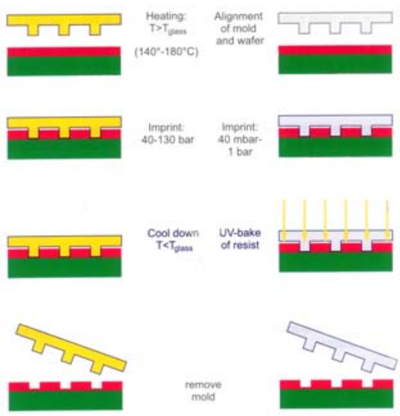
Nanoimprint Lithography

Hot embossing



UV curing

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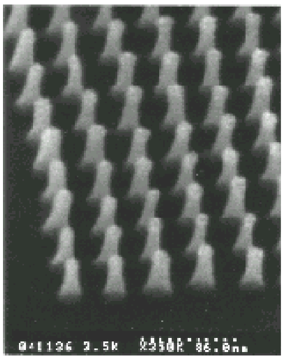
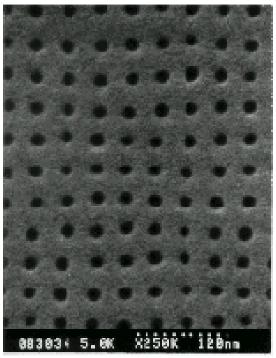
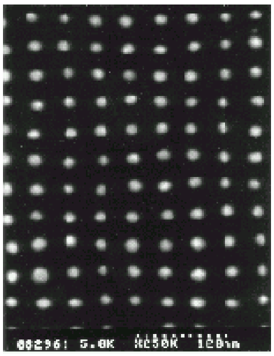
Nanoimprint Lithography Patterns



~20 nm pillars



~20 nm holes



~20 nm dots

P. R. Krauss, *et al.*, *Appl. Phys. Lett.*, **71**, 3174 (1997).

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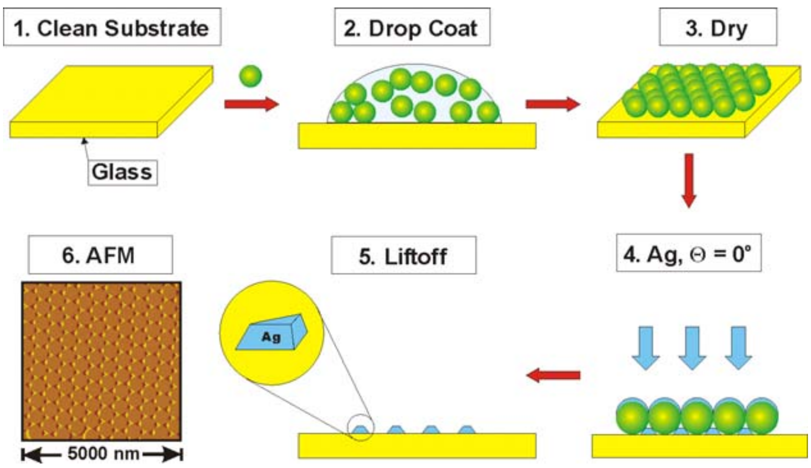
Nanosphere Lithography



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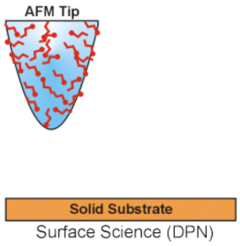
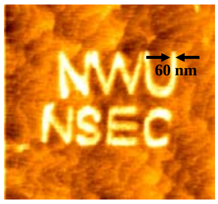
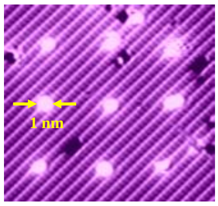
Other Lithographic Approaches

- Scanning Probe Lithographies
  - Dip-pen Nanolithography
  - Field Induced Oxidation
  - Feedback Controlled Lithography





FIO



FCL

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