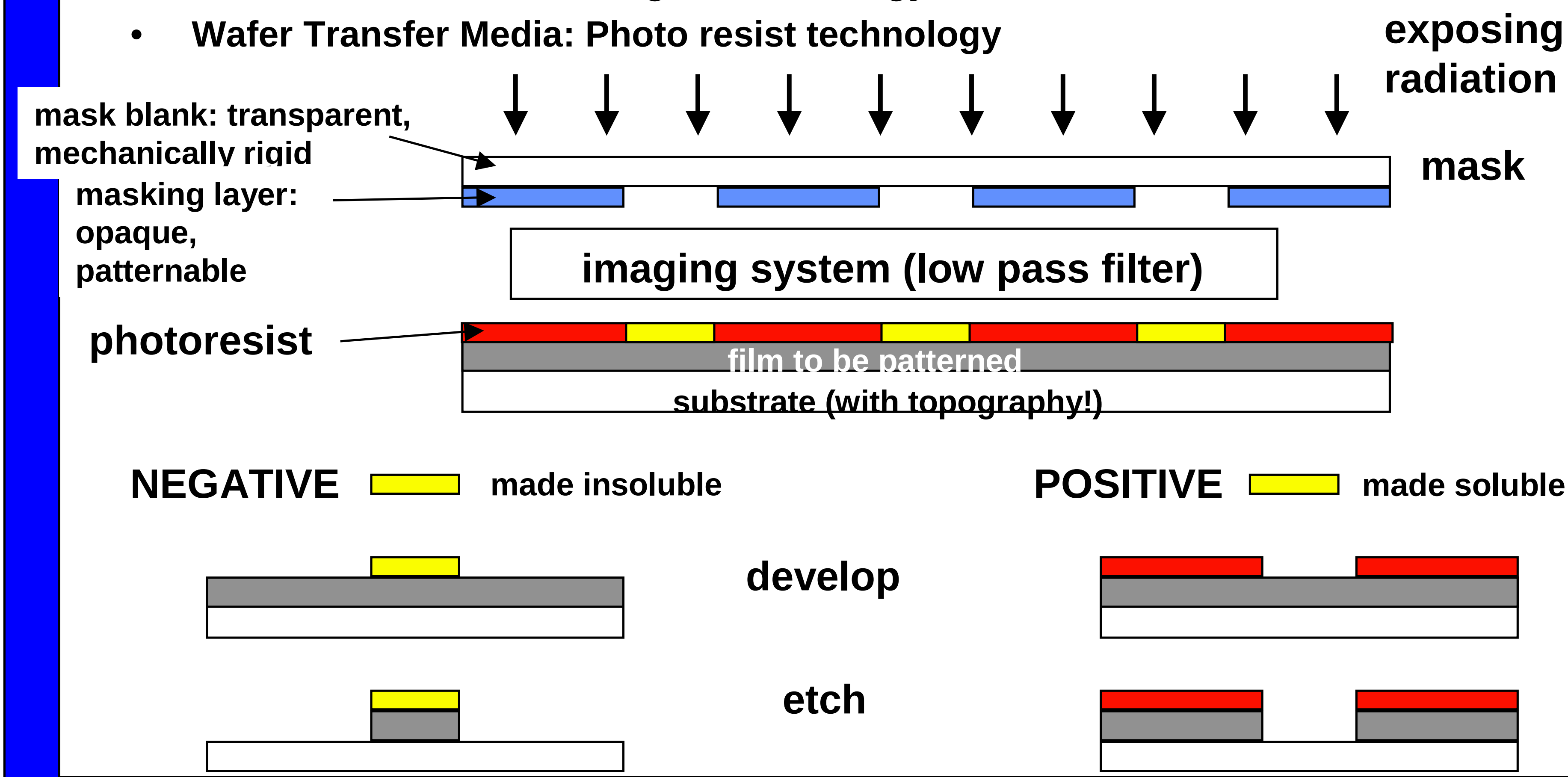
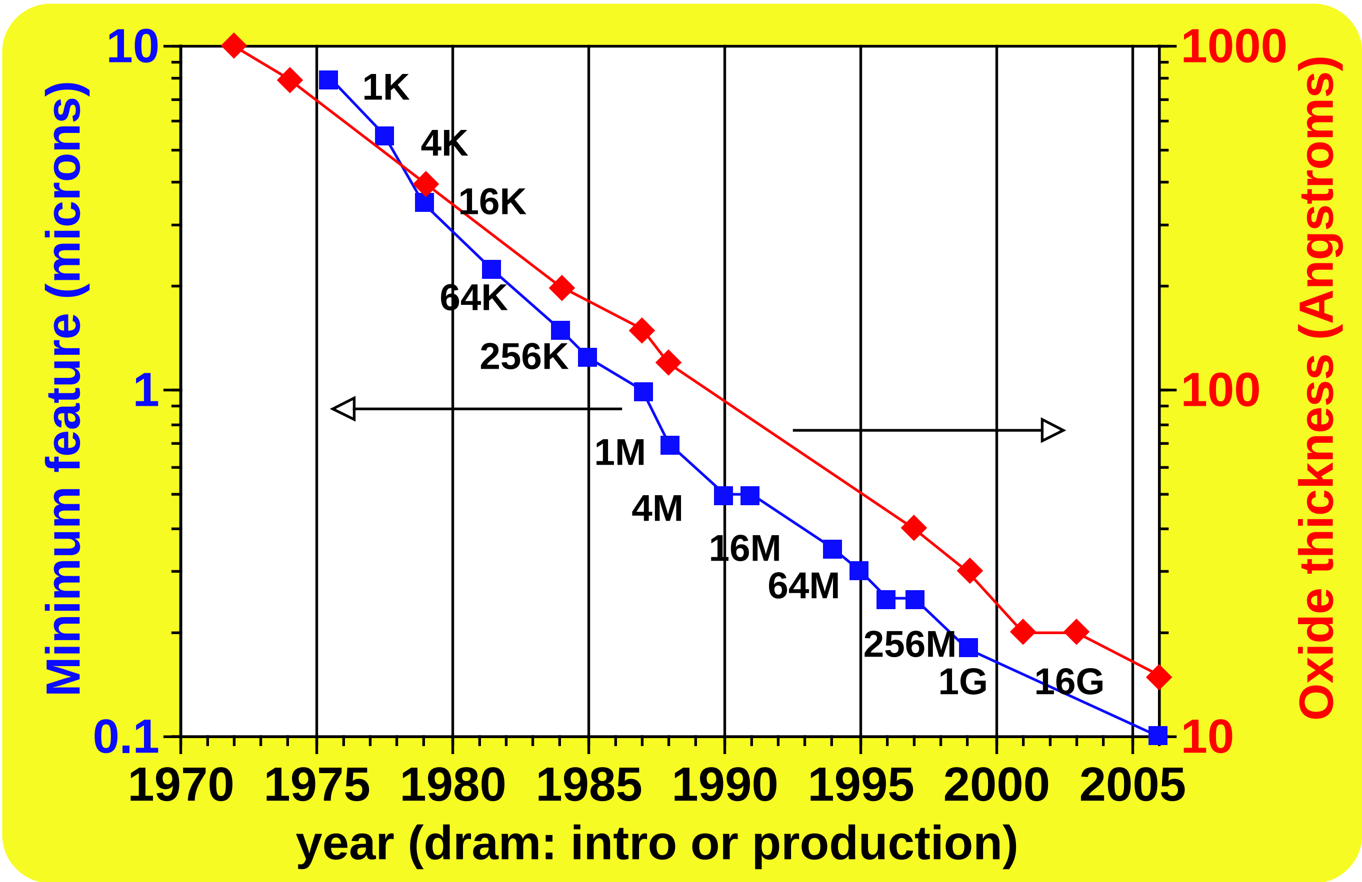
Microlithography

