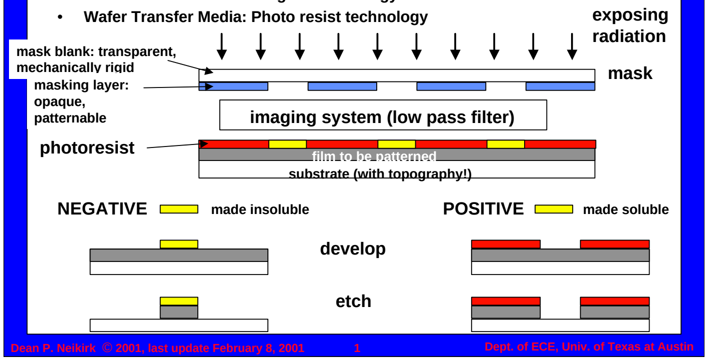
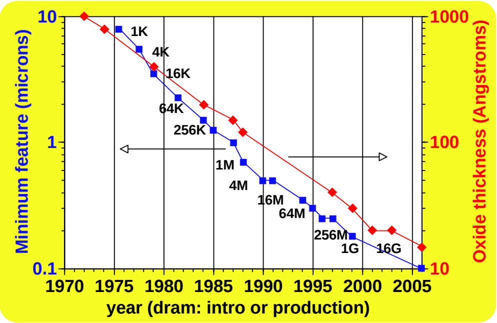
Microlithography

- Geometry Trends
- Master Patterns: Mask technology
- Pattern Transfer: Mask Aligner technology
- Wafer Transfer Media: Photo resist technology



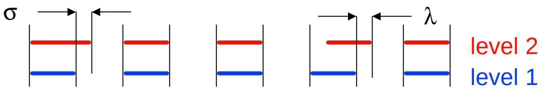
Minimum feature sizes (DRAMS)

- trend lines for feature size



Overlay errors between two patterns

- goal: align two "identical" patterns one on top of the other



- what can go wrong??
- λ: pure registration error
- σ : distortion error
  - overlay error: sum of all errors
    - really a statistical quantity
- rule of thumb: total overlay error not more than 1/3 to 1/5 of minimum feature size

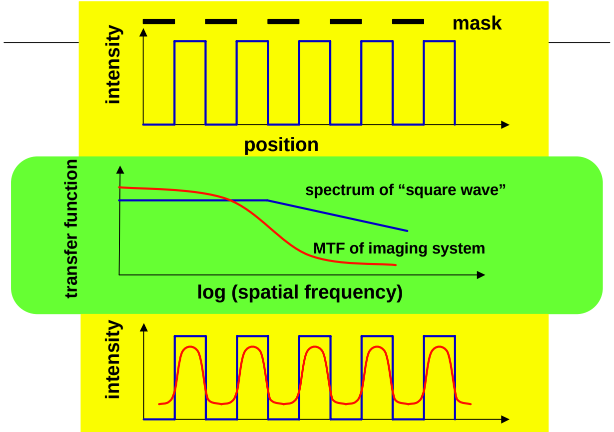
---

Image characteristics

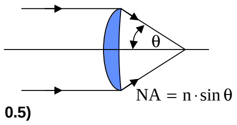
- contrast
  - intensity based: scalar quantity
    - "incoherent" imaging
  - electric field based: magnitude AND phase
    - interference effects should be included in "coherent" imaging system
- spatial variations in image
  - measure of how "fast" image varies
    - line pairs per unit distance is "digital" analogy
      - test pattern made up of periodic clear/opaque bars with sharp edges
    - frequency domain analogy: spatial frequency
      - test pattern is sinusoidal variation in optical transparency

---

Modulation transfer function (MTF)



