Nanometer Scale Patterning and Processing

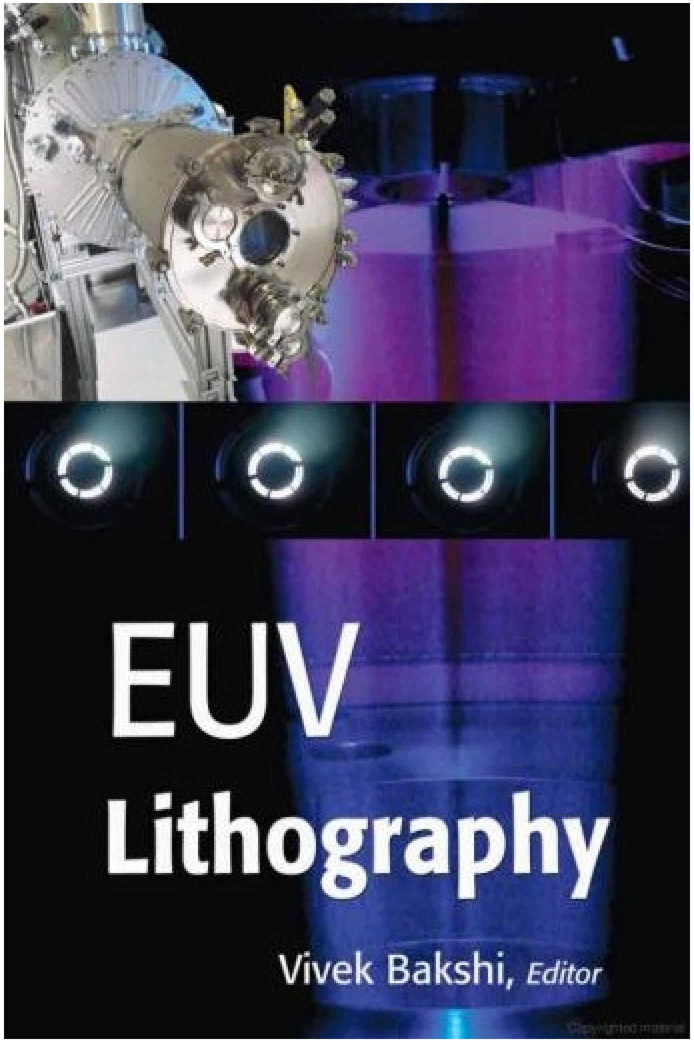
Spring 2016

Lecture 13

Extreme UV (EUV) Lithography – Overview, Why EUV Lithography?

Extreme UV (EUV) lithography

1. Overview, why EUV lithography?
2. EUV source (hot and dense plasma).
3. Optics (reflection mirrors).
4. Mask (absorber on mirrors).
5. Resist (sensitivity, LER, out-gassing).
6. Contamination control.



http://books.google.ca/books?id=91XeKLC9MUEC&pg=PA393&lpg=PA393&dq=Elemental+absorption+at+13.5nm&source=bl&ots=u2vsBa2dgr&sig=a1JKcj0vE6Gx7X-_6m_zUR9CT5k&hl=en&ei=QZsQSpTVKZS8M5aT2FI&sa=X&oi=book_result&ct=result&resnum=1#PPR7,M1

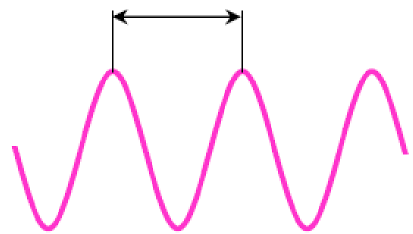
Why EUV lithography?

- Shorter λ gives higher resolution.
- No need of resolution enhancement techniques.
- Relax the requirement for NA.
- For EUV lithography, λ=13.5nm where efficient “lens” (reflected mirror) exists.