- 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



general characteristics

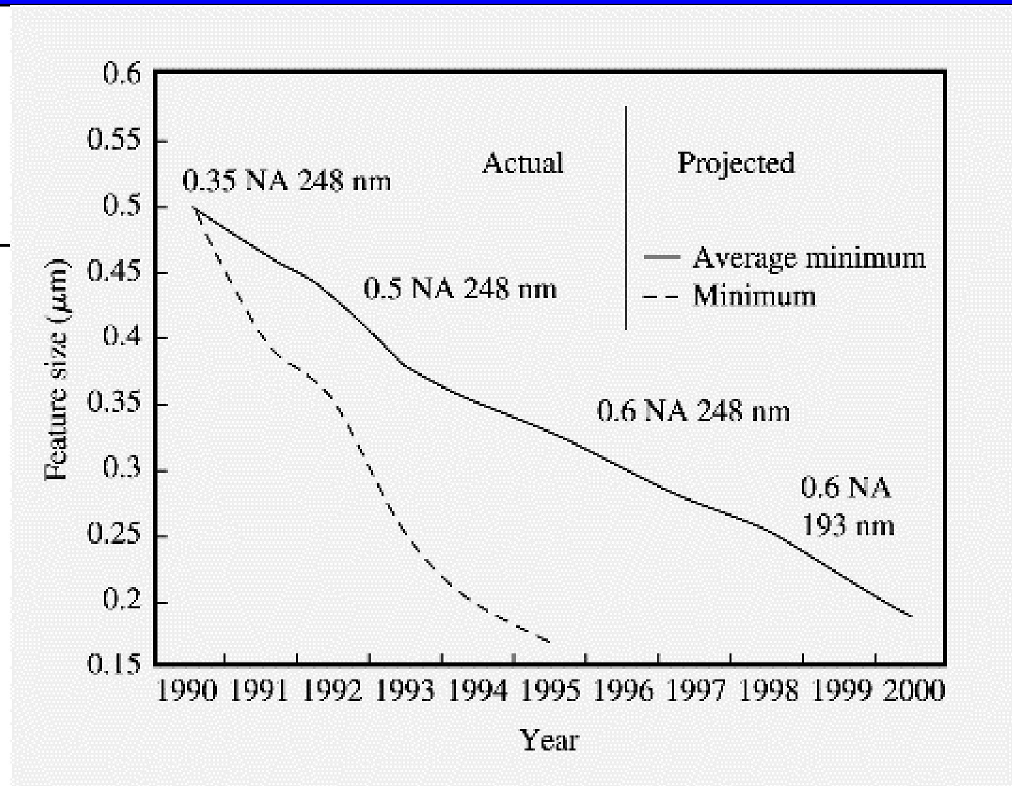


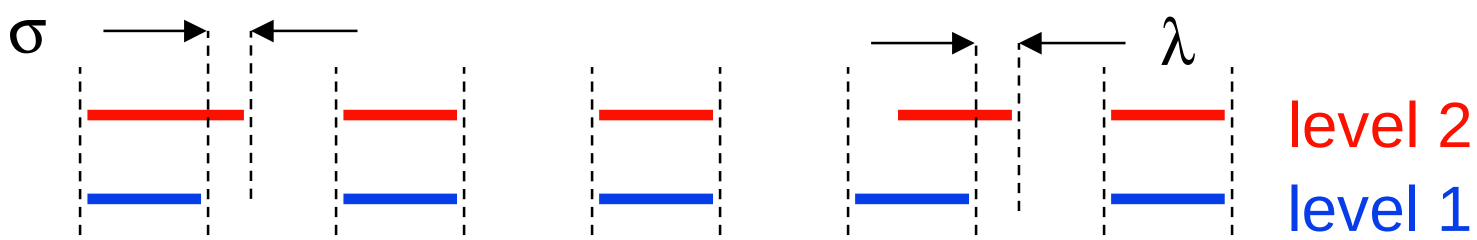
Figure 1

Actual and projected minimum ground-rule migration for development and manufacturing at ASTC during the years 1990–2000. The dashed curve shows the minimum ground rule processed in a given year. The solid curve shows the weighted average ground rule across all products and DUV exposure levels. Achieved and anticipated lithography tooling milestones (NA and wavelength) are also shown.

- **"Advanced DUV photolithography in a pilot line environment" by C. P. Ausschnitt, A. C. Thomas, and T. J. Wiltshire, IBM Journal of Research and Development, Vol. 41, No. 1/2, 1997.**
  - **http://www.almaden.ibm.com/journal/rd/411/aussc1.gif**

Overlay errors between two patterns

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

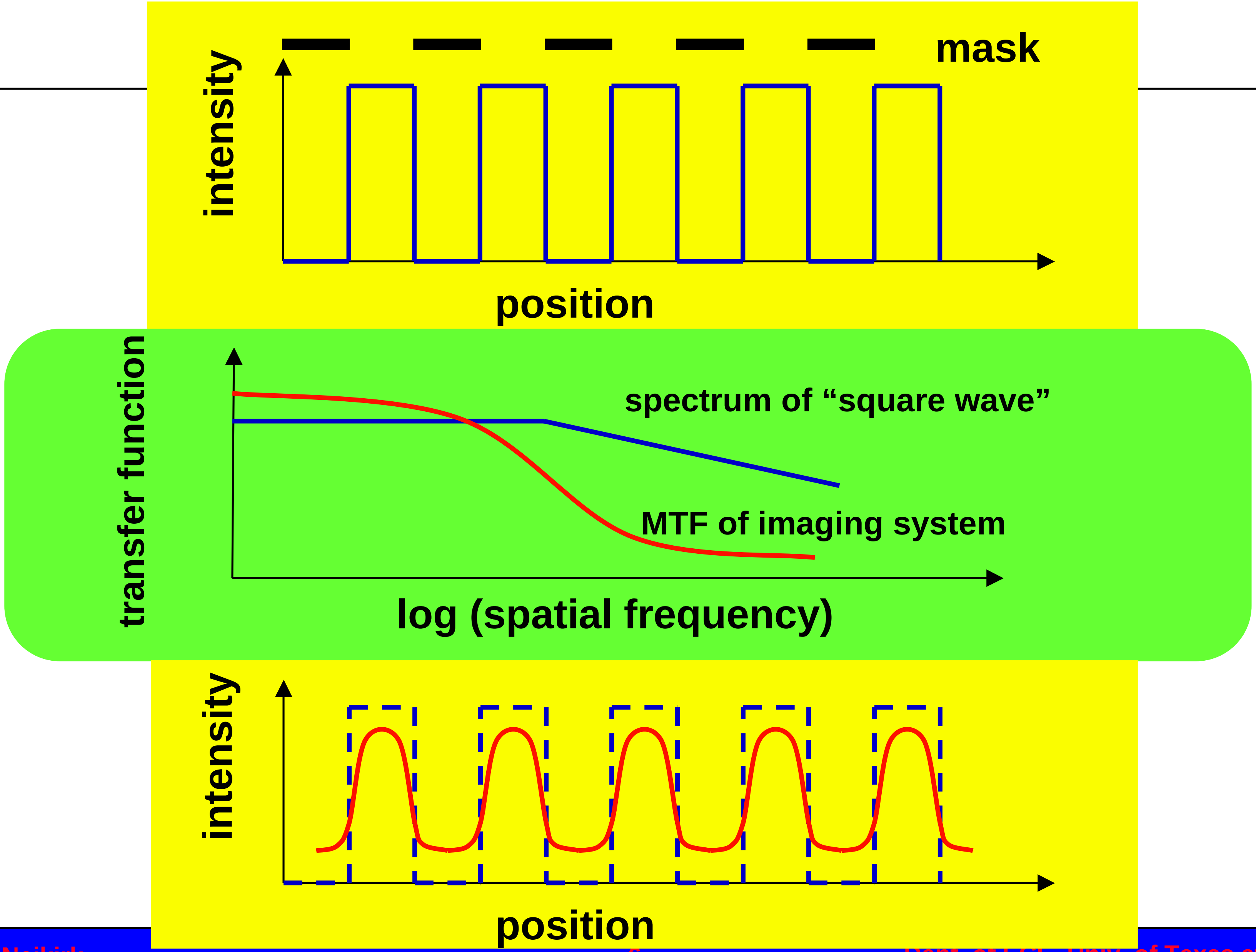


- what can go wrong??
- λ : pure registration error
- σ : distortion error
  - – overlay error: sum of all errors
    - really a statistical quantity
- rule of thumb: total overlay error not more than 1/3 to 1/5 of minimum feature size

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)

