Nanomaterials

Lecture 3: Advanced Lithography

Deep Ultra-Violet Lithography

Deep UV → Excimer Laser Sources:

XeF → 351 nm

XeCl → 308 nm

KrF → 248 nm

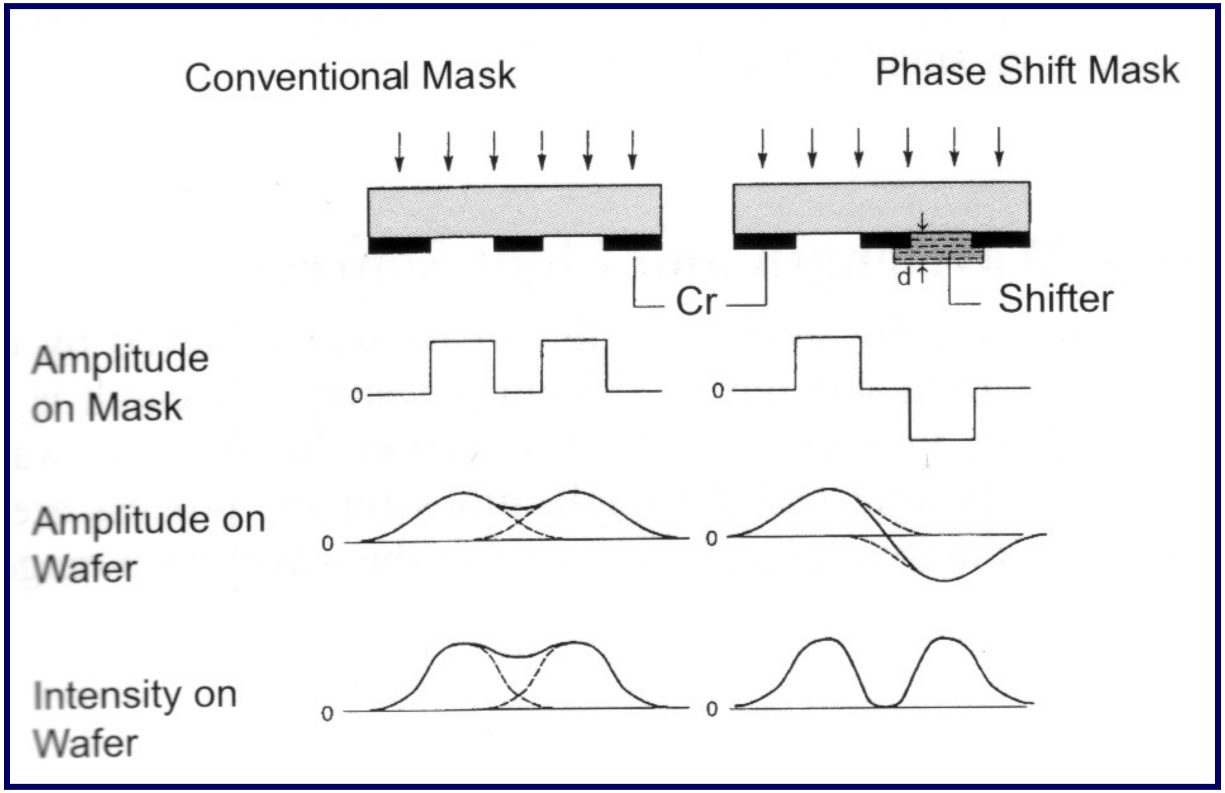
} Fused silica / quartz optics

ArF → 193 nm

F_2 → 157 nm

} CaF optics → difficult to grind and polish due to hygroscopic (water-absorbing) properties