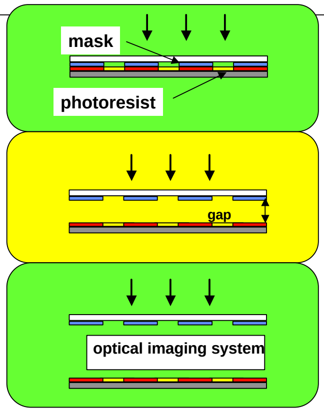
Resolution in imaging systems



- diffraction limits passband of system
  - minimum geometry $\approx k\lambda/\ NA$
    - k ~ 0.5 to 1, typically ~0.8
    - λ: exposure wavelength
    - NA: numerical aperature (typically NA = 0.5)
      - related to quality and "size" (entrance/exit pupil) of imaging system
- main difficulties
  - need high NA, low aberrations, short wavelength but:
    - depth of focus ~ $\lambda / 2(NA)^2$
  - restricted set of transparent materials for λ = 350nm
  - very difficult to get large field size <u>and</u> high NA

Basic imaging techniques

- contact
- proximity
- imaging

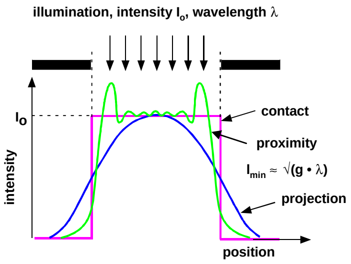


Resolution of Imaging Systems: Spatial Low Pass Filters

- contact
  - “shadow” formation, “no” diffraction
- proximity
  - some diffraction, “sharp” filter cut-off, flat response in passband

$$l_{\min} \approx \frac{3}{2}\sqrt{gap \cdot \lambda}$$

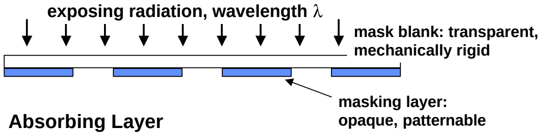
- imaging: low pass filter, “smooth” decrease in passband



Exposure radiation / wavelength choices

- want short wavelength to get small $l_{\min}$
- electromagnetic radiation
  - “optical”
    - near UV: high pressure mercury arc lamp
      - g-line: 436 nm
      - i-line: 365 nm
    - mid UV: xenon arc lamps
      - 290-350 nm
    - deep UV: excimer laser
      - 200-290 nm
        - XeCl: 308 nm
        - KrF: 248 nm
        - F_2: 157 nm
  - x-ray: synchrotron, plasma
    - 0.4- 5 nm
- particles: very short de Broglie wavelength (λ = h/mv)
  - electron beam (~50eV electron ➨ λ ≈ 1.5A)
  - ion beam

Basic Mask Structure



- Absorbing Layer
  - optical, UV wavelengths
    - photographic emulsion
    - thin metal films
      - chrome, white and black, iron oxide, silicon
  - x-ray wavelengths
    - “thick,” high Z metals: gold
- Blanks
  - optical, UV wavelengths: glass
    - soda-lime, borosilicate, quartz
  - x-ray: thin dielectric
    - boron nitride

Blanks: problem areas

- surface flatness
  - gravitational sag
    - hold mask vertically rather than horizontally
- optical transparency
  - for wavelengths < ~350nm: quartz
    - for wavelengths < ~200nm can have significant absorption
- thermal expansion
  - for 100 mm separation, 1°C ΔT
    - soda-lime: 0.9 µm
    - fused silica (quartz): 0.05 µm
    - silicon: 0.2 µm
  - traceable temperature control is essential

Mask pattern generation

- e-beam pattern generator
  - can expose very small features
    - slow, sequential exposure of pattern
    - ok for mask generation
- absorbing layer : problem areas
  - thin compared to feature width for ease of etching
    - more difficult as dimensions shrink,
    - x-ray exposure requires ~micron thick metal layer: hard to make small!
  - defect density
    - yield formula

$$Y_{single\ level} = \frac{1}{1 + D_o A} \qquad Y_{N\ levels} = \left(\frac{1}{1 + D_o A}\right)^N$$

- D_o: # of fatal defects/unit area
- A: die area
- mask must be “perfect” so “repair” is essential
  - laser etch / deposition