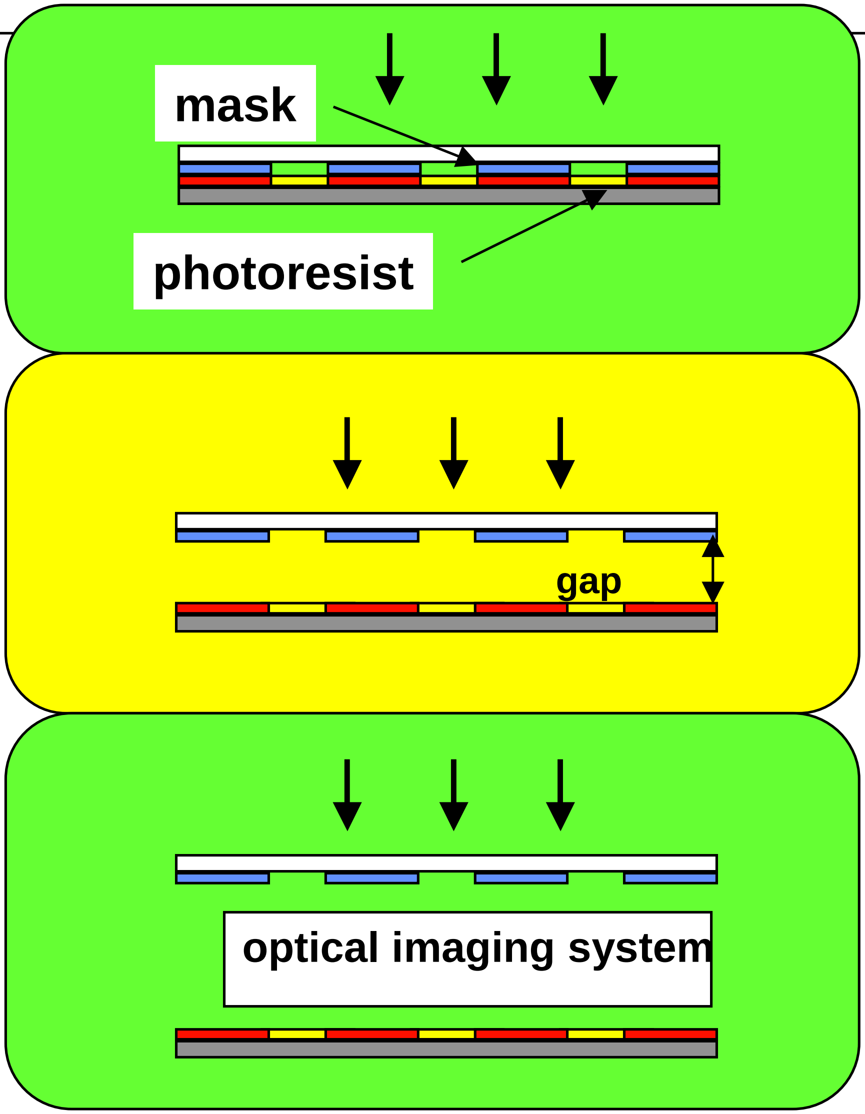


Resolution in imaging systems

- 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 $\lambda \leq$ 350nm
  - very difficult to get large field size <u>and</u> high NA

Basic imaging techniques

- contact
- proximity
- imaging

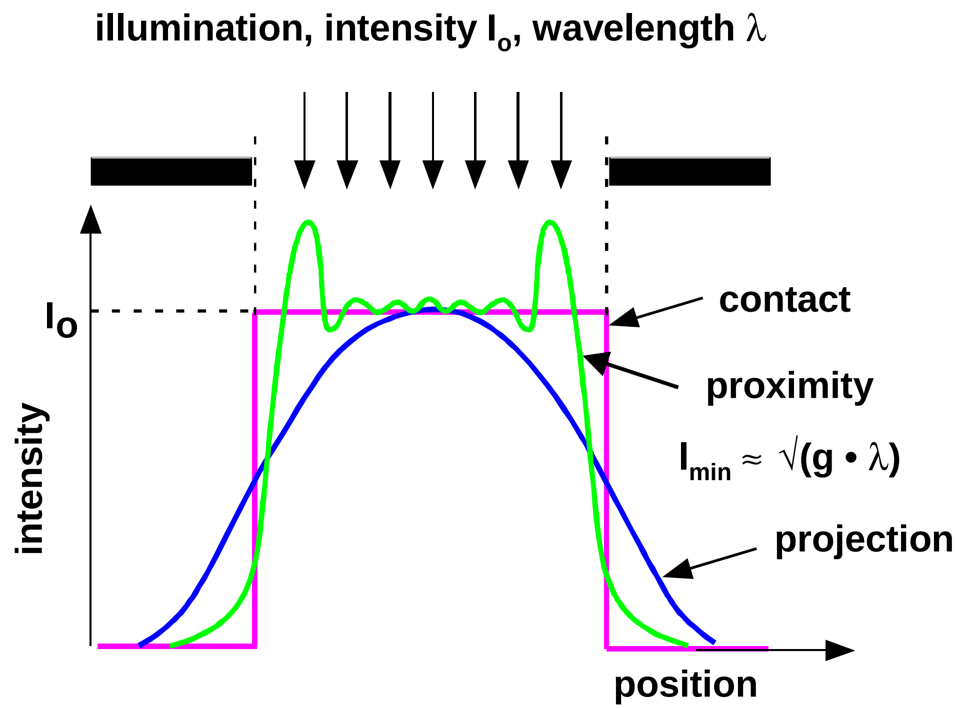


Resolution of Imaging Systems: Spatial Low Pass Filters

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

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

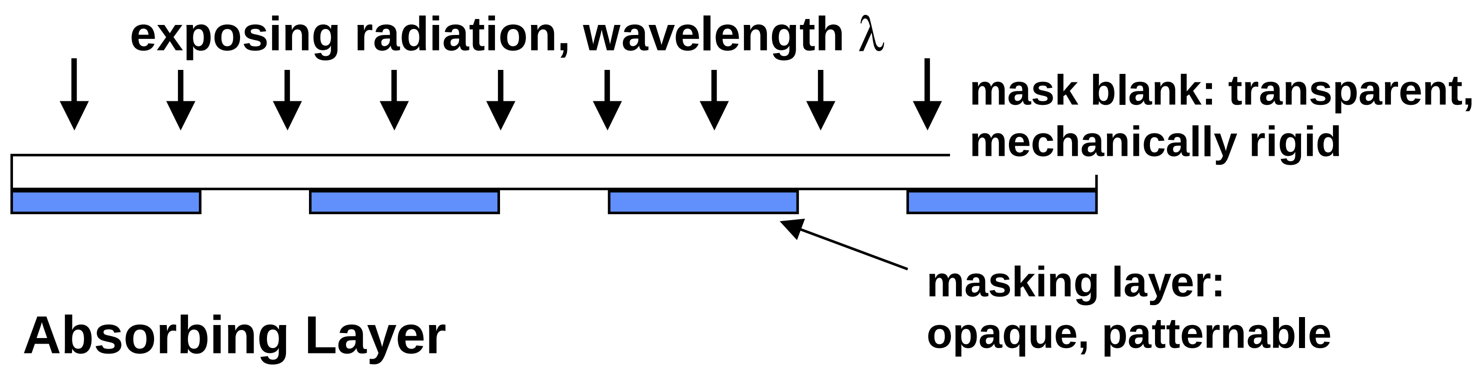
- **imaging: low pass filter, "smooth" decrease in passband**



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 ($\lambda = h/mv$)
  - electron beam (~50eV electron ➡ $\lambda \approx$ 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