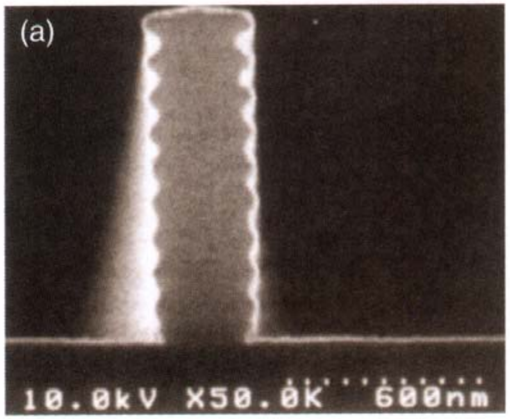
Phase Shifting Masks

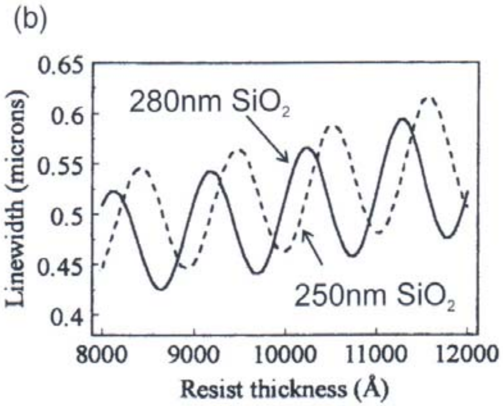


→ Minimizes diffraction effects but complicates mask making

R. Waser (ed.), *Nanoelectronics and Information Technology*, Chapter 9

Influence of Substrate Reflections



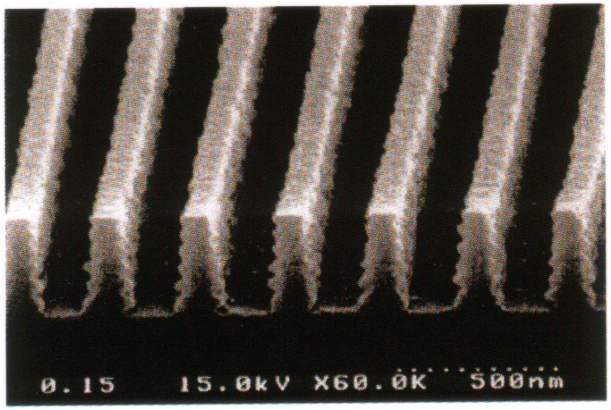


Interference between incident and reflected photon beams can lead to a standing wave pattern in the resist.

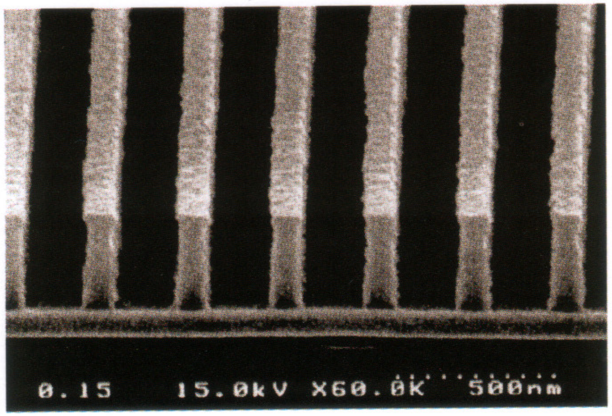
Reflections can also occur at buried interfaces, thus leading to a dependence of linewidth on buried layer thicknesses.

