Microlithography

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

- **mask blank:** transparent, mechanically rigid
- **masking layer:** opaque, patternable

- **photoresist**
  - film to be patterned
  - substrate (with topography!)

- **imaging system (low pass filter)**

- **NEGATIVE**
  - made insoluble
  - develop

- **POSITIVE**
  - made soluble
  - etch
Minimum feature sizes (DRAMs)

- trend lines for feature size
general characteristics


![Figure 1](http://www.almaden.ibm.com/journal/rd/411/aussc1.gif)

**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.
Overlay errors between two patterns

- goal: align two “identical” patterns one on top of the other
  - $\sigma$: distortion error
  - $\lambda$: pure registration error

- what can go wrong??

- 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)

- Mask
- Intensity vs. position
- Spectrum of "square wave"
- MTF of imaging system
- Log (spatial frequency) vs. transfer function
- Intensity vs. position
Resolution in imaging systems

- **diffraction limits passband of system**
  - minimum geometry $\approx k \frac{\lambda}{NA}$
    - $k \sim 0.5$ to 1, typically $\sim 0.8$
    - $\lambda$: exposure wavelength
    - NA: numerical aperture (typically $NA \leq 0.5$)
      - related to quality and “size” (entrance/exit pupil) of imaging system

- **main difficulties**
  - need high NA, low aberrations, short wavelength but:
    - depth of focus $\sim \frac{\lambda}{2(NA)^2}$
    - restricted set of transparent materials for $\lambda \leq 350 \text{nm}$
    - very difficult to get large field size and high NA
Basic imaging techniques

• contact
  - mask
  - photoresist

• proximity
  - gap

• imaging
  - optical imaging system
Resolution of Imaging Systems: Spatial Low Pass Filters

- **contact**
  - “shadow” formation, “no” diffraction

- **proximity**
  - some diffraction, “sharp” filter cut-off, flat response in passband

\[ l_{\text{min}} \approx \frac{3}{2} \sqrt{gap \cdot \lambda} \]

- **imaging:** low pass filter, “smooth” decrease in passband
Exposure radiation / wavelength choices

- want short wavelength to get small $\ell_{\text{min}}$
- 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 $\Rightarrow \lambda \approx 1.5A$)
  - 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

exposing radiation, wavelength $\lambda$

mask blank: transparent, mechanically rigid

masking layer: opaque, patternable
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 $\Delta T$
    - 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
      \[
      Y_{\text{single level}} = \frac{1}{1 + D_o A} \quad Y_{N \text{ levels}} = \left( \frac{1}{1 + D_o A} \right)^N
      \]
      - \(D_o\): # of fatal defects/unit area
      - \(A\): die area
    - mask must be “perfect” so “repair” is essential
      - laser etch / deposition
Conventional mask

Phase shift mask

- use coherent behavior and interference effects to improve image quality
Comparison of phase shift mask / no shift mask

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


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 / \((l_{\text{min}})^2\)
      - \(1 \text{ cm}^2 / (0.5 \mu\text{m})^2 = 4 \times 10^8\)
    - requires mechanical translation (step) of wafer under lens
# Stepper performance

- **ASM I-line stepper**

<table>
<thead>
<tr>
<th>Lens</th>
<th>Field Size</th>
<th>Overlay</th>
<th>Throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA</td>
<td>Resolution</td>
<td>Diameter</td>
<td>2pt. Global Alignment 200mm Wafers</td>
</tr>
<tr>
<td>0.54</td>
<td>0.45 µm</td>
<td>25.5 mm</td>
<td>70 Exp., 200mJ/cm²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>≤70 nm</td>
<td>≥48 wph</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Resolution</th>
<th>Light source</th>
<th>Reduction ratio</th>
<th>Exposure area</th>
<th>Alignment accuracy</th>
<th>Throughput (8 in. (200mm) wafer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25 micron</td>
<td>KrF excimer laser (248nm)</td>
<td>1:5</td>
<td>22 x 22 mm</td>
<td>50 nm</td>
<td>85 wafers/hr.</td>
</tr>
<tr>
<td>0.35 micron</td>
<td>I-line (365 nm)</td>
<td></td>
<td></td>
<td></td>
<td>87 wafers/hr.</td>
</tr>
</tbody>
</table>


Lens performance

- recall that for diffraction limited imaging

\[ l_{\text{min}} \propto \frac{\lambda}{NA} \]


