Semiconductor Manufacturing Technology

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Chapter 14

Photolithography: Alignment and Exposure

Objectives

After studying the material in this chapter, you will be able to:

1. Explain the purpose of alignment and exposure in photolithography.
2. Describe the properties of light and exposure sources important for optical lithography.
3. State and explain the critical aspects of optics for optical lithography.
4. Explain resolution, describe its critical parameters, and discuss how it is calculated.
5. Discuss each of the five equipment eras for alignment and exposure.
6. Describe reticles, explain how they are manufactured and discuss their use in microlithography.
7. Discuss the optical enhancement techniques for sub-wavelength lithography.
8. Explain how alignment is achieved in lithography.

Eight Basic Steps of Photolithography

Step	**Chapter Covered**
1. Vapor prime	13
2. Spin coat	13
3. Soft bake	13
4. **Alignment and exposure**	**14**
5. Post-exposure bake	15
6. Develop	15
7. Hard bake	15
8. Develop inspect	15

Table 14.1

Three Functions of the Wafer Stepper

1. Focus and align the quartz plate reticle (that has the patterns) to the wafer surface.
2. Reproduce a high-resolution reticle image on the wafer through exposure of photoresist.
3. Produce an adequate quantity of acceptable wafers per unit time to meet production requirements.

Reticle Pattern Transfer to Resist

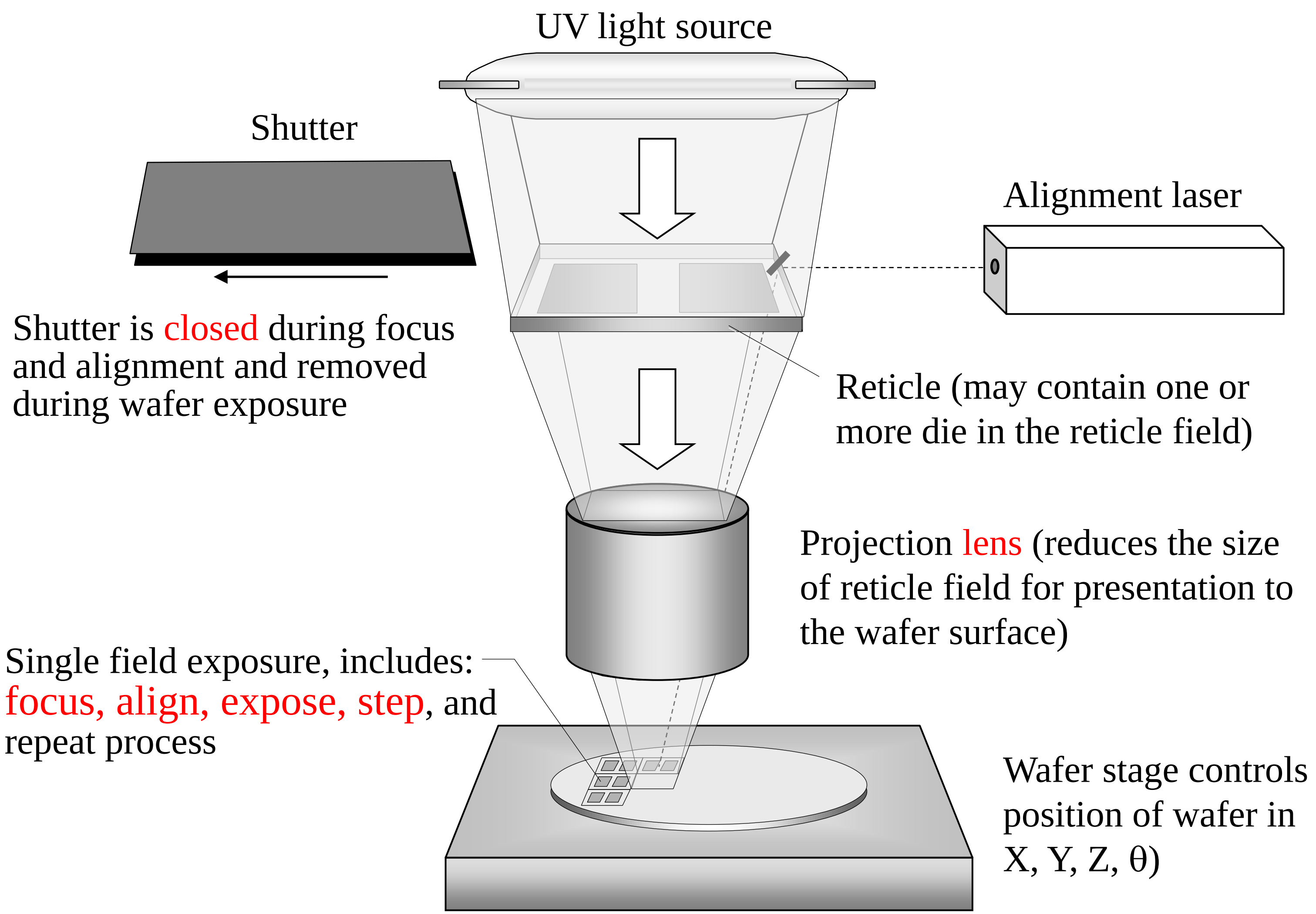
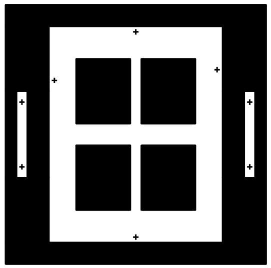
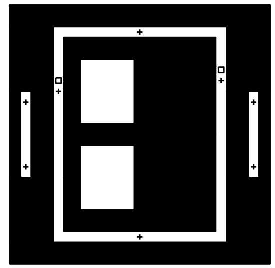