R. Waser (ed.), *Nanoelectronics and Information Technology*, Chapter 9

Effect of Anti-Reflective Coatings



Without Anti-Reflective Coating



With Anti-Reflective Coating

R. Waser (ed.), *Nanoelectronics and Information Technology*, Chapter 9

Extreme Ultra-violet Lithography

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

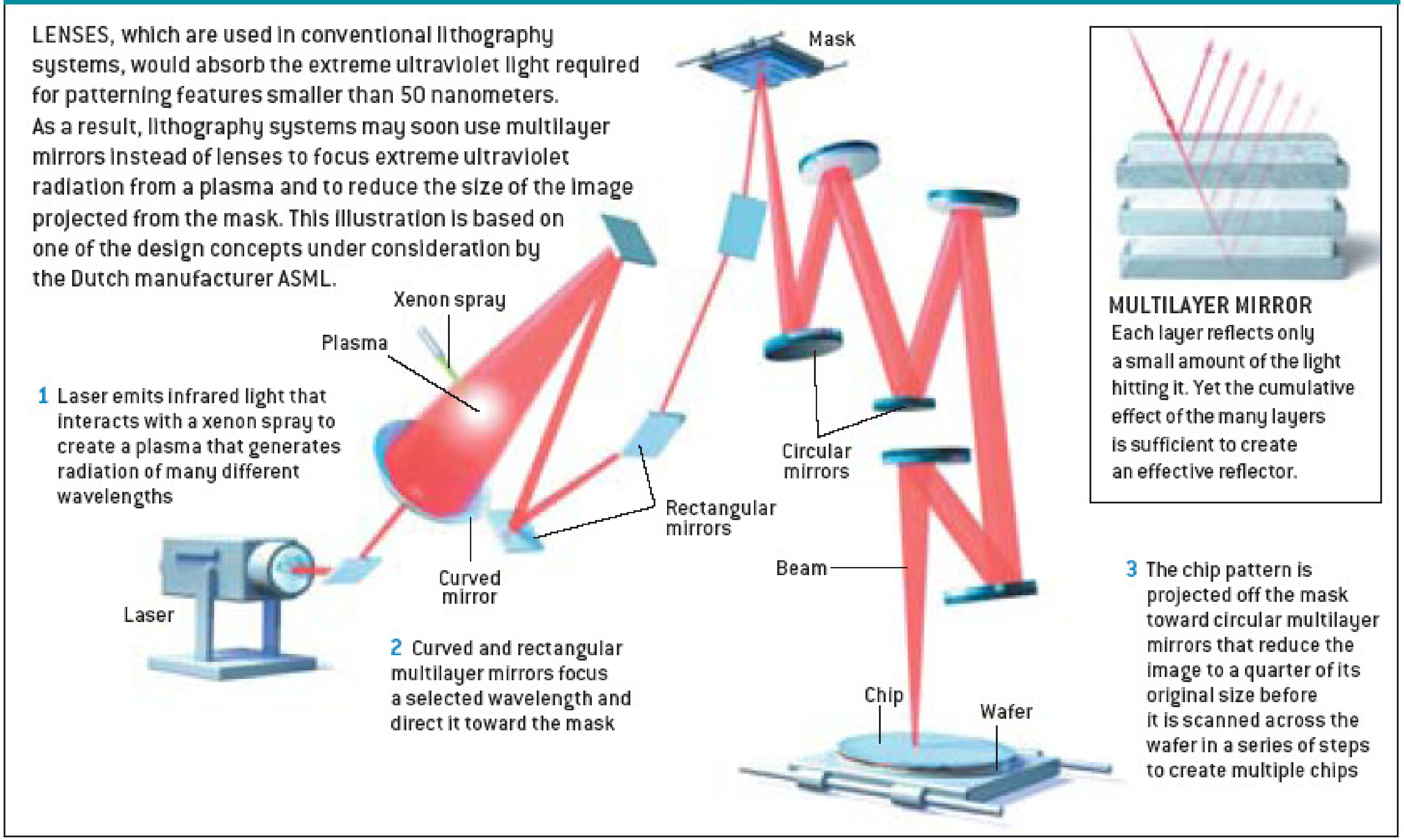
• Developed at Sandia National Laboratory in 1996
• EUV source based on a plasma created when a laser is focused on a beam of Xe gas clusters expanding at supersonic speeds
• $\lambda \sim 10$ nm