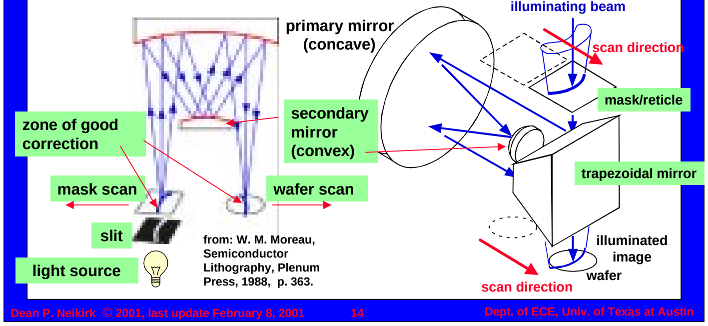
Mask Aligner Technology

- Requirements:
  - faithfully reproduce master mask pattern on wafer (low distortion errors, high resolution)
  - allow accurate alignment between pattern on wafer and mask (low registration errors)
    - overlay error = 1/3 - 1/5 resolution
    - this is a mechanical process!
  - throughput!!!

Scanning projection aligners

- reflective optics
  - wavelength independent ray paths
    - no chromatic aberration
  - difficult to produce object-to-image size change
    - 1:1 mask / wafer pattern
  - low image distortion over only a limited area
    - requires scanning to cover full mask / wafer

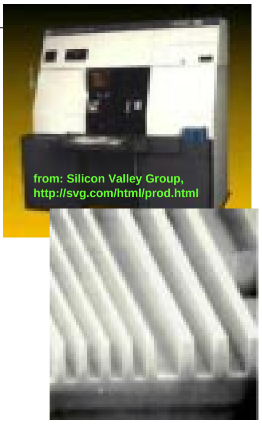
D. J. Elliott, Microlithography: Process Technology for IC Fabrication. New York: McGraw-Hill Book Company, 1986, p. 119.



from: W. M. Moreau, Semiconductor Lithography, Plenum Press, 1988, p. 363.

Scanner performance

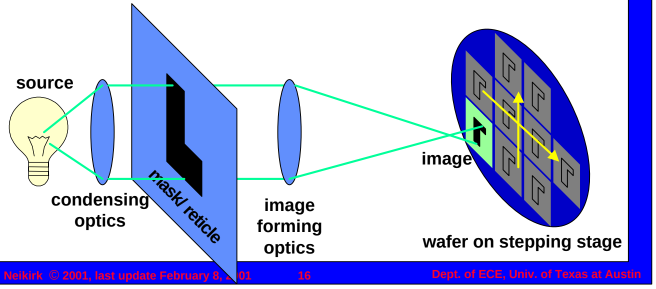
- Performance Specifications for SVG Micralign
  - Resolution
    - 1.25µm lines and spaces, UV-4 (340-440nm)
    - 1.0µm lines and spaces, UV-3 (300-350nm)
  - Machine to Machine overlay
    - ±0.25µm, 125/100mm systems, 98% of data
    - +0.30µm, 150mm systems, 98% of data
  - Throughput
    - 120 wafers per hour, 125/100mm systems
    - 100 wafers per hour, 150mm systems
  - Depth of Focus: ± 6 µm for 1.5 µm lines and spaces
  - Numerical Aperture: 0.167
  - Spectral Range 240nm Through Visible
  - Exposure -10 selectable bands within the range 240-440nm
  - Wafer / Substrate Sizes: 100mm, 125mm, 150mm



from: Silicon Valley Group, http://svg.com/html/prod.html

Step and repeat (stepper) lithography systems

- "conventional" refractive optics
  - can produce image smaller than object
  - cannot make lens with sufficient resolution to project image over whole wafer
    - "pixel" count: field size / $(l_{\min})^2$
      - $1\ \text{cm}^2 / (0.5\ \mu\text{m})^2 = 4 \times 10^8$
    - requires mechanical translation (step) of wafer under lens