Figure 14.1

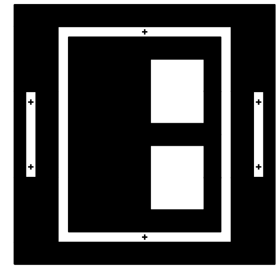
Layout and Dimensions of Reticle Patterns



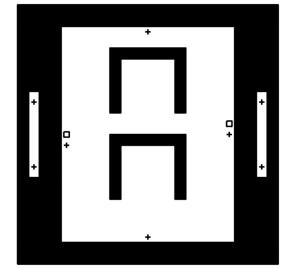
1) STI etch



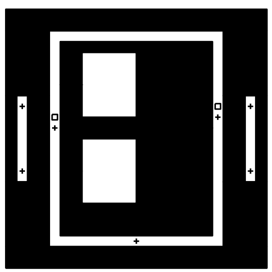
2) P-well implant



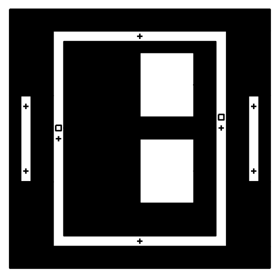
3) N-well implant



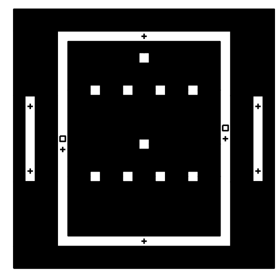
4) Poly gate etch



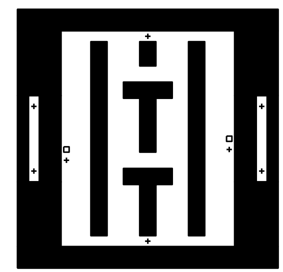
5) N^+ S/D implant



6) P^+ S/D implant

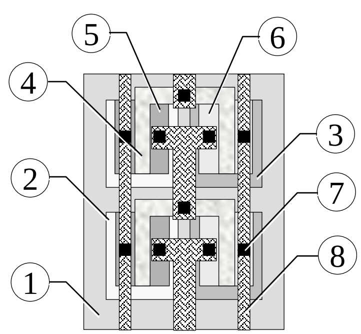


7) Oxide contact etch

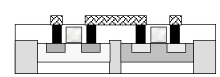


8) Metal etch

Resulting layers



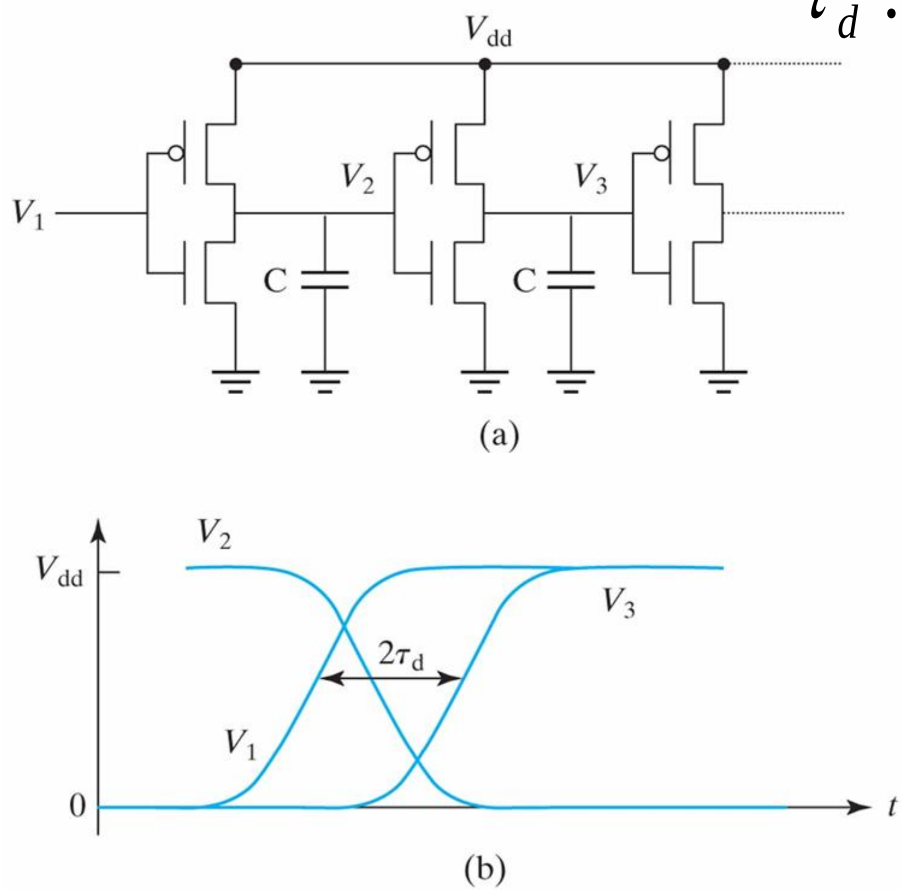
Top view



Cross section

Figure 14.2

Inverter Speed – propagation delay



τ_d :

- Propagation delay time is the time delay for a signal to propagate from one gate to the next in a chain of identical gates.