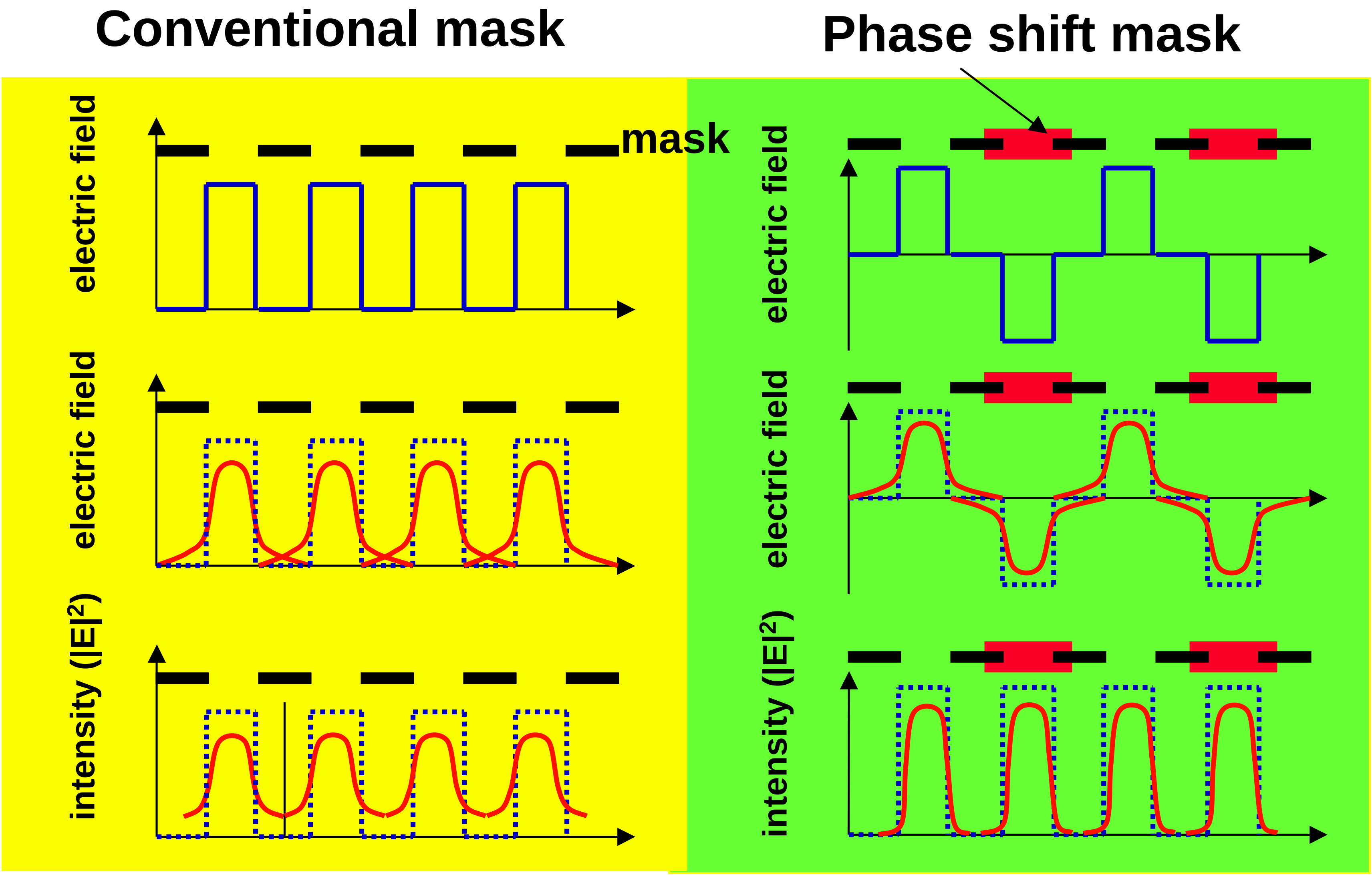
- surface flatness
  - gravitational sag
    - hold mask vertically rather than horizontally
- optical transparency
  - for wavelengths < ~350nm: quartz
    - for wavelengths < ~200nm can have significant absorption
- thermal expansion
  - for 100 mm separation, 1˚C ΔT
    - soda-lime: 0.9 µm
    - fused 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

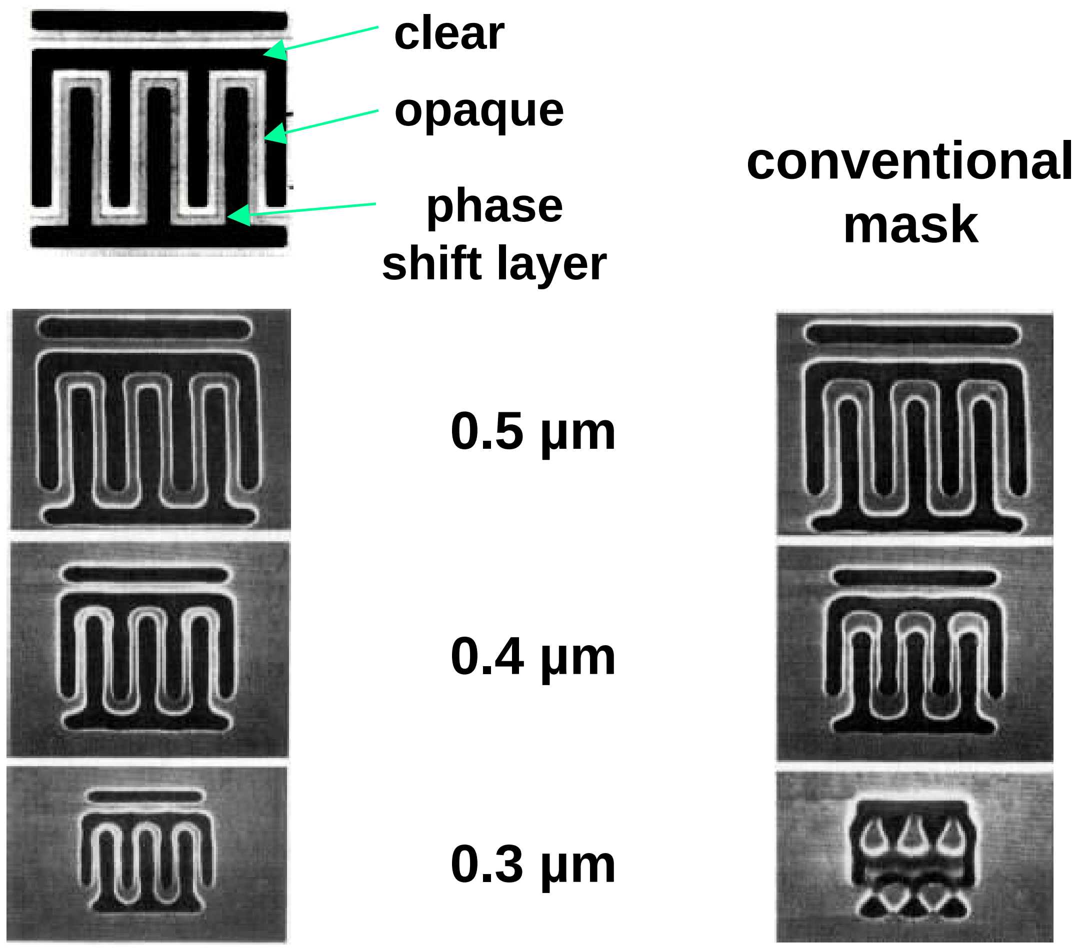
$$Y_{single\ level} = \frac{1}{1 + D_o A} \qquad Y_{N\ levels} = \left(\frac{1}{1 + D_o A} \right)^N$$

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



- use coherent behavior and interference effects to improve image quality

Comparison of phase shift mask / no shift mask



from: M. Levenson, Wavefront Engineering for Photolithography, Physics Today, July 1993, p. 32.

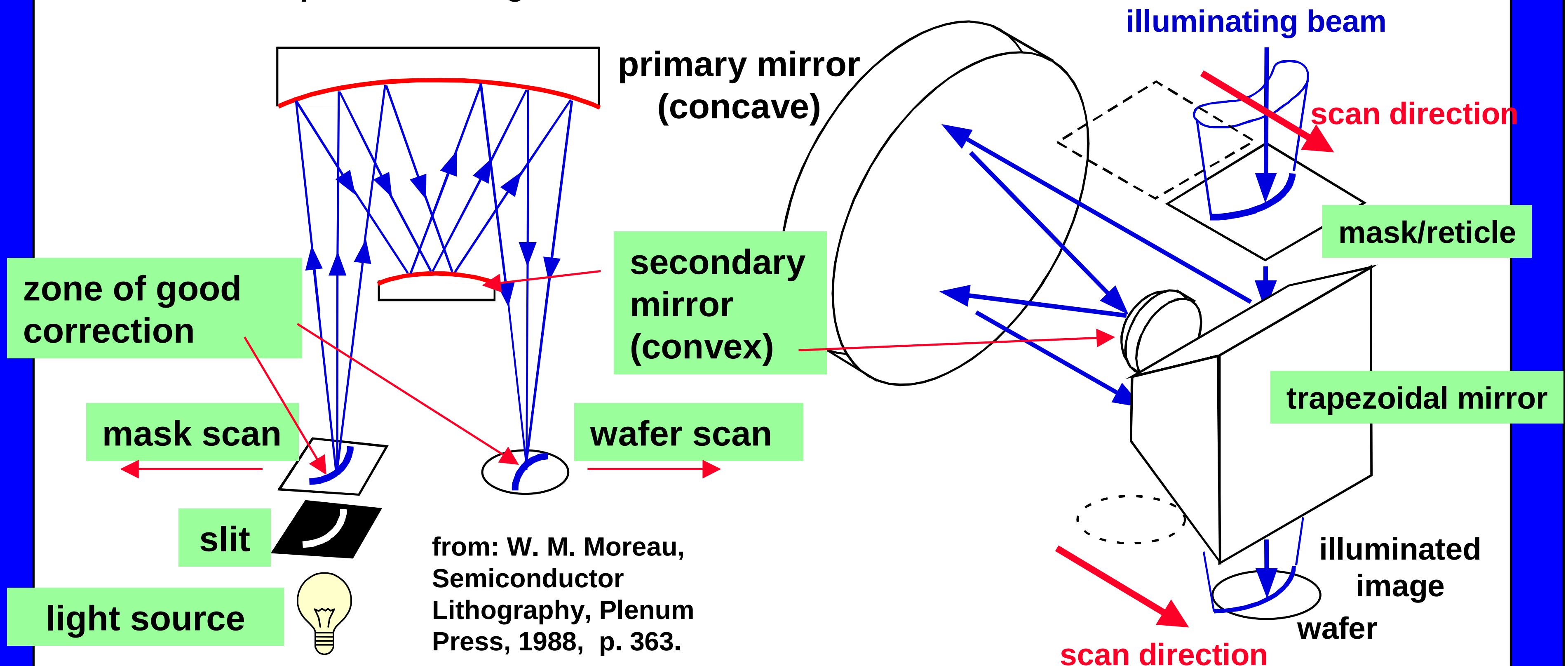
Mask Aligner Technology

- **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.
  - 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