<u>NOTE</u>: At short λ, optical materials are highly absorptive

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

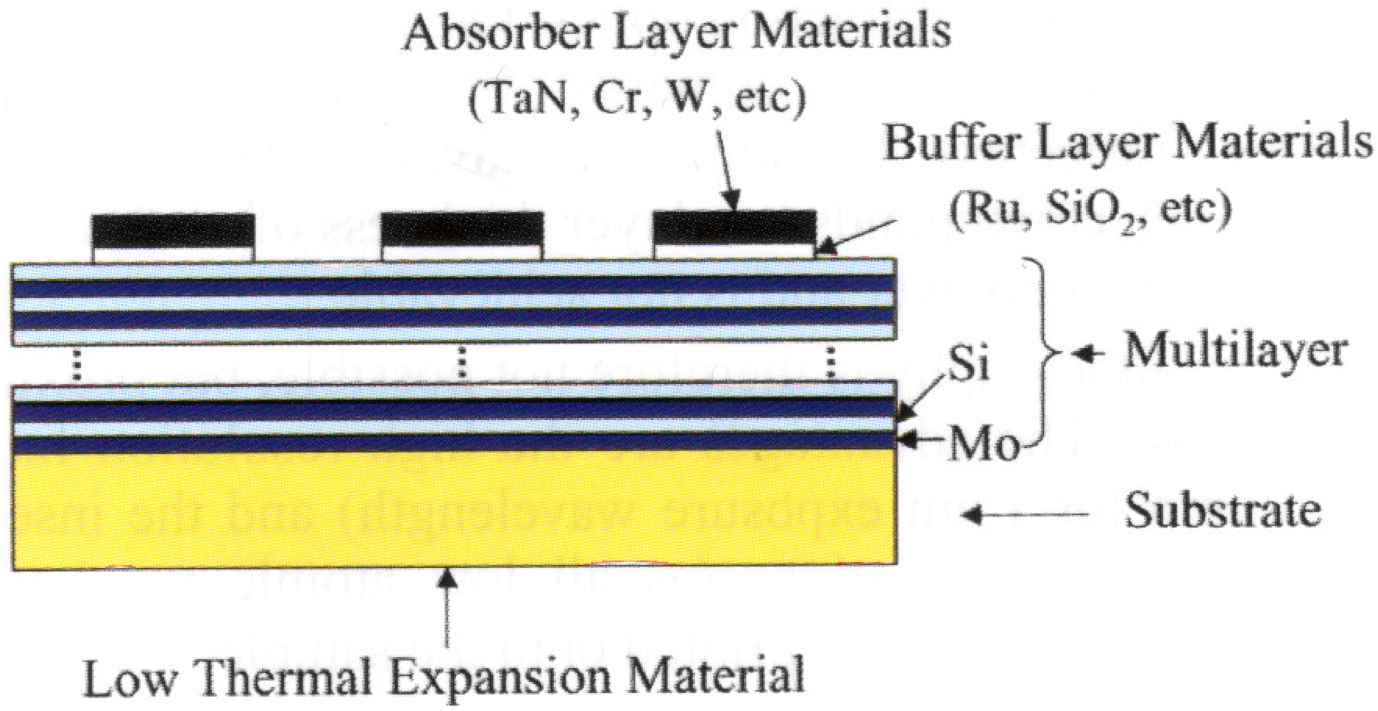
e.g., at $\lambda = 13$ nm, reflector consists of 40 layer pairs of Mo and Si with 7 nm periodicity per layer pair