$$\text{Spatial Resolution} = \frac{k\lambda}{NA}$$

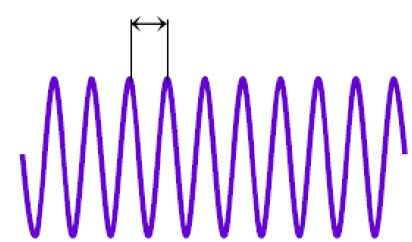
visible light

λ = 500 nm



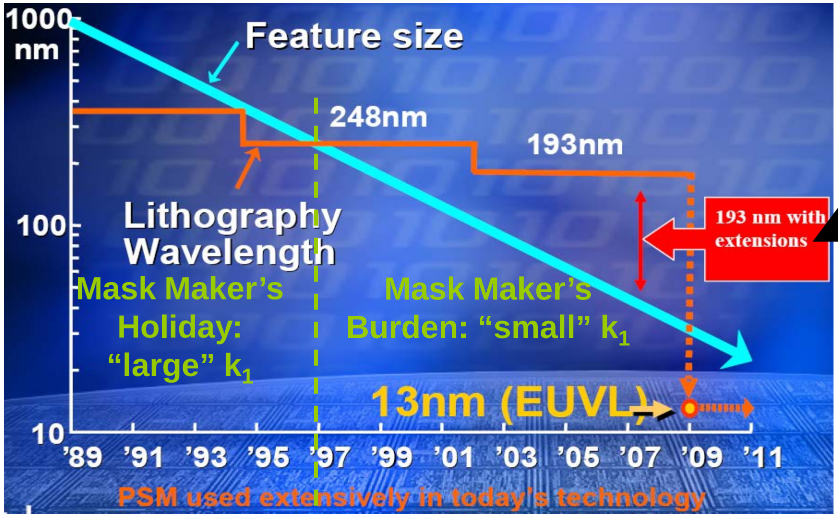
Extreme ultra-violet and soft x-ray light

λ = 1 - 50 nm



EUV and SXR microscopy can potentially resolve full-field images with 10-100x smaller features than conventional visible microscopy

Transitions to EUV is a big jump



There are only so many "tricks" to increase this gap, and they are very expensive … we must go to a shorter wavelength!

From	To	Comment
g-line	i-line	Minor process changes.
i-line	KrF	Major changes: • Type of light source (arc lamp → excimer laser). • Invention of new resist concept was required. • Only fused silica for lenses. • It took a decade.
KrF	ArF	Few significant changes: • Light sources still excimer lasers. • Resists still based on existing concept.
ArF	ArF immersion	Few significant changes: • Same light sources, resist platforms.
ArF immersion	EUV	Total paradigm shift

Lithography Plan as of Feb. 2010

- *Intel: (logic chip maker, large profit margin)*
  * 193-nm immersion with pitch division is the only option for high-volume manufacturing at 15-nm (for 2013)
  * there will be pilot line production with EUV at 15nm
  * at 11-nm, Intel is also looking at 193-nm immersion, with a quint--or five mask--patterning (there is currently double and triple lithography)
- *Nikon:* (tool vendor)

* 193-nm immersion tool called the NSR-S620D. The tool features a lens with a numerical aperture (NA) of 1.35 (improved from first version 1.30)

* a new platform, dubbed the Streamlign. Overlay is 2-nm and throughput is 200 wafers an hour

- *Samsung: (memory maker, small profit margin)*

The general problem with double-patterning is cost. In simple terms, the mask must be exposed twice in double-patterning. It is 2.5 times more expensive than current 193-nm immersion, due to the added process steps.

Samsung and others want EUV, which, in theory, brings single-exposure back into play, thereby lowering cost

Why not the next Excimer line?

Current 193nm DUV lithography

- Lenses are very effective and perfectly transparent for 193nm and above, so many are used: a single “lens” may be up to 60 fused silica surfaces.
- System maintained at atmospheric pressure.
- Exposure field 26x32mm^2.
- Steppers capable of exposing 109 steps per 300mm wafer, and produce >100 wafers per hour. Exposure times ~10-20ns (one pulse of excimer laser).

www.tnlc.ncsu.edu/information/ceremony/lithography.ppt

Current 193nm lithography: mask material

- Photo-masks today are made from fused silica.
- Fused silica has a number of advantageous properties.
  - Chemical stability.
  - Transparency for ultraviolet light.
  - No intrinsic birefringence.
  - A low coefficient of thermal expansion.
- A low coefficient of thermal expansion: 0.5ppm/^{o}C.
  - If a mask changes temperature by 0.1^{o}C, then the distance between two features separated by 50mm will change by 2.5 nm.
  - This change in registration can be absorbed into overlay budgets, after reduction by 4× (i.e. pattern on resist misaligns by 2.5/4=0.6nm, OK).

Why not the next excimer line (157nm) or 46nm?

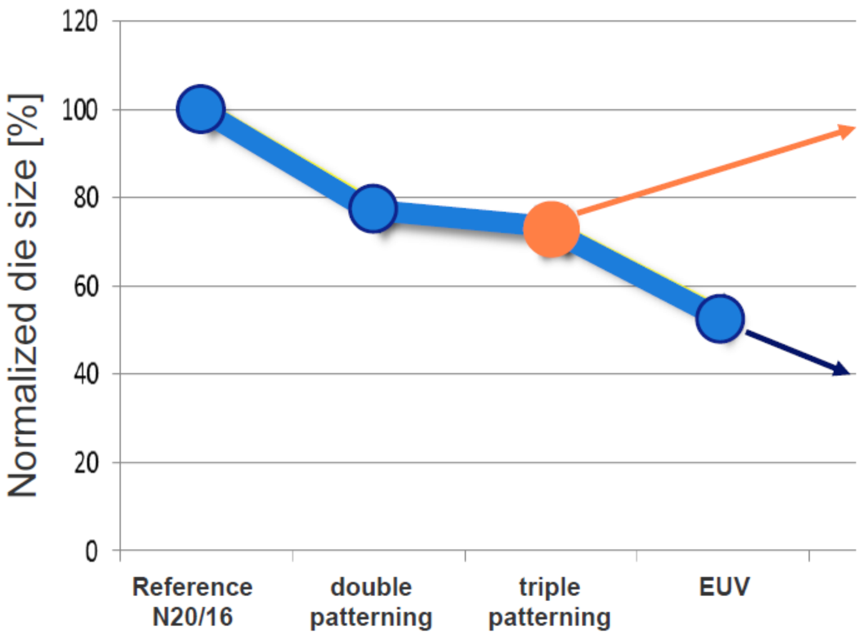
Why not a stop at 157nm?