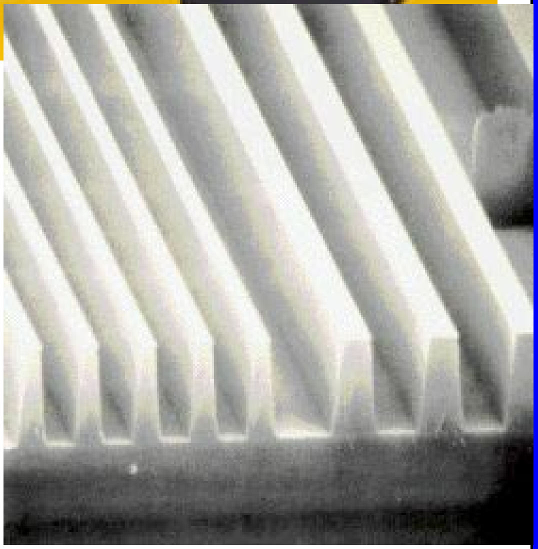
D. J. Elliott, Microlithography: Process Technology for IC Fabrication. New York: McGraw-Hill Book Company, 1986, p. 119.



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

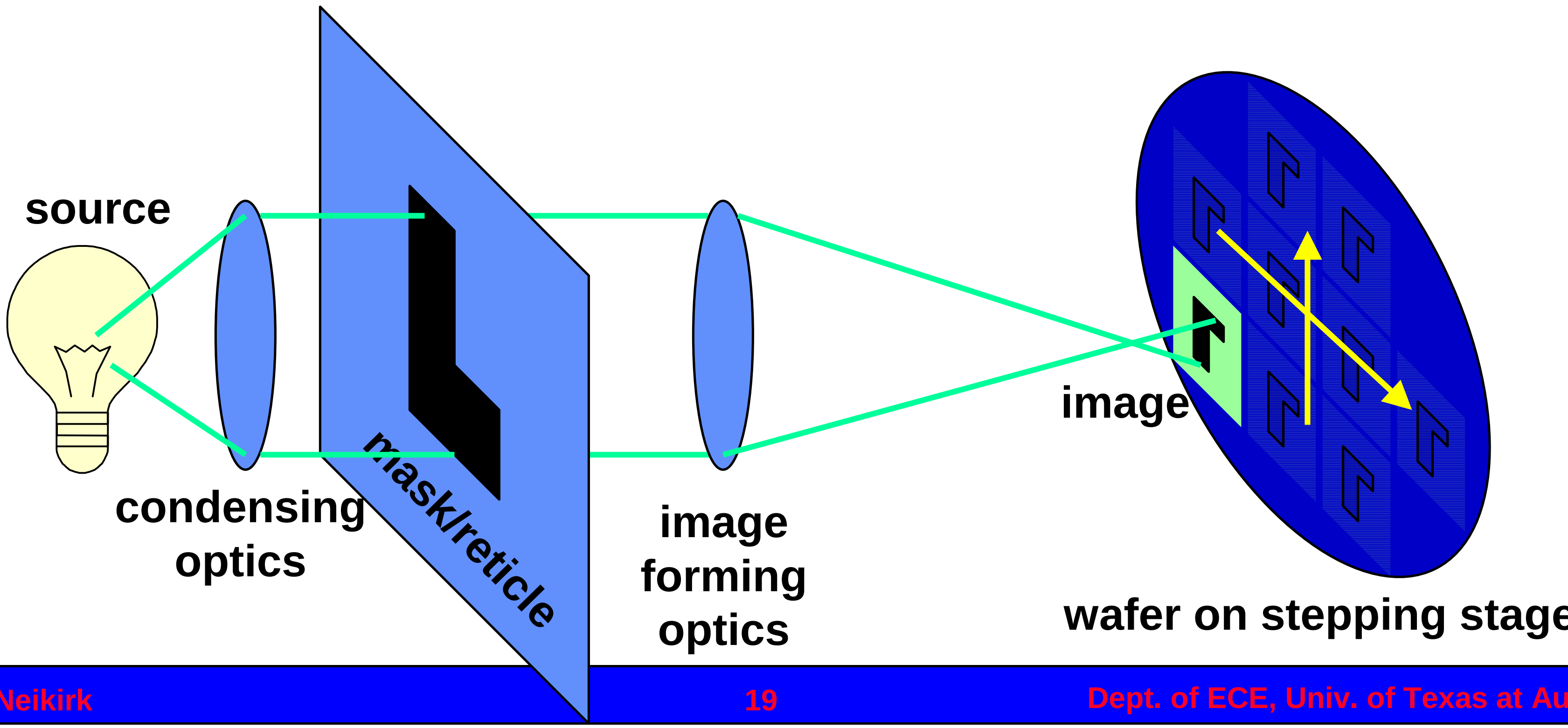
Scanner performance

- 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



Step and repeat (stepper) lithography systems

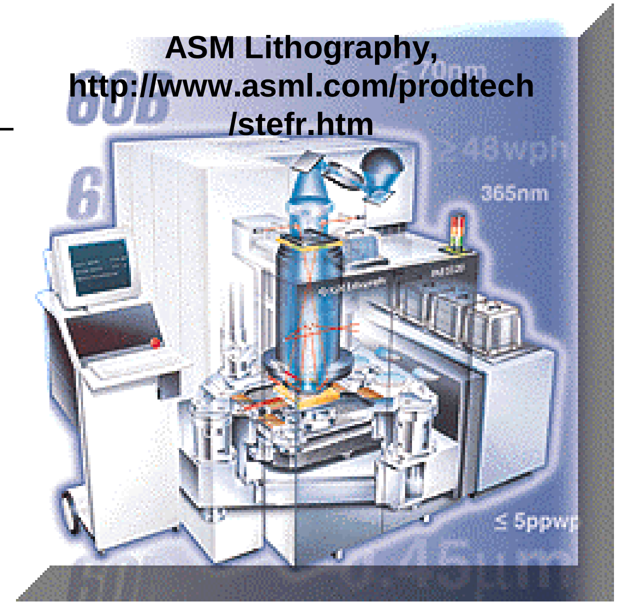
- "conventional" refractive optics
  - can produce image smaller than object
  - cannot make lens with sufficient resolution to project image over whole wafer
    - "pixel" count: field size / $(\ell_{min})^2$
      - $1\ cm^2 / (0.5\ \mu m)^2 = 4 \times 10^8$
    - requires mechanical translation (step) 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	$\leq$70 nm	$\geq$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**

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

- **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**

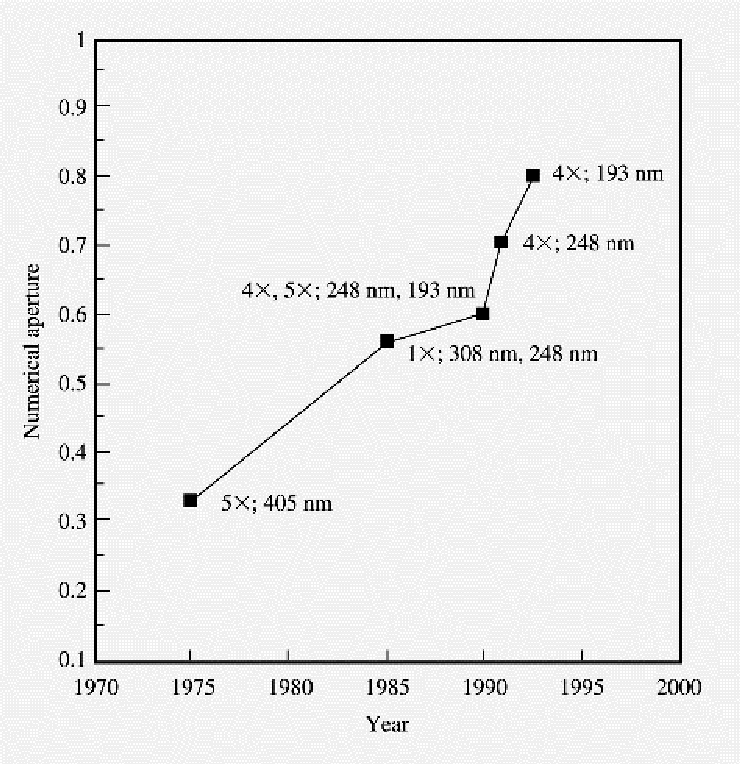


Figure 5

A summary of IBM high-NA lens designs.