Stepper performance

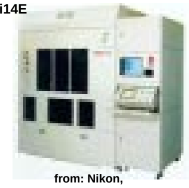
- ASM I-line stepper

Lens		Field Size	Overlay	Throughput
NA	Reso-lution	Dia-meter	2pt. Global Alignment	200mm Wafers 70 Exp., 200mJ/cm^2
0.54	0.45 µm	25.5 mm	≤70 nm	≥48 wph

ASM Lithography, http://www.asml.com/prodtech/stefr.htm

- Nikon Step-and-Repeat Systems NSR-2205EX14C and NSR-2205i14E

	NSR-2005EX14C	NSR-2205i14E
Resolution	0.25 micron	0.35 micron
Light source	KrF excimer laser (248nm)	I -line (365 nm)
Reduction ratio	1:5	
Exposure area	22 x 22 mm	
Alignment accuracy	50 nm	
Throughput (8 in. (200mm) wafer)	85 wafers/hr.	87 wafers/hr.



from: Nikon, http://www.nikon.co.jp/main/eng/news/dec14e_97.htm

---

Lens performance

- recall that for diffraction limited imaging

$$l_{\min} \propto \frac{\lambda}{NA}$$

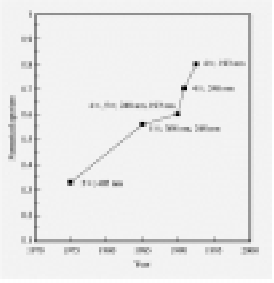


Figure 8

A summary of IBM high-NA lens designs.

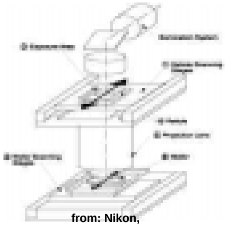
- from "High-numerical-aperture optical designs," R. N. Singh, A. E. Rosenbluth, G. L.-T. Chiu, and J. S. Wilczynski, IBM Journal of Research and Development, Vol. 41, No. 1/2, 1997.
  - http://www.almaden.ibm.com/journal/rd/411/singh.html

Photoresists

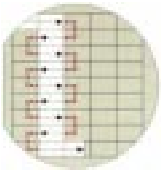
- negative: exposed regions REMAIN after development
  - one component: PMMA, COP (e-beam resist)
  - two component: Kodak KTFR
  - dominant PR until early 1980s
- positive: exposed regions REMOVED after development
  - one component: acrylates
  - two components: diazoquinone / novolac resin
  - higher resolution, but “slower”
    - largely supplanted negative resists in 80s

Step and scan

- for smaller features it is hard to maintain low abberation (distortion of image) over full field of view
- scan within each step
- combination of reflective and refractive optics
  - can use short wavelength
  - can produce size reduction from mask to feature

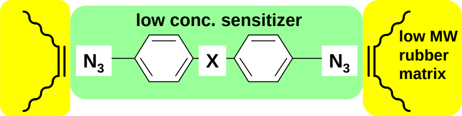


from: Nikon, http://www.nikon.co.jp/main/eng/news/dec202e_97.htm



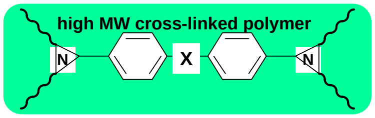
from: Silicon Valley Group, http://svg.com/html/prod.html

Two component negative resists



- UV exposure: λ ˜ 365nm, dose ˜ 1 mJoule / cm^2
- photo driven cross linking

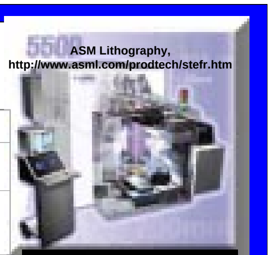
↓ hν



- solvent-based developer (xylene)
  - based on differential dissolution rate of “low” and “high” molecular weight polymers
  - problem for small features: swelling of exposed resist in solvent

---

Scanning steppers

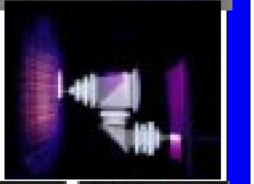


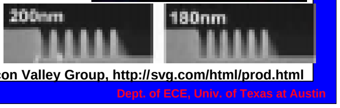
ASM Lithography, http://www.asml.com/prodtech/stefr.htm