EXTREME ULTRAVIOLET LITHOGRAPHY



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

Typical EUV Mask



R. Waser (ed.), *Nanoelectronics and Information Technology*, Chapter 9

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

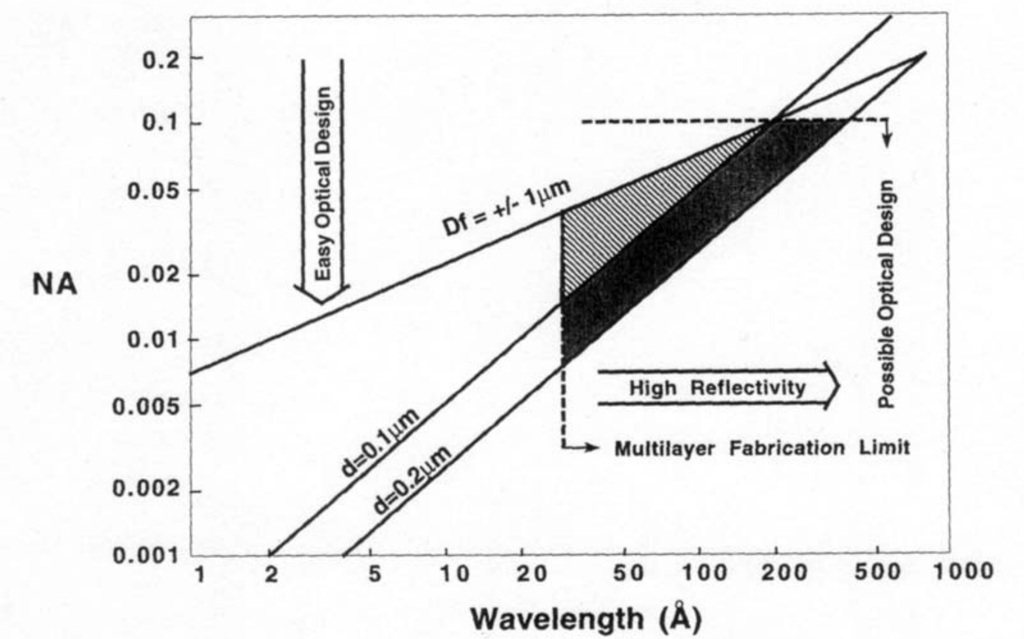


FIGURE 16. Sets of numerical aperture and EUV wavelengths capable of meeting the diffraction limited resolution and depth of focus requirements of a projection camera design. The shaded regions correspond to a bound of ± 1 µm of DOF and two different resolutions, $d = 0.2$ and $d = 0.1$ µm[70].

G. Timp, *Nanotechnology*, Chapter 4

Example of resist patterned with EUV lithography:

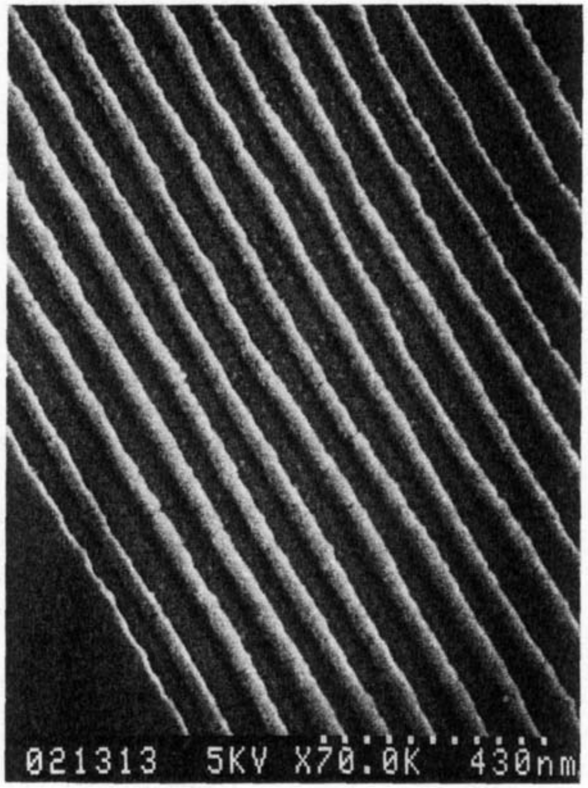


FIGURE 17. A 50 nm line and space pattern in PMMA resist, patterned by reduction EUV lithography[71].