Example high NA lens

- from “High-numerical-aperture optical designs” by 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.

Table 6

NonBS Lens Design Data in mm

Surf Type	Radius	Thickness	Glass
OBJECT	Infinity	0	
1	Infinity	235	
2	−134.146	30	SILICA
3	−148.477	5	
4	702.681	30	SILICA
5	640.35	668.1274	
6	−192.513	15	SILICA
7	−1417	30	
STOP	−354.599	−30	MIRROR
9	−1417	−15	SILICA
10	−192.513	668.127	
11	640.35	−30	SILICA
12	702.681	−5	
13	−148.477	−30	SILICA
14	−134.146	100	
15		0	0
16	Infinity	0	MIRROR
17	———	145	0
18	607.6066	14	SILICA
19	−4929	2.5	
20	299.9345	16	SILICA
21	145.9961	5.5	
22	147.8041	14	SILICA
23	548.3378	383.0459	
24	−135.779	34.9045	SILICA
25	−388.431	9.0893	
26	500.691	34.5545	SILICA
27	−825.455	31.1656	
28	−301.421	31.163	SILICA
29	−198.273	1	
30	561.9237	30	SILICA
31	−8202	1	
32	519.5236	39.7716	SILICA
33	1727.545	38.0492	
34	503.7716	44.7175	SILICA
35	−1785	1	
36	246.9601	50.3312	SILICA
37	759.9896	1	
38	161.6256	28.9637	SILICA
39	270.6681	2.7724	
40	83.4617	31.4153	SILICA
41	63.4713	92.4596	
42	65.1023	61.2545	SILICA
43	1171.922	0	
44	Infinity	0.501249	
45	Infinity	0	
IMAGE	Infinity	0	

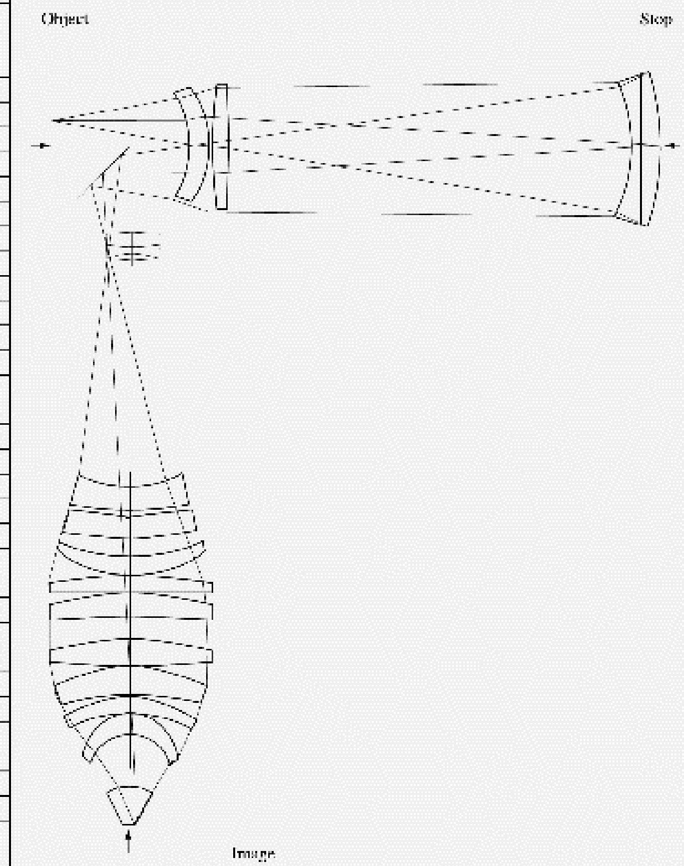
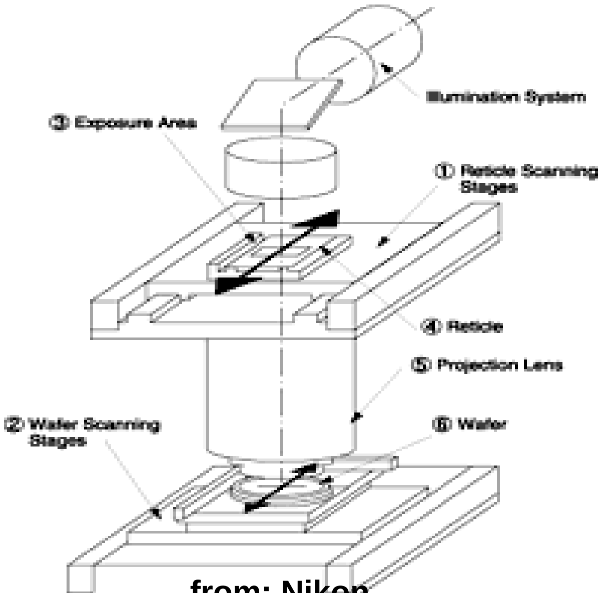


Figure 4

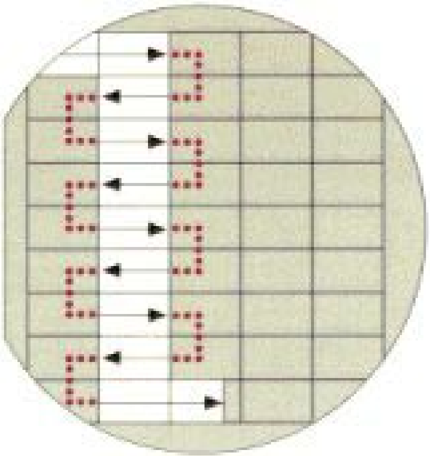
Configuration of the 4× non-beam-splitter lens.

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

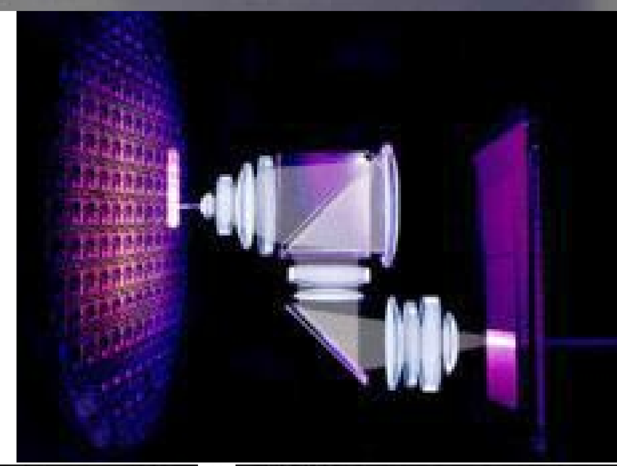


from: Silicon Valley Group,
http://svg.com/html/prod.html

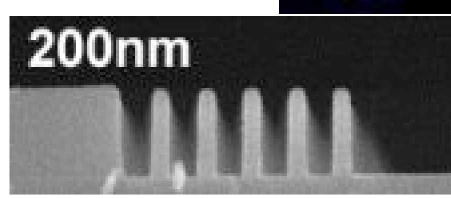
Scanning steppers

- **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	$\leq$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

Aligner spec summary

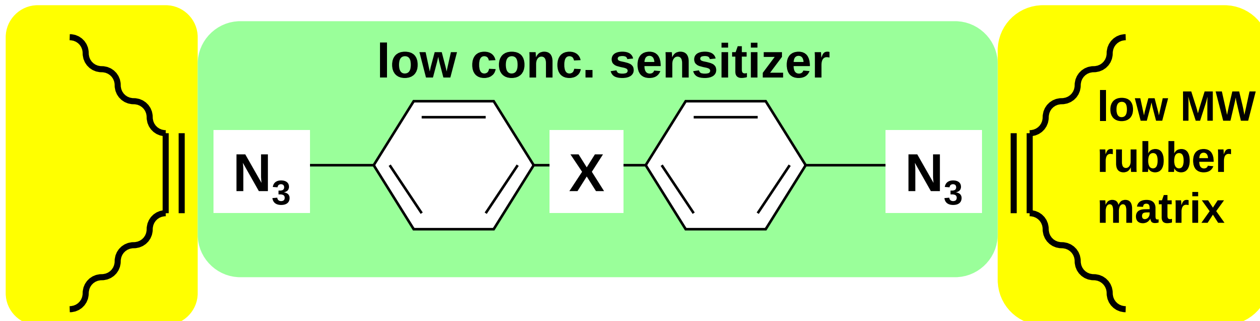
- from "High-numerical-aperture optical designs" by R. N. Singh, A. E. Rosenbluth, G. L.-T. Chiu, and J. S. Wilczynski, IBM Journal of Research and Development, Vol. 41, No. 1/2, 1997.