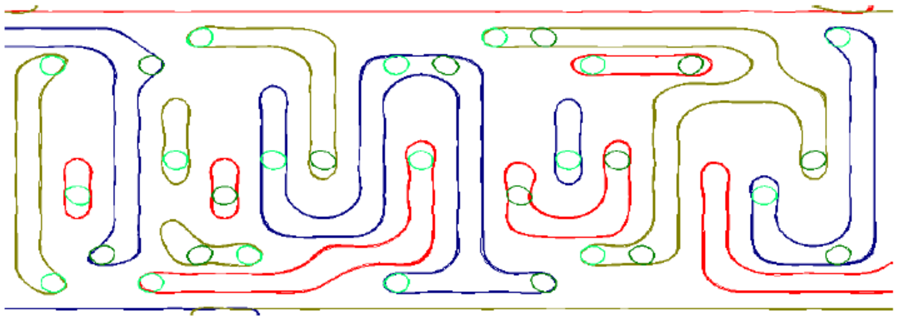
- Fused silica and atmospheric oxygen become absorptive by 157nm, so even incremental decreases in wavelength (by only 36nm) start to require a major system modification: vacuum exposure, use CaF_2 as lens material.
- The coefficient of thermal expansion of CaF_2 is 19ppm/^{o}C, versus 0.5ppm/^{o}C for fused silica.
- The 2.5nm of mask registration error now becomes nearly 100 nm (25nm after ¼ reduction, still too high).
- Below 157nm, no excimer laser line has the required output power.

Why not a stop at 46nm?

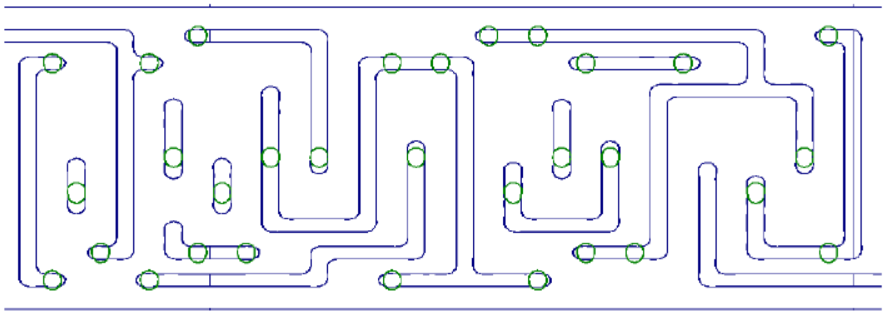
- Ne-like-Ar X-ray Laser (capillary discharge laser developed at CSU) produces EUV at this wavelength.
- The wavelength is >3× longer than 13.5nm, so lower resolution.
- Still need reflectance optics, but hard to get high reflectance.
- Materials and thicknesses issues (high absorption).