G. Timp, *Nanotechnology*, Chapter 4

X-Ray Lithography

- λ = 1 nm BUT resolution = $k(\lambda g)^{1/2}$

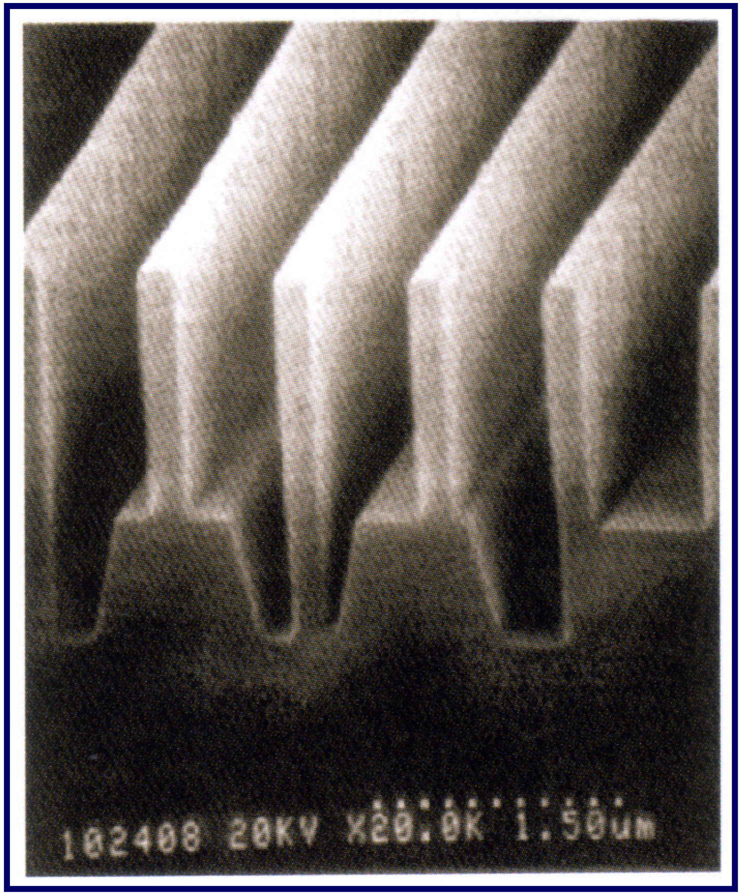
  where g = size of gap between mask and substrate
  (tends to be 5 – 40 μm in production)

- 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

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

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