- The delay is the time for the on-state transistor supplying a current Ion to change the output by $V_{dd}/2$ (not V_{dd})

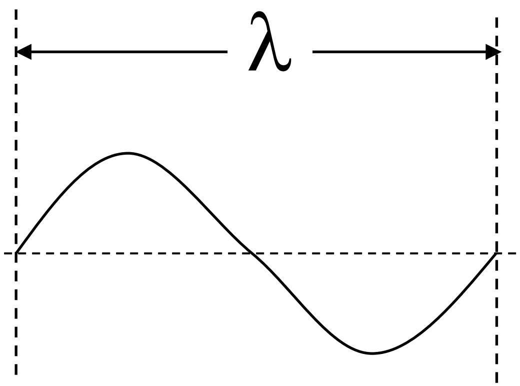
Optical Lithography

Light

- Interference of Light Waves
  - Optical Filters
- Electromagnetic Spectrum

Light Wavelength and Frequency

$$\lambda = \frac{v}{f}$$



v = velocity of light, 3×10^8 m/sec

f = frequency in Hertz (cycles per second)

λ = wavelength, the physical length of one cycle of a frequency, expressed in meters

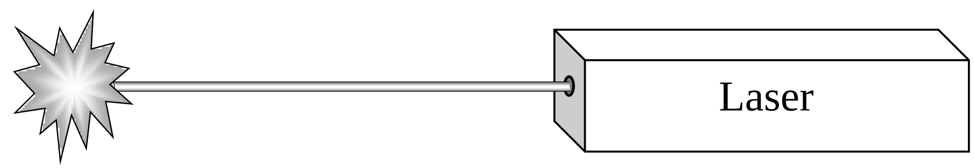


Figure 14.3

Wave Interference

- Sinusoidal waves of any type (e.g. light, electrical, or sound) that have the same frequency (monochromatic) can have interference between the individual waves.