EUV Enables more Scaling for the 10 nm logic node



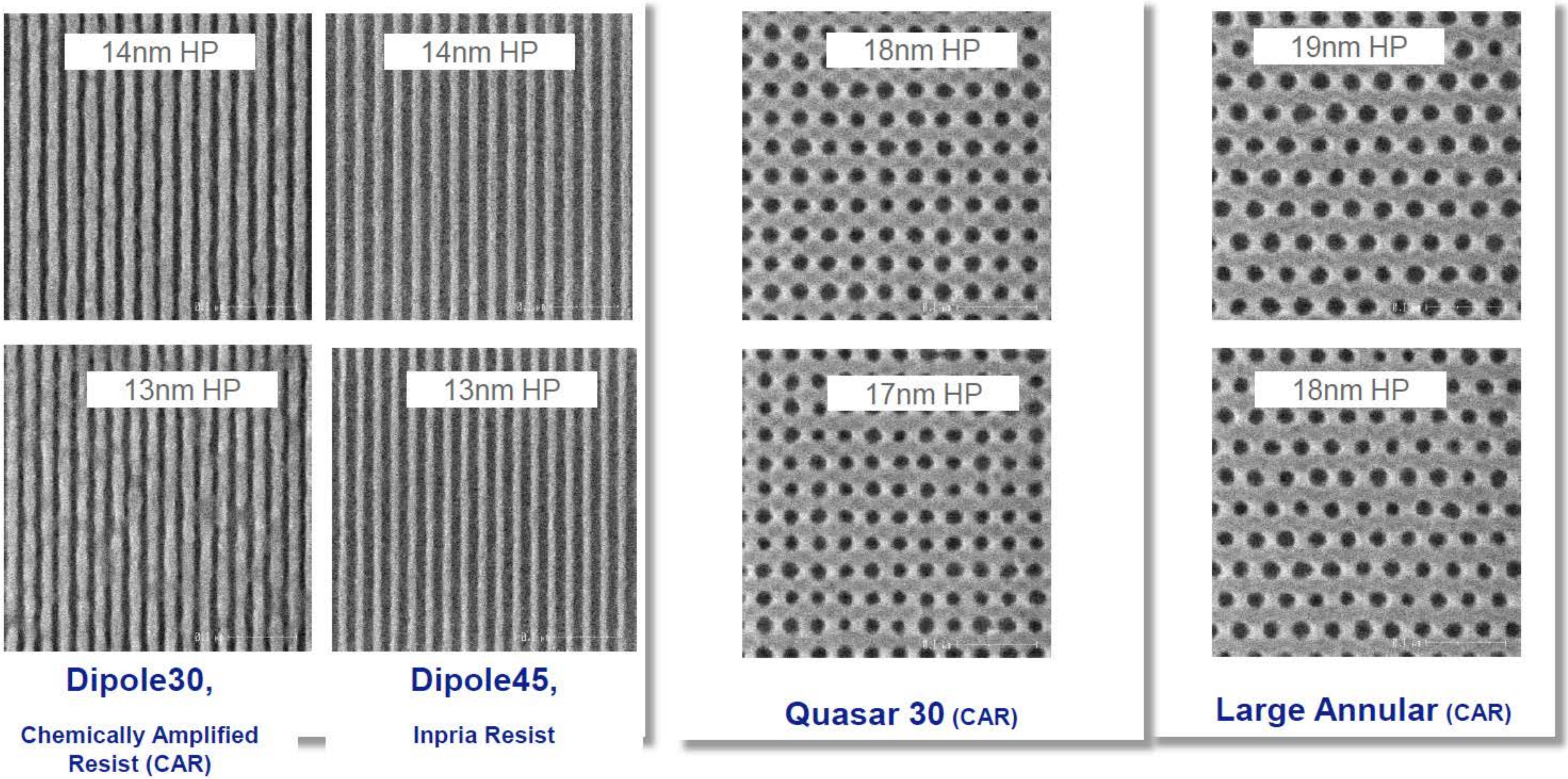


Triple patterning does not show a process window



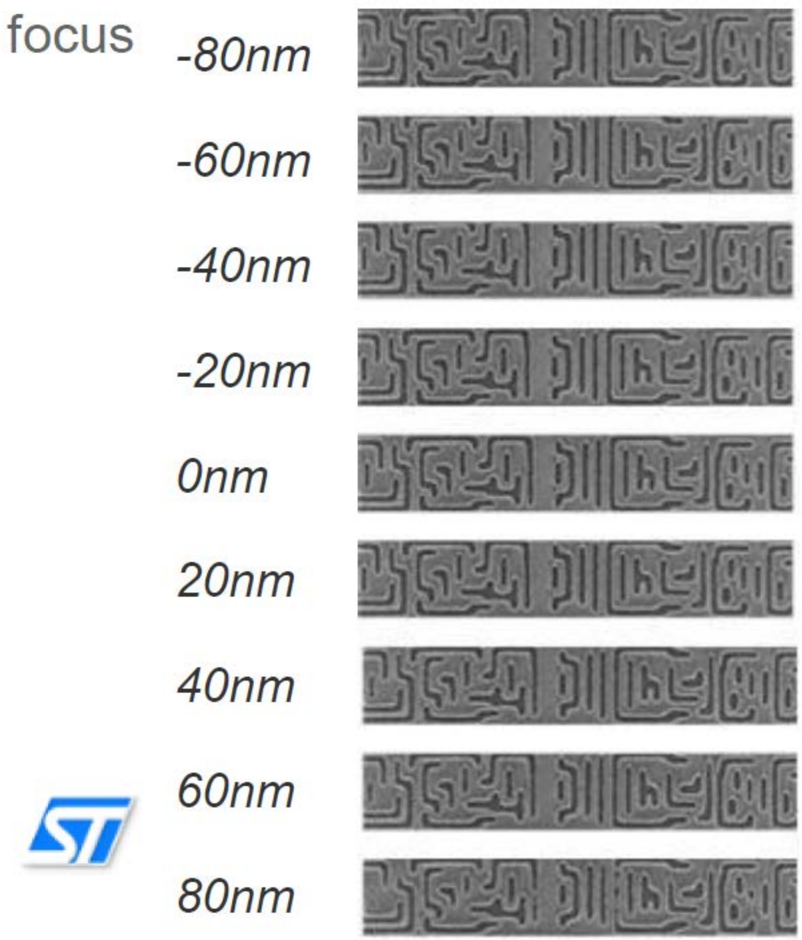
EUV meets all litho requirements

EUV Lithography Capability (Nov. 2013)