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

Electron Beam Lithography

- Very popular in research environments
- Used for mask making commercially
- $\lambda = h/(2mE)^{1/2}$ → $\lambda = 7.7$ 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)

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

Projection Electron Beam Lithography

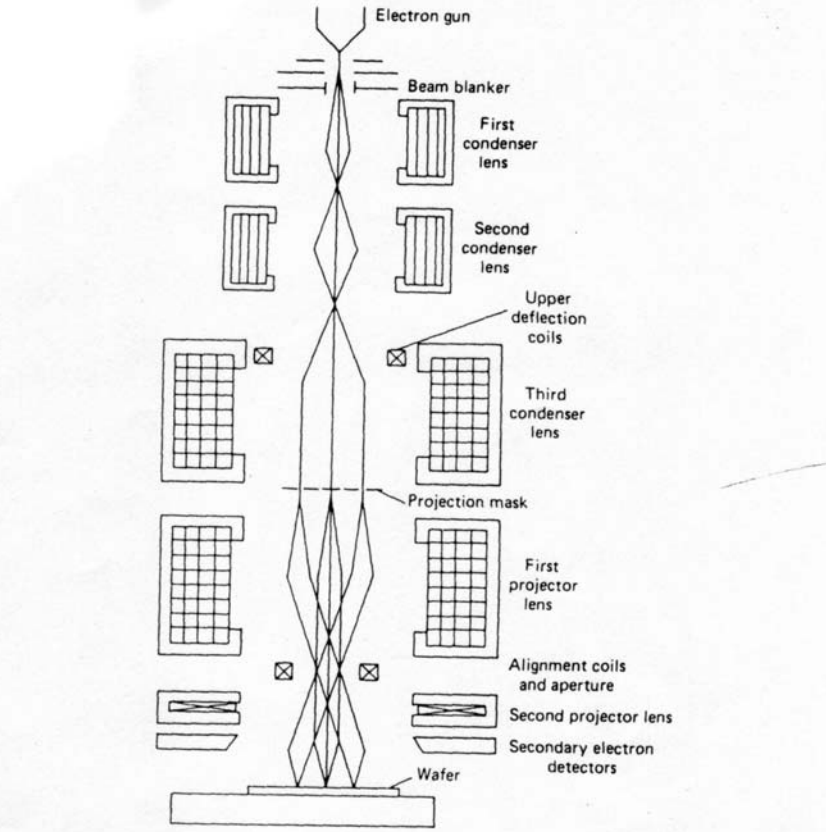
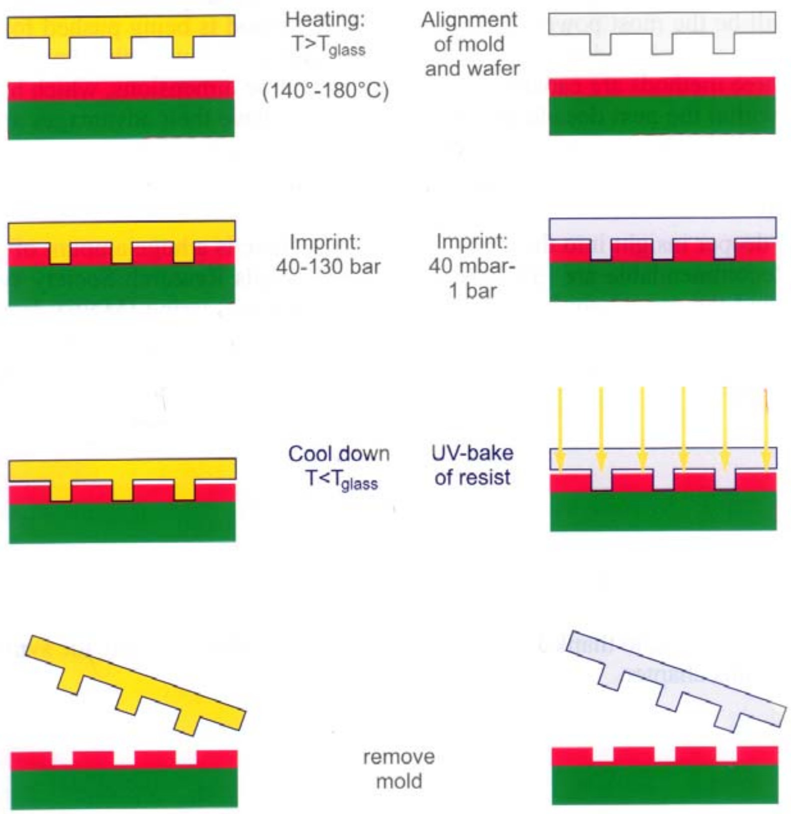