Manufacturer	***Model number***	***Reduction***	***NA***	***Wafer* (in.)**	***Reso-lution* (µm)**	***Field size* (mm)**	***DOF* (µm)**
I-line (365 nm)							
NIKON	NSR2205i11D	--	0.5-0.63	8	0.4	31 diag**	0.92
CANON	FPA3000i4	5X	0.6	8	0.43	31 diag	1.01
ASM	PAS5500/100D	5X	0.48-0.62	8	0.41	29.7 diag	0.95
248 nm							
NIKON	NSRS201A	4X	0.6	8	0.29	25 × 33	0.69
CANON	FPA3000EX3	5X	0.6	10	0.35	31 diag	0.69
CANON	FPA3000EXLS	4X	0.6	--	--	25 x 32.5	0.69
ASM	PAS5500/step	4X	0.63	8	0.25	31 diag	0.62
ASM	PAS5500/scan	4X	0.63	8	0.25	26 x 34	0.62
SVGL	MS III	4X	0.6	8	0.35	26 x 32.5	0.69
ULTRATECH	Half Dyson	1X	0.7	12	0.25	20 x 40	0.5
193 nm							
SVGL	Prototype to LL^	4X	0.5	8	0.6/0.23	22 x 32.5	0.77

Photoresists

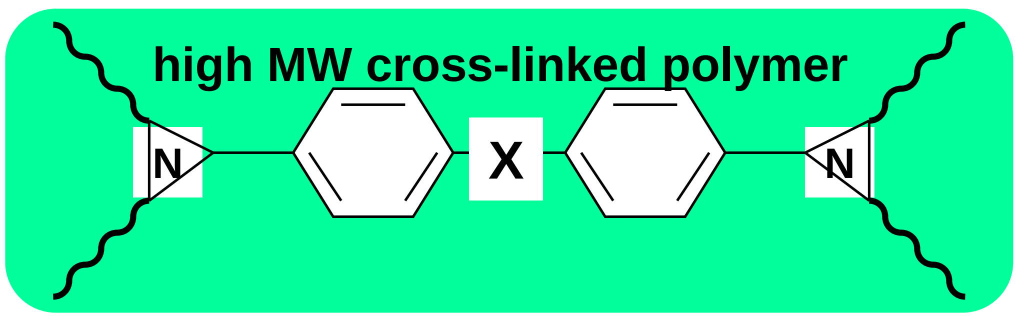
- negative: exposed regions REMAIN after development
  - one component: PMMA, COP (e-beam resist)
  - two component: Kodak KTFR
  - dominant PR until early 1980's
- positive: exposed regions REMOVED after development
  - one component: acrylates
  - two components: diazoquinone / novolac resin
  - higher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

Two component negative resists



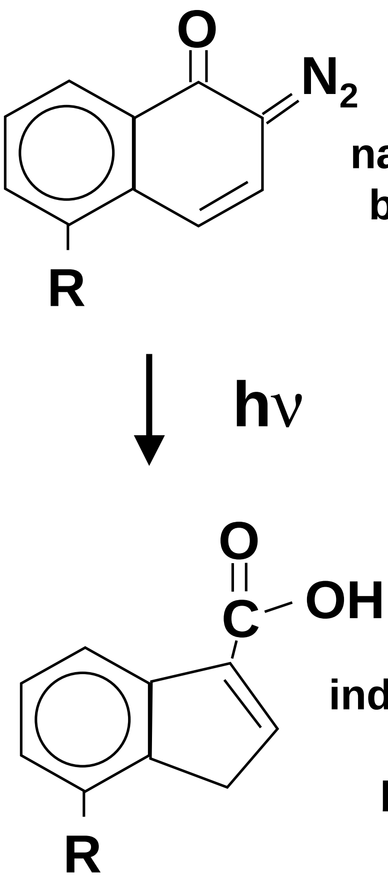
- UV exposure: λ ≈ 365nm, dose ≈ 1 mJoule / cm^2
- photo driven cross linking

↓ hν



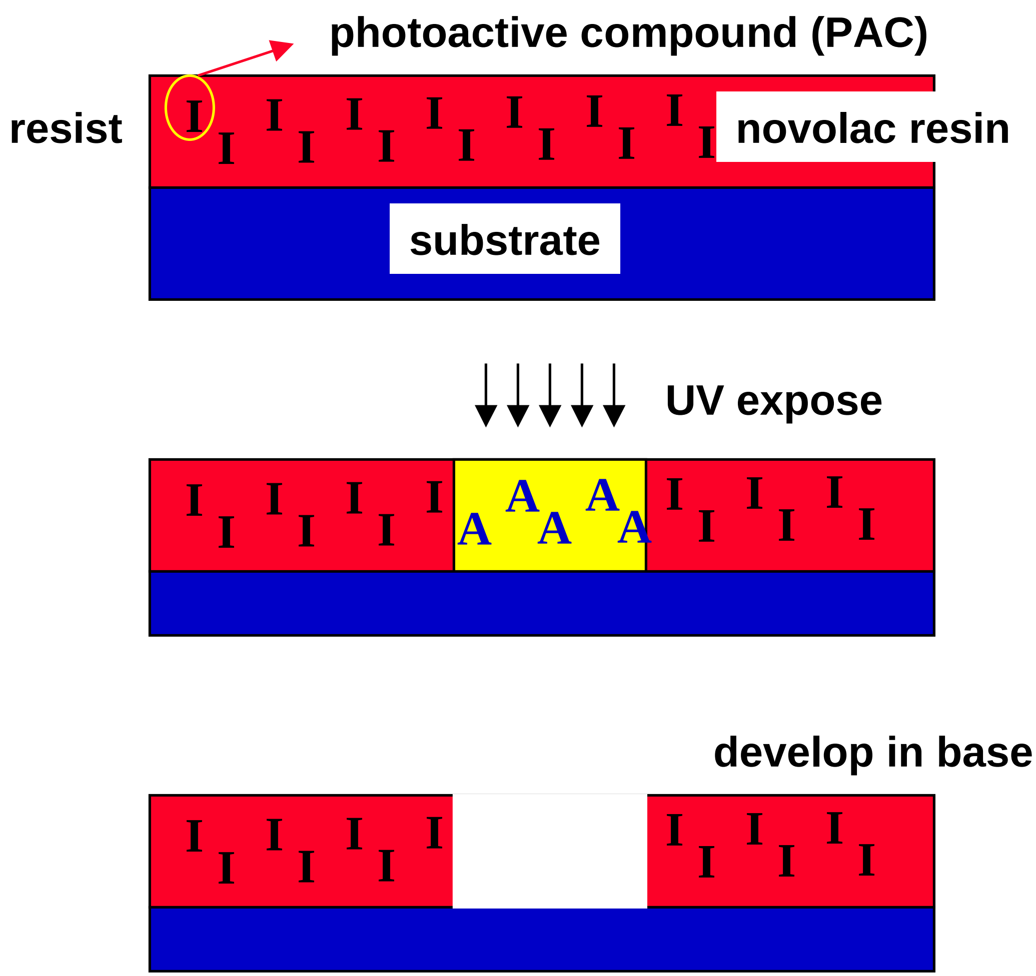
- solvent-based developer (xylene)
  - based on differential dissolution rate of "low" and "high" molecular weight polymers
  - problem for small features: swelling of exposed resist in solvent