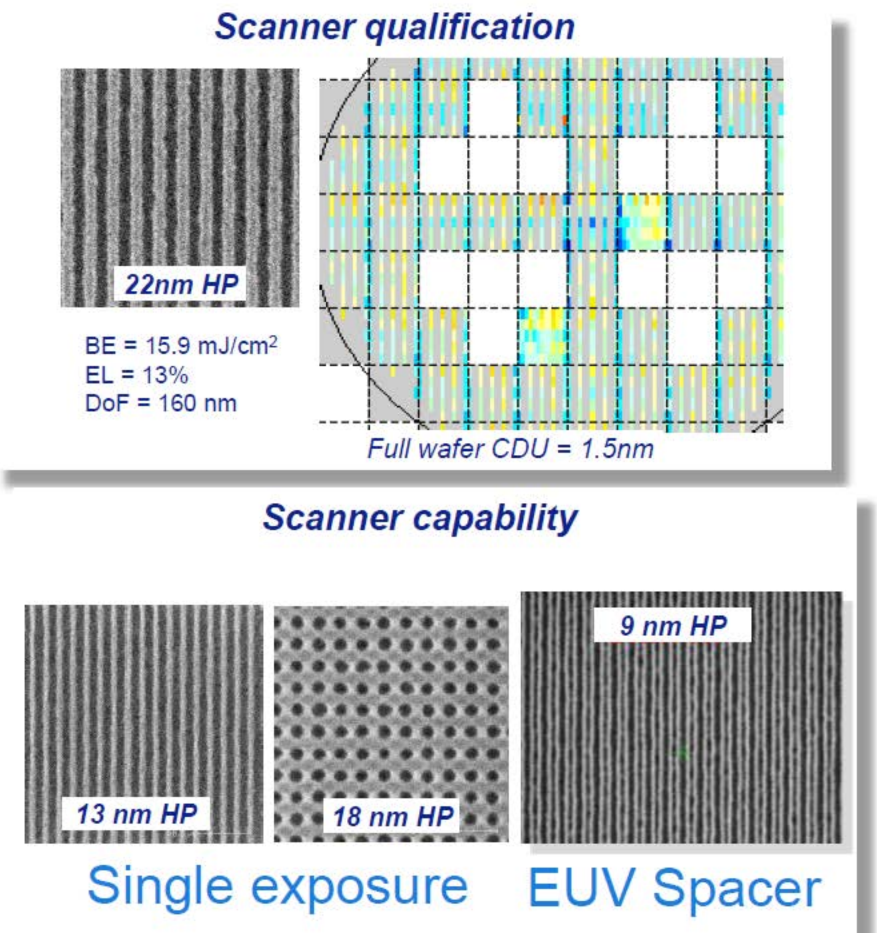
- ASML NXE 3300B

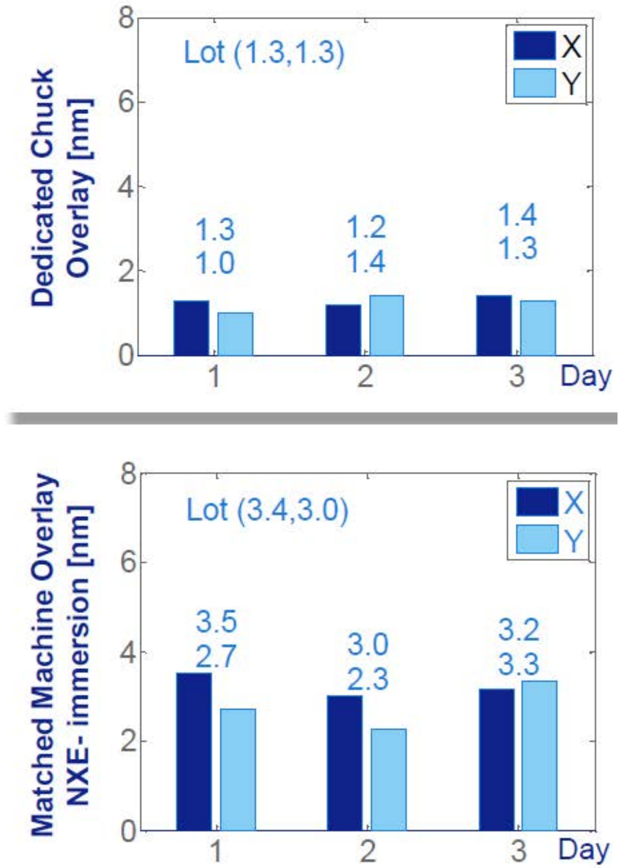
Large Depth of Focus



- Best focus difference ~ 10 nm
- Overlapping DoF: 100 ~ 120 nm