Fig. 10.16 Schematic of a demagnifying electron projection printing system. From Thornton [13]. Reprinted with permission from *Advances in Electronics and Electron Physics*.

Nanoimprint Lithography

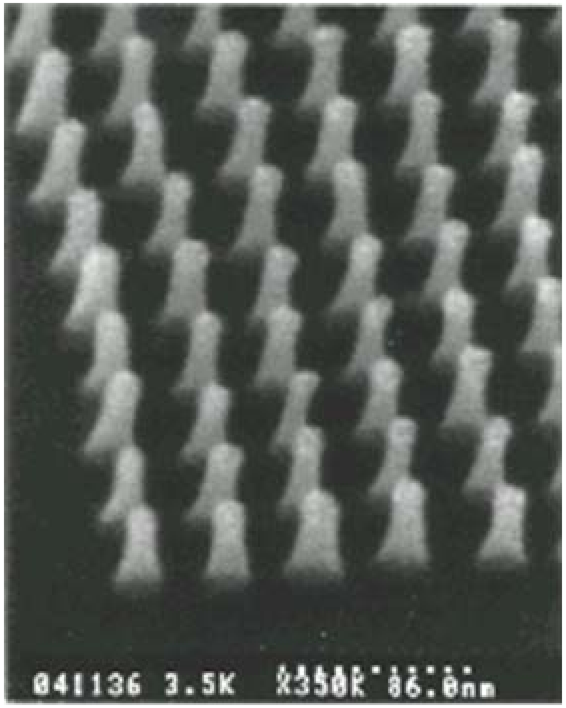
Hot embossing

UV curing

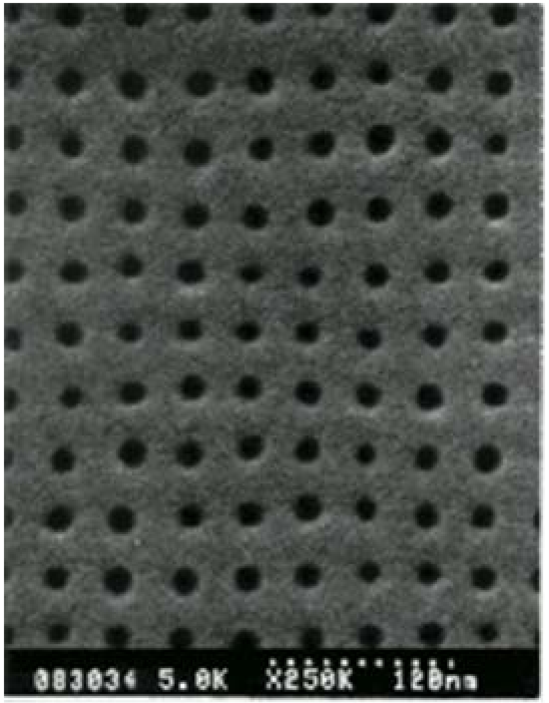


R. Waser (ed.), *Nanoelectronics and Information Technology*, Chapter 9

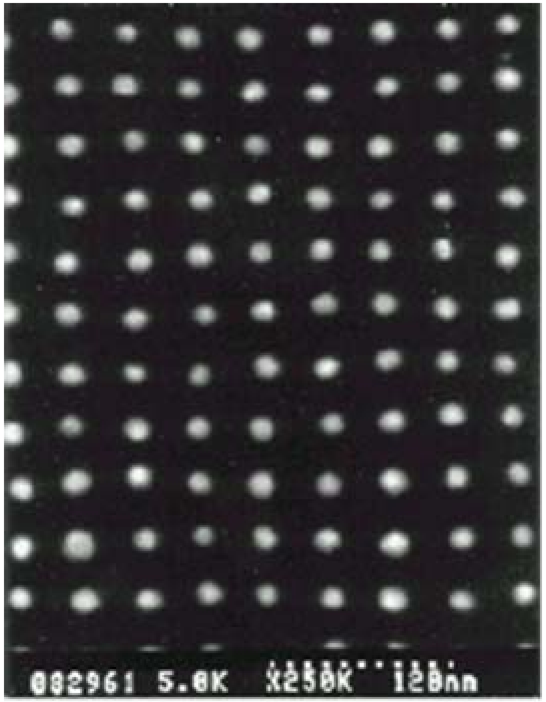
Nanoimprint Lithography Patterns



~20 nm pillars



~20 nm holes

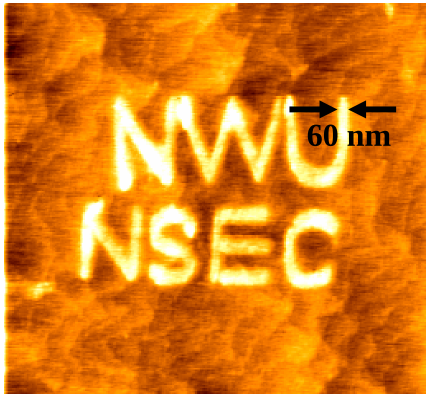


~20 nm dots

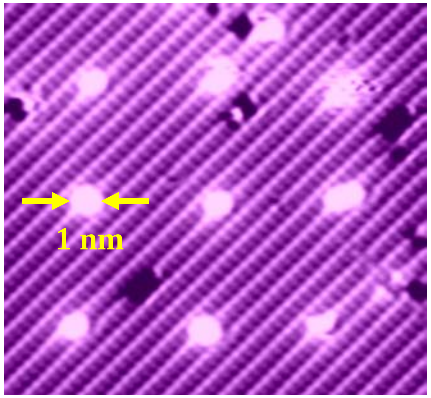
P. R. Krauss, *et al.*, *Appl. Phys. Lett.*, **71**, 3174 (1997).

Other Lithographic Approaches

- Microcontact Printing
- Nanosphere Lithography
- Scanning Probe Lithographies
  - Dip-pen Nanolithography
  - Field Induced Oxidation
  - Feedback Controlled Lithography
- We will revisit these approaches later in the course



FIO



FCL