- ASM Step & Scan system

Lens		Field Size	Overlay	Throughput
NA	Resolu-tion	X & Y	2pt. Global Alignment	200mm Wafers 46 Exp.,
0.45 to 0.63	150 – 130 nm	26 X 33 mm	≤40 nm	10 mJ/cm^2 60 wph

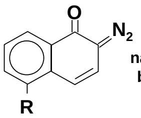
- SVG MSIII+ Performance Specifications
  - Resolution: 180nm for Grouped Lines
  - Image Reduction: 4x
  - Numerical Aperture: 0.6 to 0.4
  - Alignment / Overlay: mean + 3σ = 55nm
  - Wafer Size: 200mm (150mm Capable)
  - Throughput: 390 wph (200mm wafers), 26 fields (26mm x 34mm) @ =40 mj/cm^2
  - Excimer Laser (λ = 248nm; BW = 0.3 nm)
  - Maximum Field Size: 26mm x 34mm
  - Reticle Size: 6" x 6" x 0.25" thick





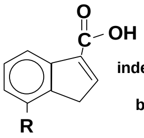
from: Silicon Valley Group, http://svg.com/html/prod.html

Two component DZN positive resist

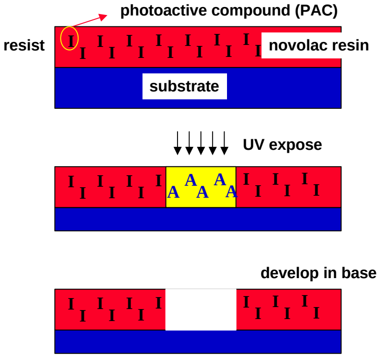


diazo-naphthoquinone base insoluble inhibiter

↓ hν



indene carboxylic acid base soluble



Double-sided alignment

- for many mems devices patterns exist on BOTH sides of the substrate
  - typically contact aligners in current use
  - EVG double-sided optical system
    - use microscopes indexed mechanically to both sides of wafer
    - requires transparent wafer chuck

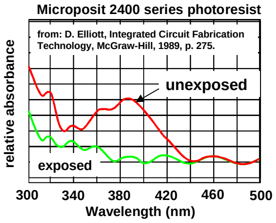
http://www.evgroup.com/products/precisionalignment.htm

Positive resist characteristics

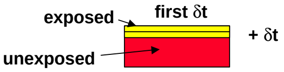
- base resin + PAC (20 - 30% by volume)
  - chemical reaction liberates N_2
    - at high UV intensities N_2 evolution rate can be “explosive”
  - reaction rates sensitive to residual solvent and water content
    - control of pre-bake time & temperature, relative humidity critical
- etch rates in developer:
  - unexposed : base resin : exposed
    0.1 nm/sec : 15 nm/sec : 150 nm/sec
- thickness (typical at 5 krpm)
  - 1350 B 0.5 µm
  - 1350 J 1.5 µm
    - thickness depends on
      - v(spin speed)
      - viscosity
- PR is <u>conformal</u> <u>to</u> <u>substrate</u>
- solvents
  - acetone
  - slightly soluble in alcohols

Exposure properties

- full exposure is set by energy threshold
  - time •intensity = energy
  - ~linearly increases with resist thickness
    - ~ 20 mJ / µm of thickness
- unexposed resist is “opaque” to the exposing UV radiation
  - resist bleaches as it exposes



from: D. Elliott, Integrated Circuit Fabrication Technology, McGraw-Hill, 1989, p. 275.