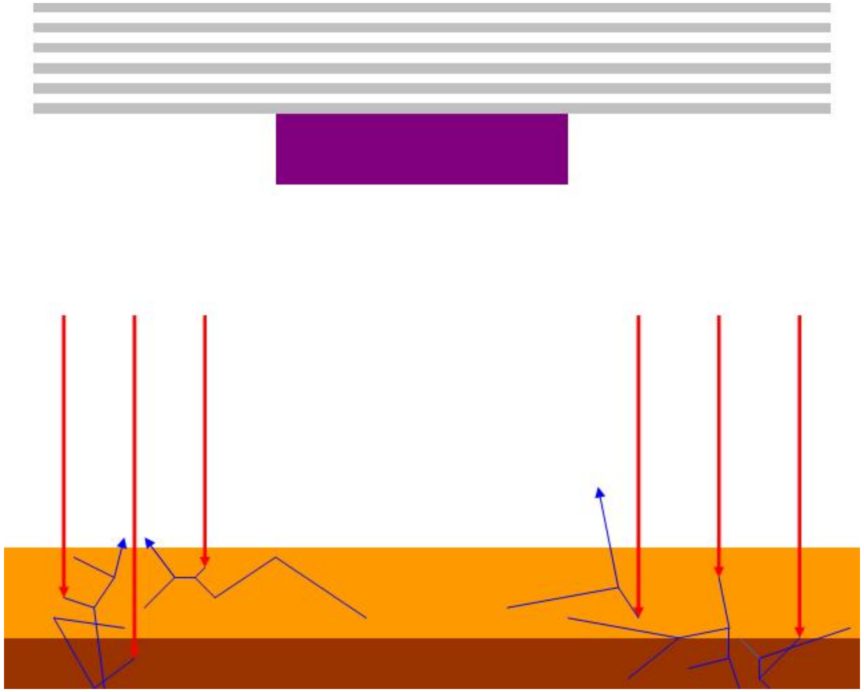
Overlay (within tool and cross tool)





- Matched overlay to immersion ~ 3.5 nm

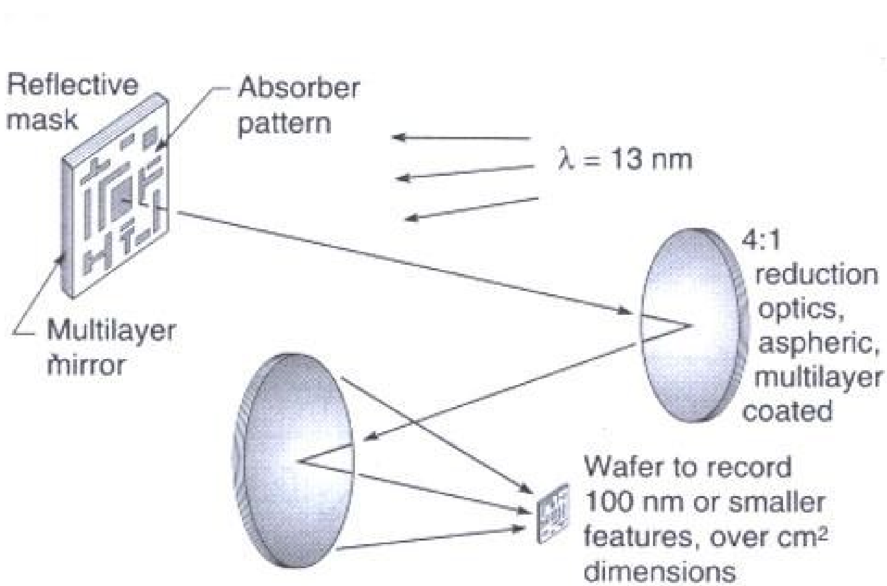
Simplest picture of EUV exposure (from Wikipedia)