Figure 5
A summary of IBM high-NA lens designs.
Example high NA lens

Step and scan

- for smaller features it is hard to maintain low aberration (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,

from: Silicon Valley Group,
Scanning steppers

- **ASM Step & Scan system**

<table>
<thead>
<tr>
<th>Lens</th>
<th>Field Size</th>
<th>Overlay</th>
<th>Throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA</td>
<td>Resolution</td>
<td>X &amp; Y</td>
<td>200mm Wafers</td>
</tr>
<tr>
<td>0.45 to 0.63</td>
<td>150 – 130 nm</td>
<td>26 X 33 mm</td>
<td>46 Exp.,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>≤40 nm</td>
<td>10 mJ/cm²</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>60 wph</td>
</tr>
</tbody>
</table>

- **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/cm²
  - Excimer Laser (λ = 248nm; BW ≤ 0.3 nm)
  - Maximum Field Size: 26mm x 34mm
  - Reticle Size: 6” x 6” x 0.25” thick

# Aligner spec summary


<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model number</th>
<th>Reduction</th>
<th>NA</th>
<th>Wafer (in.)</th>
<th>Resolution (µm)</th>
<th>Field size (mm)</th>
<th>DOF (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-line (365 nm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NIKON</td>
<td>NSR2205i11 D</td>
<td>--</td>
<td>0.5-0.63</td>
<td>8</td>
<td>0.4</td>
<td>31 diag**</td>
<td>0.92</td>
</tr>
<tr>
<td>CANON</td>
<td>FPA3000i4</td>
<td>5X</td>
<td>0.6</td>
<td>8</td>
<td>0.43</td>
<td>31 diag</td>
<td>1.01</td>
</tr>
<tr>
<td>ASM</td>
<td>PAS5500/100 D</td>
<td>5X</td>
<td>0.48-0.62</td>
<td>8</td>
<td>0.41</td>
<td>29.7 diag</td>
<td>0.95</td>
</tr>
<tr>
<td>248 nm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NIKON</td>
<td>NSRS201A</td>
<td>4X</td>
<td>0.6</td>
<td>8</td>
<td>0.29</td>
<td>25 x 33</td>
<td>0.69</td>
</tr>
<tr>
<td>CANON</td>
<td>FPA3000EX3</td>
<td>5X</td>
<td>0.6</td>
<td>10</td>
<td>0.35</td>
<td>31 diag</td>
<td>0.69</td>
</tr>
<tr>
<td>CANON</td>
<td>FPA3000EXLS</td>
<td>4X</td>
<td>0.6</td>
<td>--</td>
<td>--</td>
<td>25 x 32.5</td>
<td>0.69</td>
</tr>
<tr>
<td>ASM</td>
<td>PAS5500/step</td>
<td>4X</td>
<td>0.63</td>
<td>8</td>
<td>0.25</td>
<td>31 diag</td>
<td>0.62</td>
</tr>
<tr>
<td>ASM</td>
<td>PAS5500/scan</td>
<td>4X</td>
<td>0.63</td>
<td>8</td>
<td>0.25</td>
<td>26 x 34</td>
<td>0.62</td>
</tr>
<tr>
<td>SVGL</td>
<td>MS III</td>
<td>4X</td>
<td>0.6</td>
<td>8</td>
<td>0.35</td>
<td>26 x 32.5</td>
<td>0.69</td>
</tr>
<tr>
<td>ULTRATECH</td>
<td>Half Dyson</td>
<td>1X</td>
<td>0.7</td>
<td>12</td>
<td>0.25</td>
<td>20 x 40</td>
<td>0.5</td>
</tr>
<tr>
<td>193 nm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SVGL</td>
<td>Prototype to LL^</td>
<td>4X</td>
<td>0.5</td>
<td>8</td>
<td>0.6/0.23</td>
<td>22 x 32.5</td>
<td>0.77</td>
</tr>
</tbody>
</table>
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: $\lambda \approx 365\text{nm}$, dose
  $\approx 1\text{ mJoule/cm}^2$
- photo driven cross linking

- 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

photoactive compound (PAC)

novolac resin

substrate

hv

UV expose

develop in base

diazo-naphthoquinone base insoluble inhibitor

indene carboxylic acid base soluble

O

N₂

R

O

C

OH

R
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
      - √(spin speed)
      - viscosity
- PR is conformal to substrate
- solvents
  - acetone
  - slightly soluble in alcohols
Exposure properties

- full exposure is set by energy threshold
  - time \cdot intensity = energy
  - \sim linearly increases with resist thickness
    - \sim 20 \text{ mJ} / \mu\text{m of thickness}
- unexposed resist is "opaque" to the exposing UV radiation
  - resist bleaches as it exposes
  - can NOT easily compensate for underexposure by overdevelopment


Wavelength (nm)
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

Interference effects

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

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 throughput until brighter sources are found
Electron beam exposure systems

- dominant mask making tool.
- potential < 0.1 \( \mu \text{m} \) 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.