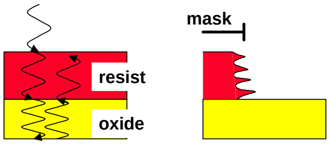


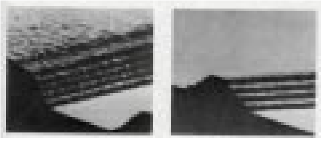
- can NOT easily compensate for underexposure by overdevelopment

---

Potential exposure problems

- “substrate” induced reflections
  - multiple reflections induce standing wave pattern
    - destructive interference: underexposed
    - primarily an issue near an edge
  - for metals, BCs require “zero” tangential E field at interface!
    - can cause underexposure over metals
      - contact windows may shrink

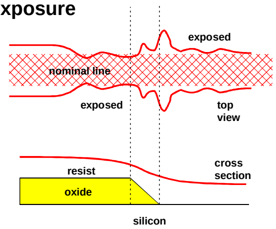


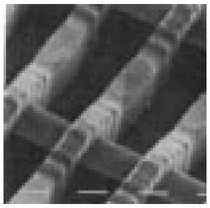


from: Thompson, Willson, & Bowden, Introduction to Microlithography,ACS Symposium Series 219, 1983, p. 45.

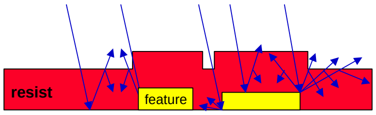
Interference effects

- step edges also produce non-uniform resist thickness and exposure



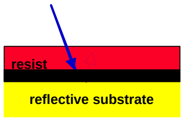


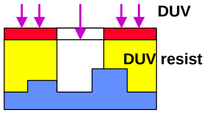
from: Thompson, Willson, & Bowden, Introduction to Microlithography,ACS Symposium Series 219, 1983, p. 293.



Interference effects

- fixes
  - post exposure bake
    - try to diffuse exposed PAC
  - AR coating
    - place highly absorbing layer under PR
    - must then be able to pattern AR layer
  - planarize!
- multi-layer resist schemes
  - portable conformal mask (PCM)
    - thin “normal” PR on top of thicker, planarizing deep UV PR
      - expose/develop thin layer normally
      - use as “contact” mask for DUV exposure of underlying layer
  - contrast enhancement materials (CEM)
    - photo-bleachable material with VERY sharp threshold placed <u>above</u> PR
      - for energies below threshold PR is “masked”
      - above threshold CEM becomes transparent, resist below exposed
    - sharpens edges





Other approaches to high resolution lithography

- e - beam systems (“direct - write”):
  - high resolution (< 0.2 µm)
  - no mask requirement
  - low throughput
- e - beam proximity printers:
  - requires mask but has high throughput potential
- X - ray systems (proximity - type contact printers):

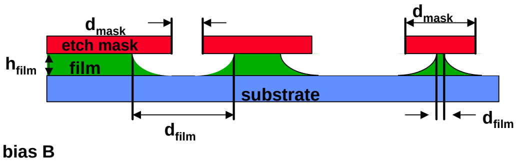
$$l_{\min} \approx \frac{3}{2}\sqrt{gap \cdot \lambda}$$

  - high resolution if λ is small
    - for g ~ 10 µm, λ ~ 10 Å ? l_{min} ~ 0.15 µm
  - may also be overlay limited
    - not clear if sub 0.2-ish micron possible
  - mask technology very complex
  - low throughput until brighter sources are found

Electron beam exposure systems

- dominant mask making tool.
- potential < 0.1 µm resolution (on flat, uniform substrates).
- usually step - and - repeat format, e - beam computer driven
- typical resist:
  - poly (methyl methacrylate)
- low throughput
- problem in electron beam systems:
  - most electrons do not stop in the photoresist:
    - potential damage problem
    - back scattered electrons cause pattern edges to blur
  - most e- beam pattern generators contain computer code to reduce dose near edges to control proximity effects.

Etching terminology



- bias B
  - B ≡ d_f - d_m (i.e., twice the "undercut)
- anisotropy A
  - $A_{film} \equiv 1 - v_l / v_v$
    - v_l ≡ lateral etch rate
    - v_v ≡ vertical etch rate
  - for films etched <u>just to completion</u>
    - $A_f = 1 - |B| / 2h_f$
      - h_f ≡ film thickness
  - $A_f = 0$ isotropic
  - $A_f = 1$ perfectly anisotropic