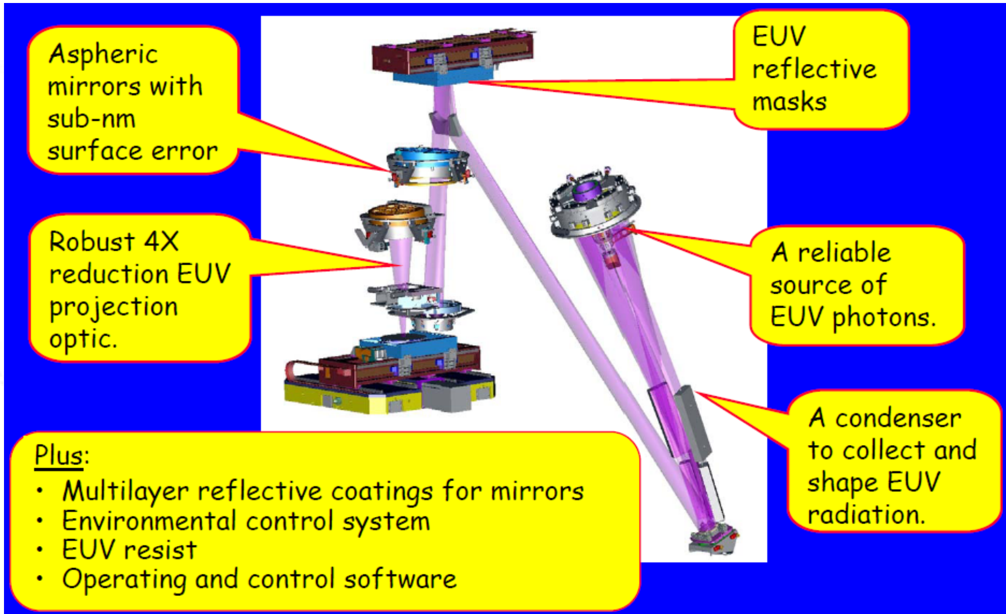


- **Image formation mechanism in EUV lithography.** *Top:* EUV multilayer and absorber (purple) constituting mask pattern for imaging a line. *Bottom:* EUV radiation (red) reflected from the mask pattern is absorbed in the resist (amber) and substrate (brown), producing photoelectrons and secondary electrons (blue).
- These electrons increase the extent of chemical reactions in the resist. A secondary electron pattern that is random in nature is superimposed on the optical image. The unwanted secondary electron exposure results in loss of resolution, observable line edge roughness and linewidth variation.

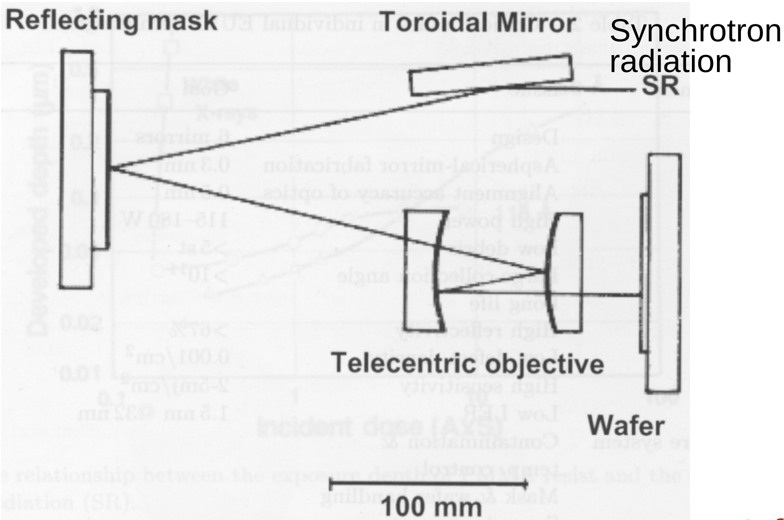
EUV lithography characteristics

- EUV radiation is strongly absorbed in virtually all materials, even gases, so EUV imaging must be carried out in a near vacuum.
- There is no refractive lenses usable - EUVL imaging systems are entirely reflective.
- But EUV reflectivity of individual materials at near-normal incidence is very low, so distributed Bragg reflectors (period about $\lambda/2$) are used.
- The best of these function in the region between 11 and 14nm (Si/Mo material)
- EUV absorption in standard optical photo-resists is very high (low penetration depth into resist), so new resist and processing techniques will be required





A few optical designs (using reflective lens/mask)



An early simple two-mirror system

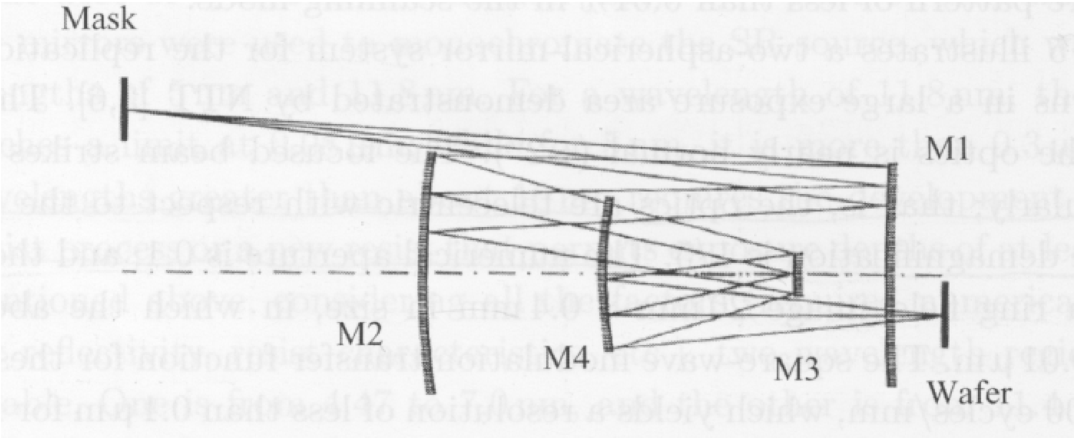


Figure 6. A four-mirror ring-field system devised by Tania Jewell *et al.*

A four-mirror system, holes in M4 to let light pass through.