Two component DZN positive resist



diazo-
naphthoquinone
base insoluble
inhibiter

indene carboxylic
acid
base soluble



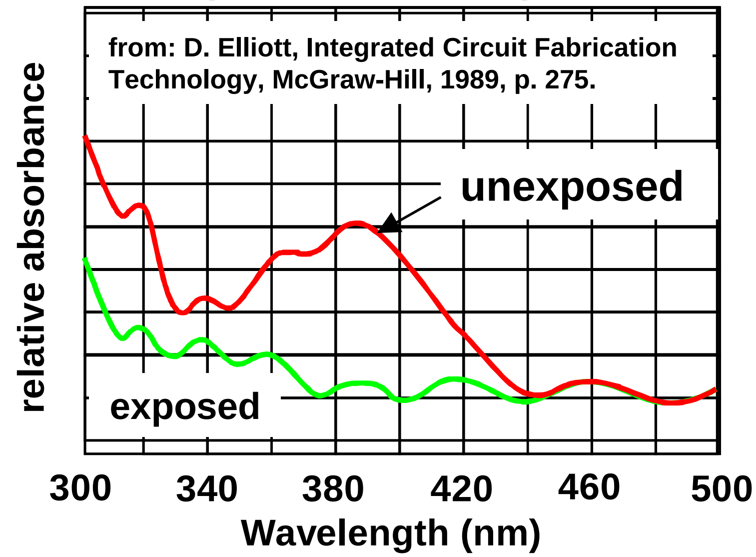
Positive resist characteristics

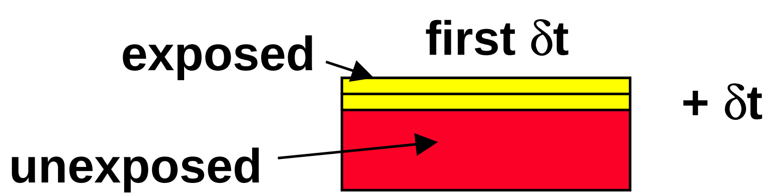
- base resin + PAC (20 - 30% by volume)
  - chemical reaction liberates N_2
    - at high UV intensities N_2 evolution rate can be “explosive”
  - reaction rates sensitive to residual solvent and water content
    - control of pre-bake time & temperature, relative humidity critical
- etch rates in developer:
    - 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
      - $\sqrt{}$(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

Micropossit 2400 series photoresist

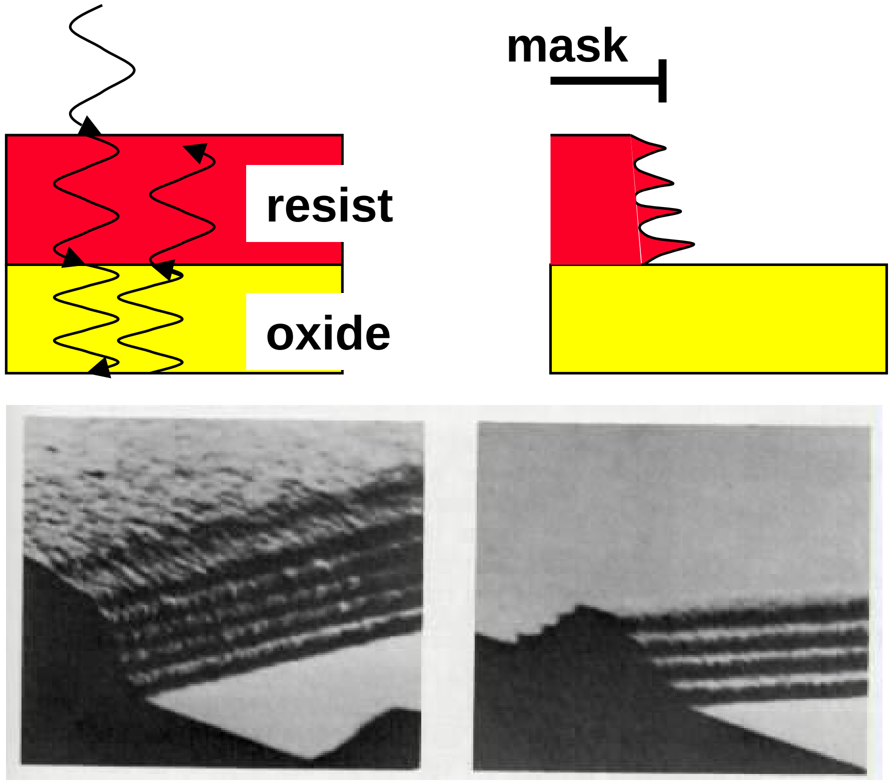




  - can NOT easily compensate for underexposure by overdevelopment

Potential exposure problems

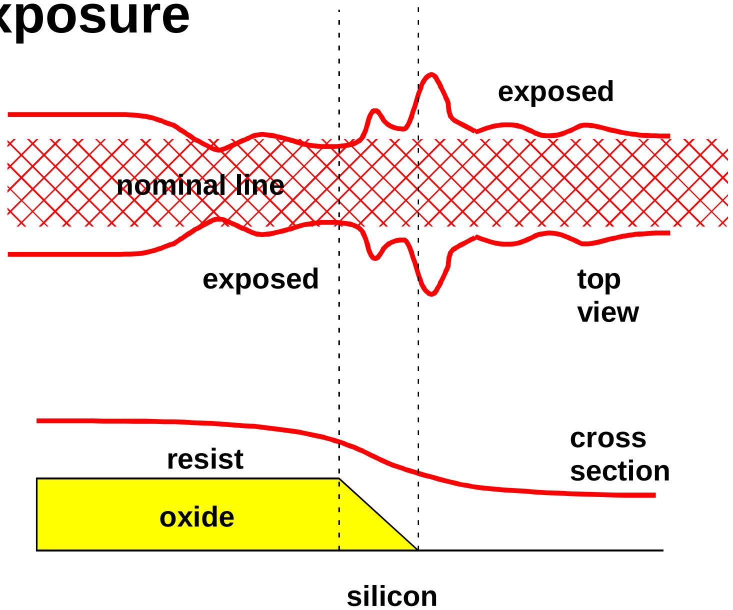
- "substrate" induced reflections
  - multiple reflections induce standing wave pattern
    - destructive interference: underexposed
    - primarily an issue near an edge
  - for metals, BCs require "zero" tangential E field at interface!
    - can cause underexposure over metals
      - contact windows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

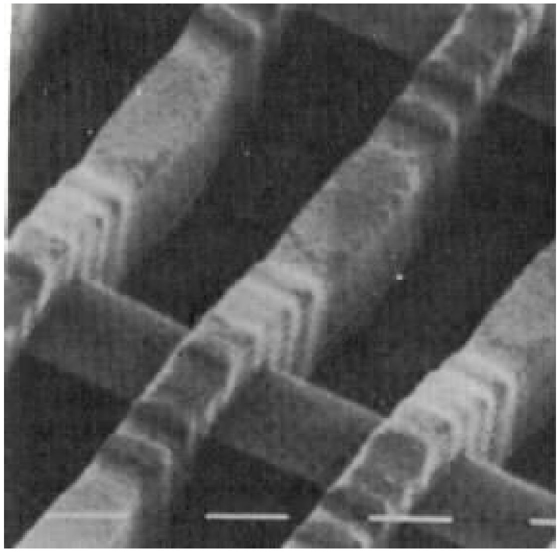


from: Thompson, Willson, & Bowden, Introduction to Microlithography,ACS Symposium Series 219, 1983, p. 45.

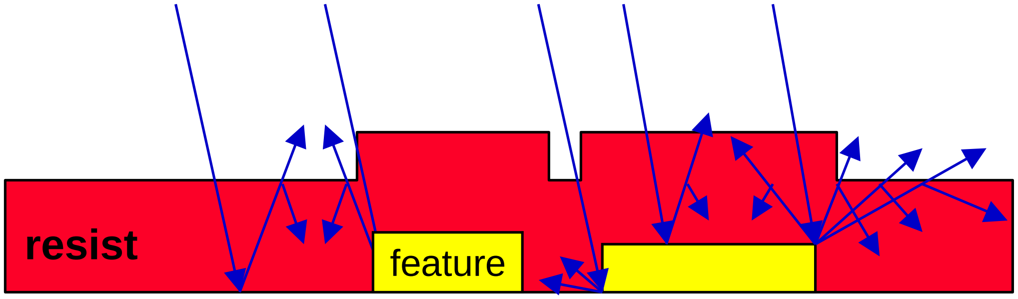
Interference effects

- **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 above PR
    - 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):
  - very high resolution; probably overlay limited
    - not clear if sub 0.2-ish micron possible
  - mask technology very complex
  - low through put 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.