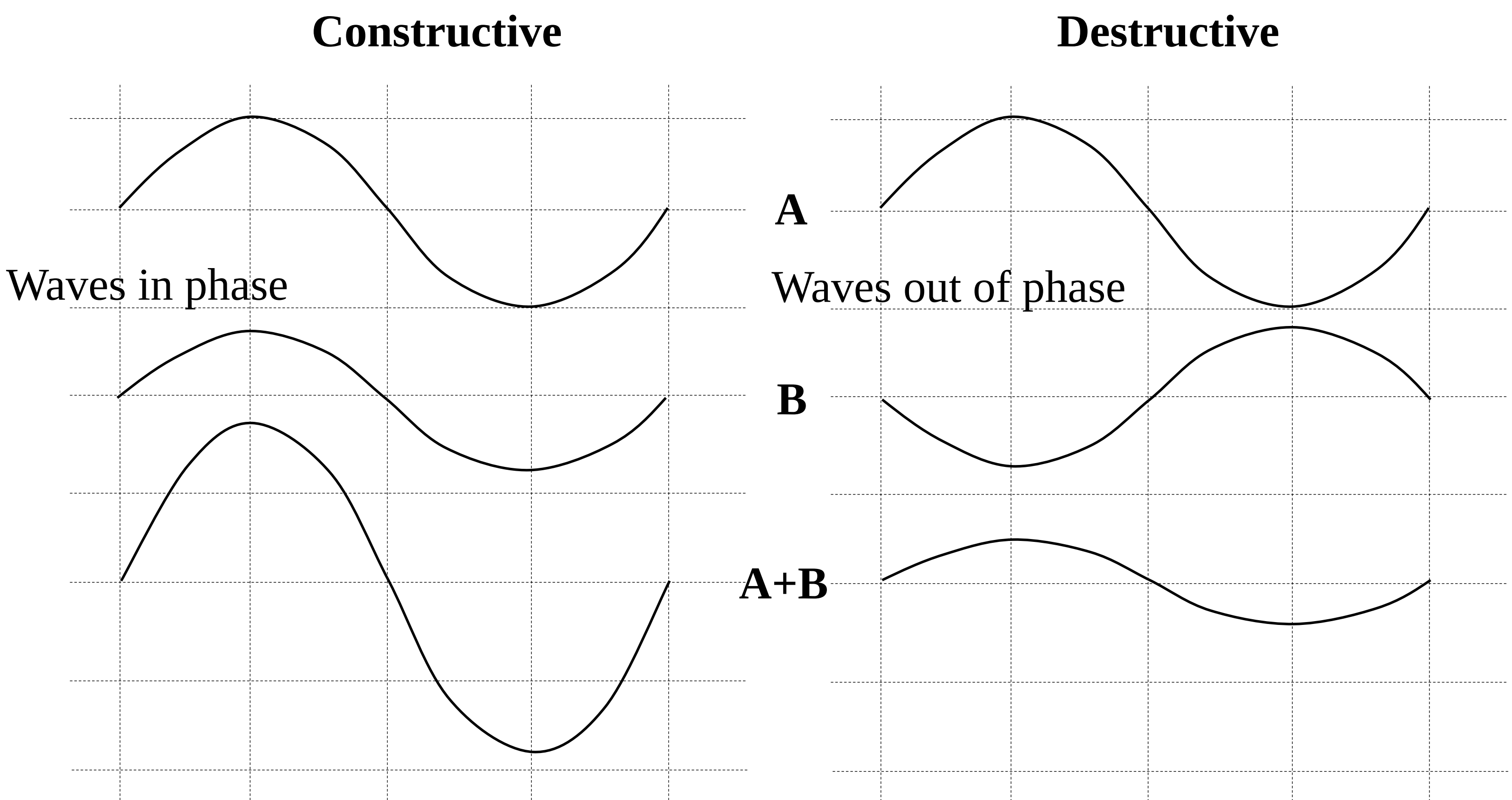


Figure 14.4

Optical Filtration

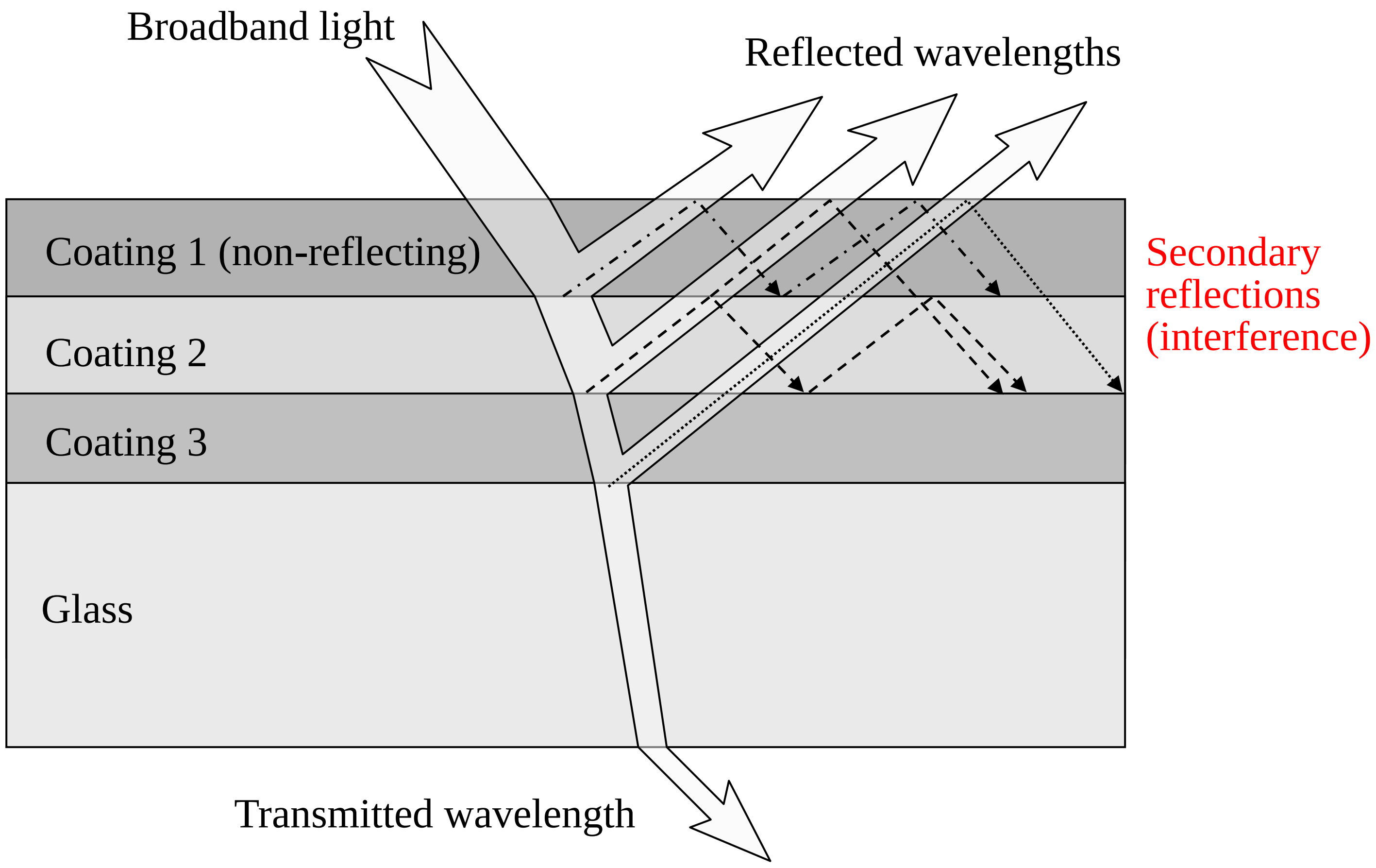


Figure 14.5

Ultraviolet Spectrum

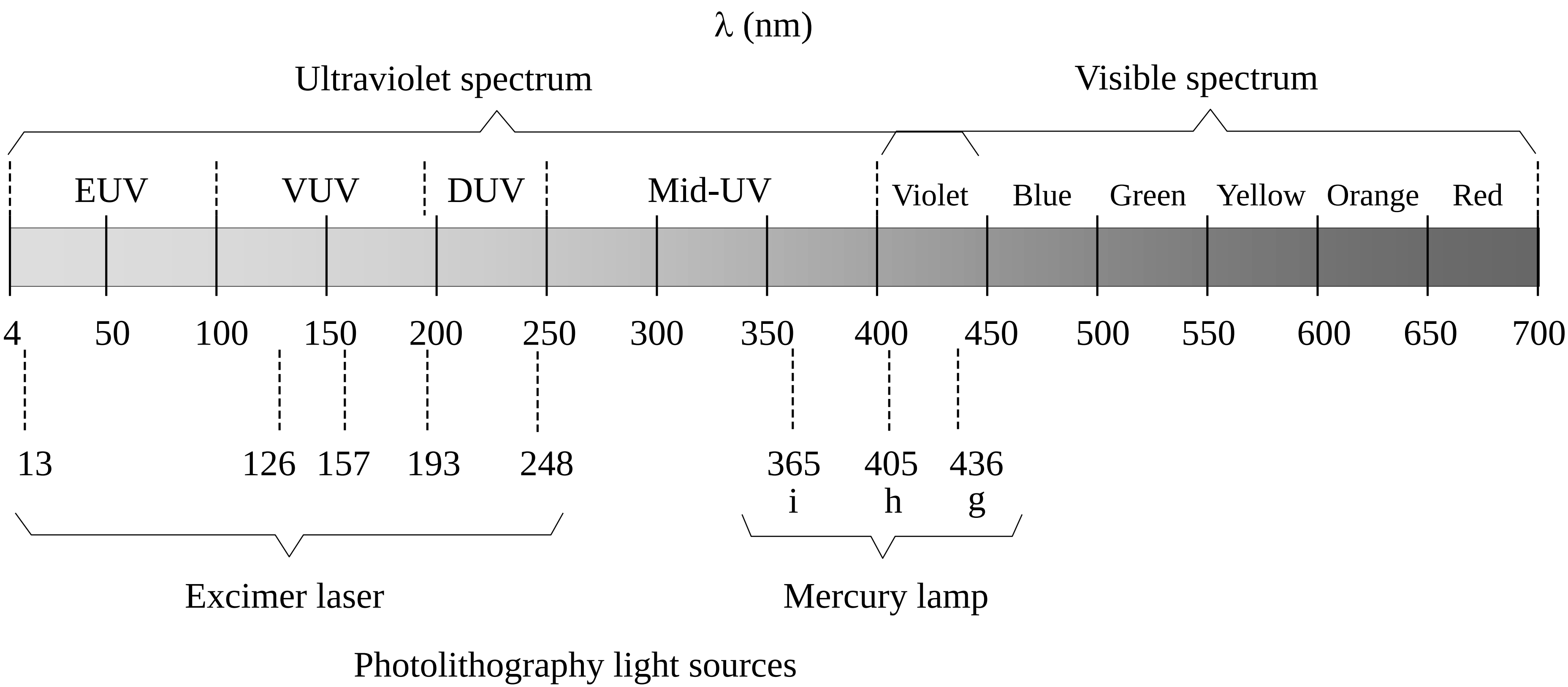


Figure 14.6

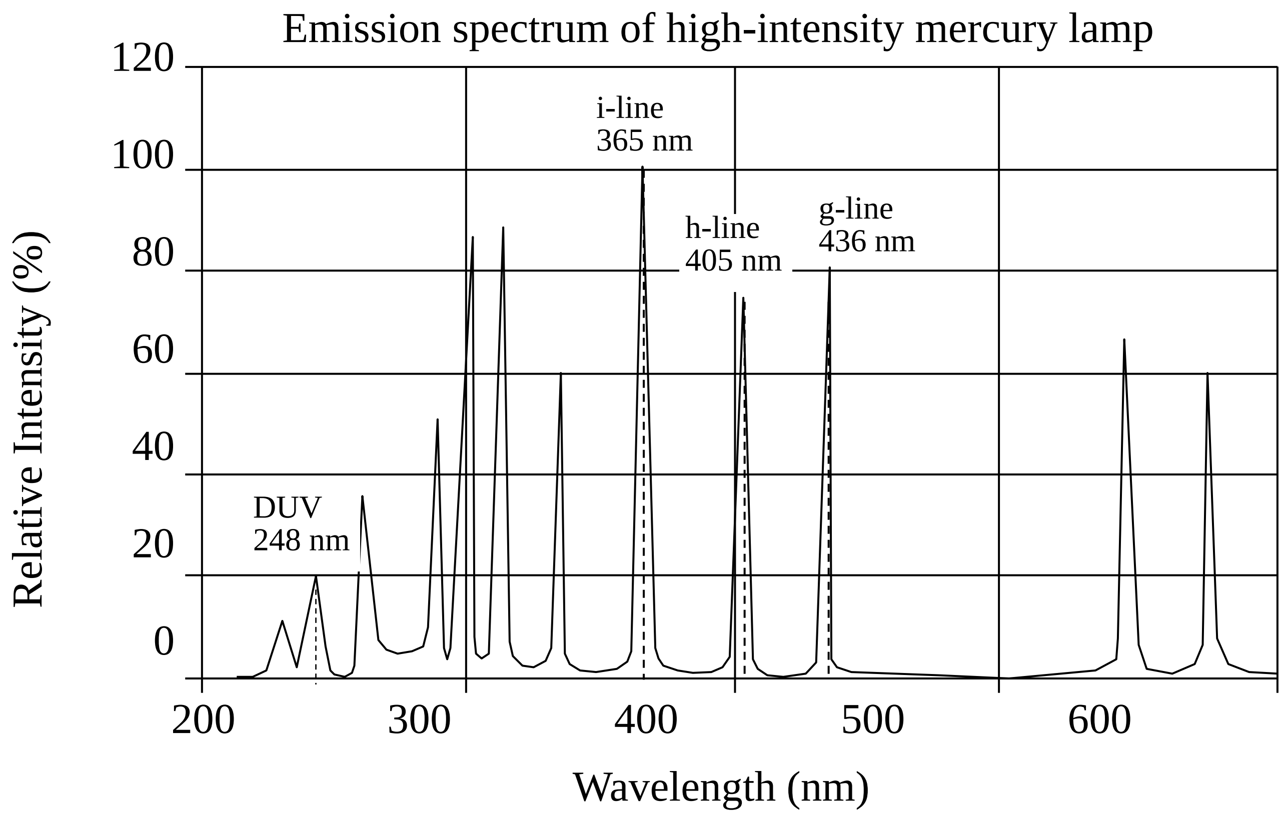
Optical Lithography

- During exposure of the resist, photochemical transformation occur in the resist material to transfer the pattern from the mask.
- This is a critical step in photolithography.
- It must occur in the shortest amount of time and be repeatable for high-volume production of wafers.

Exposure Sources

- Mercury Arc Lamp
- Excimer Laser
  - Spatial Coherence
- Exposure Control

Emission Spectrum of Typical High Pressure Mercury Arc Lamp



- The high-pressure mercury arc lamp is used as the UV illumination source in all conventional i-line steppers
- DNQ-novolak resist responds to the UV i-line wavelength of 365 nm

Figure 14.7

Mercury Arc Lamp Intensity Peaks

UV Light Wavelength (nm)	Descriptor	CD Resolution (μm)
436	g-line	0.5
405	h-line	0.4
365	i-line	0.35
248	Deep UV (DUV)	0.25

Table 14.2

Spectral Emission Intensity of 248 nm Excimer Laser vs. Mercury Lamp

- Energy= power x time, low power needs long time
- High-pressure of noble gas and halogen
- Excited by a high-voltage pulse discharge