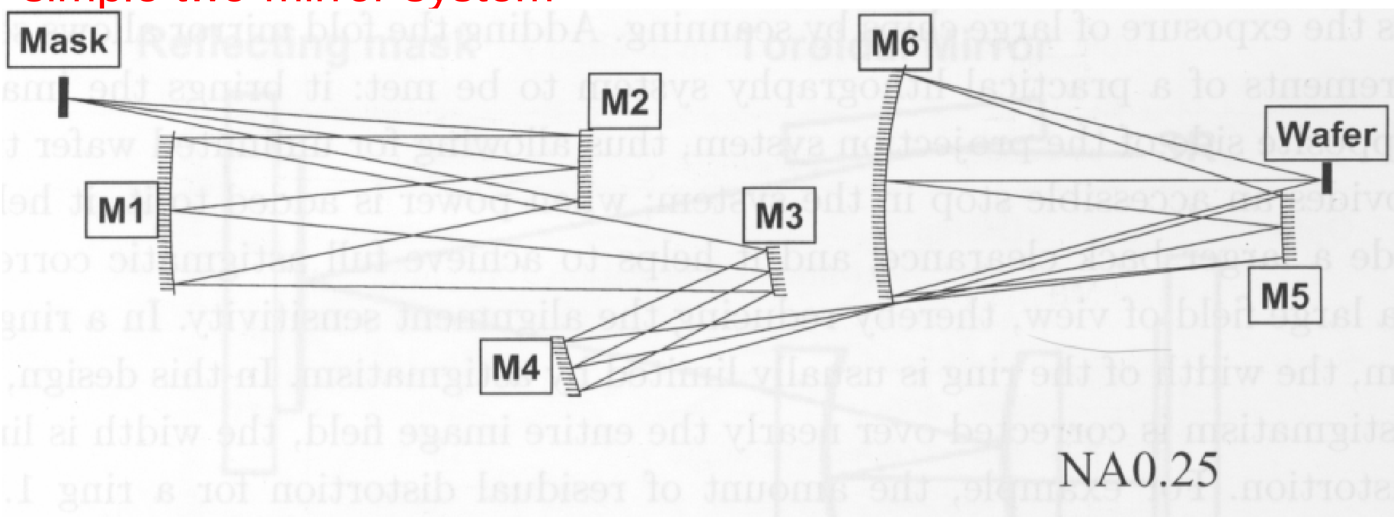
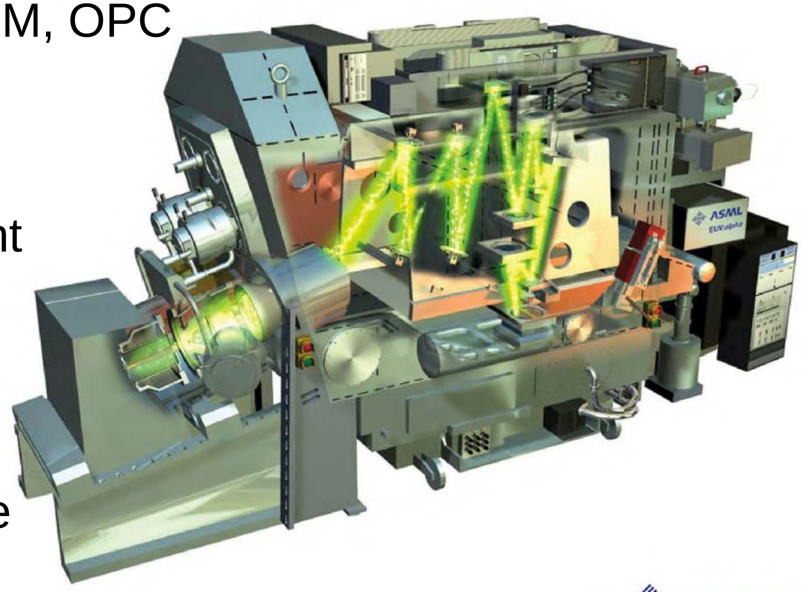


Figure 8. A 6-aspherical-mirror optics devised by Williamson in 1998.

A six-mirror system having NA 0.25

EUV is an Extension of Optical Projection Lithography

- Similarities
  - Resolution and Depth of focus scale with NA and wavelength: half pitch = $k_1\lambda/NA$
  - Uses reduction optics
  - Builds on optical lithography experience base
  - Supports optical extension tricks: OAI, PSM, OPC
  - Employs step and scan printing
- Differences
  - Uses very short wavelength (13.5 nm) light
  - 13.5 nm radiation absorbs by all materials
  - All optics are reflective
  - **Uses reflective masks**
  - No mask protective cover during exposure
  - Vacuum operation
  - Unique (difficult) source for EUV light



Courtesy of Dr. Hans Meiling, ASML