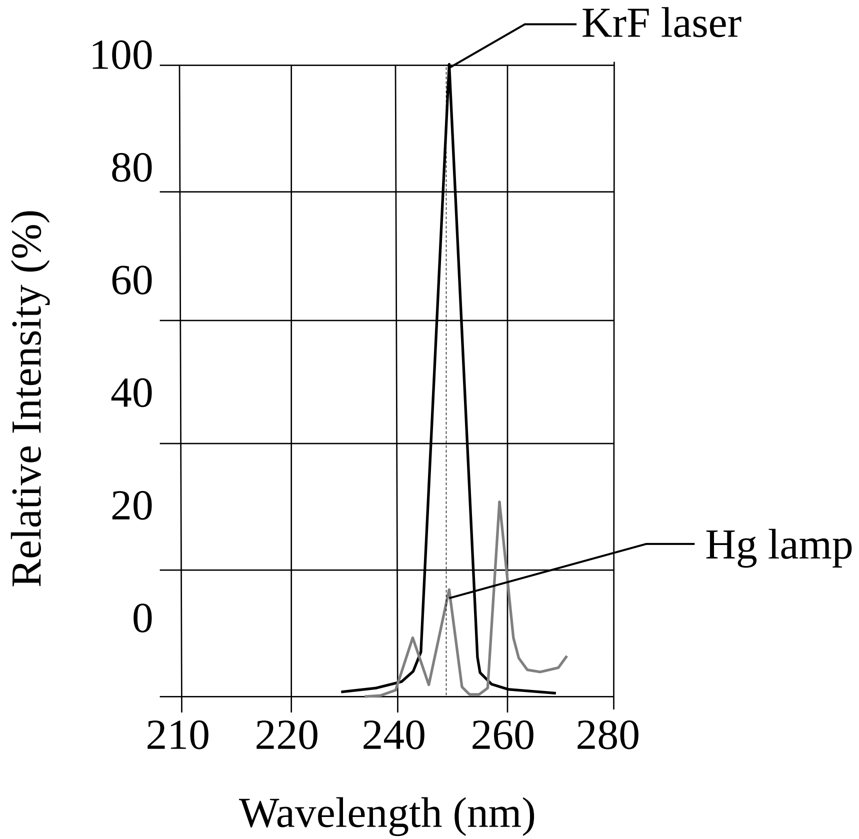
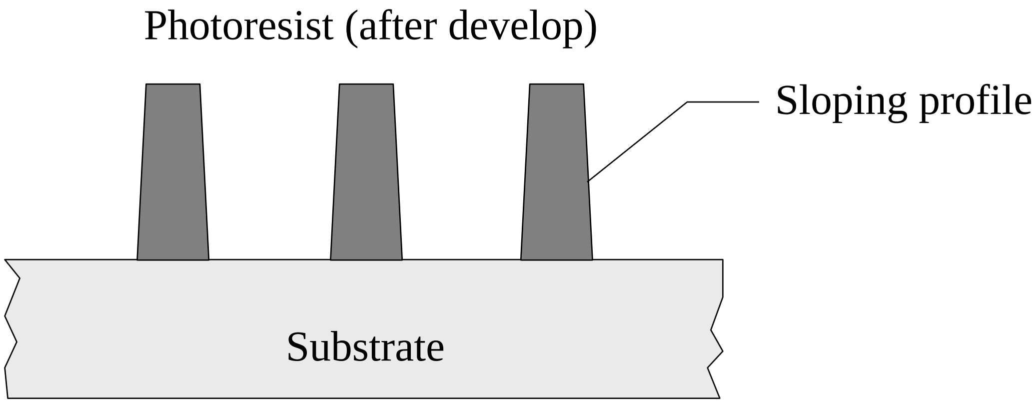


Figure 14.8

Excessive Resist Absorption of Incident Light



- Resist resin is excessive absorbance of incident radiation
- The light intensity at the bottom of the resist is considerably less than that received at the top
- To achieve straight-wall images, the resist absorb only ~20 %

Figure 14.9

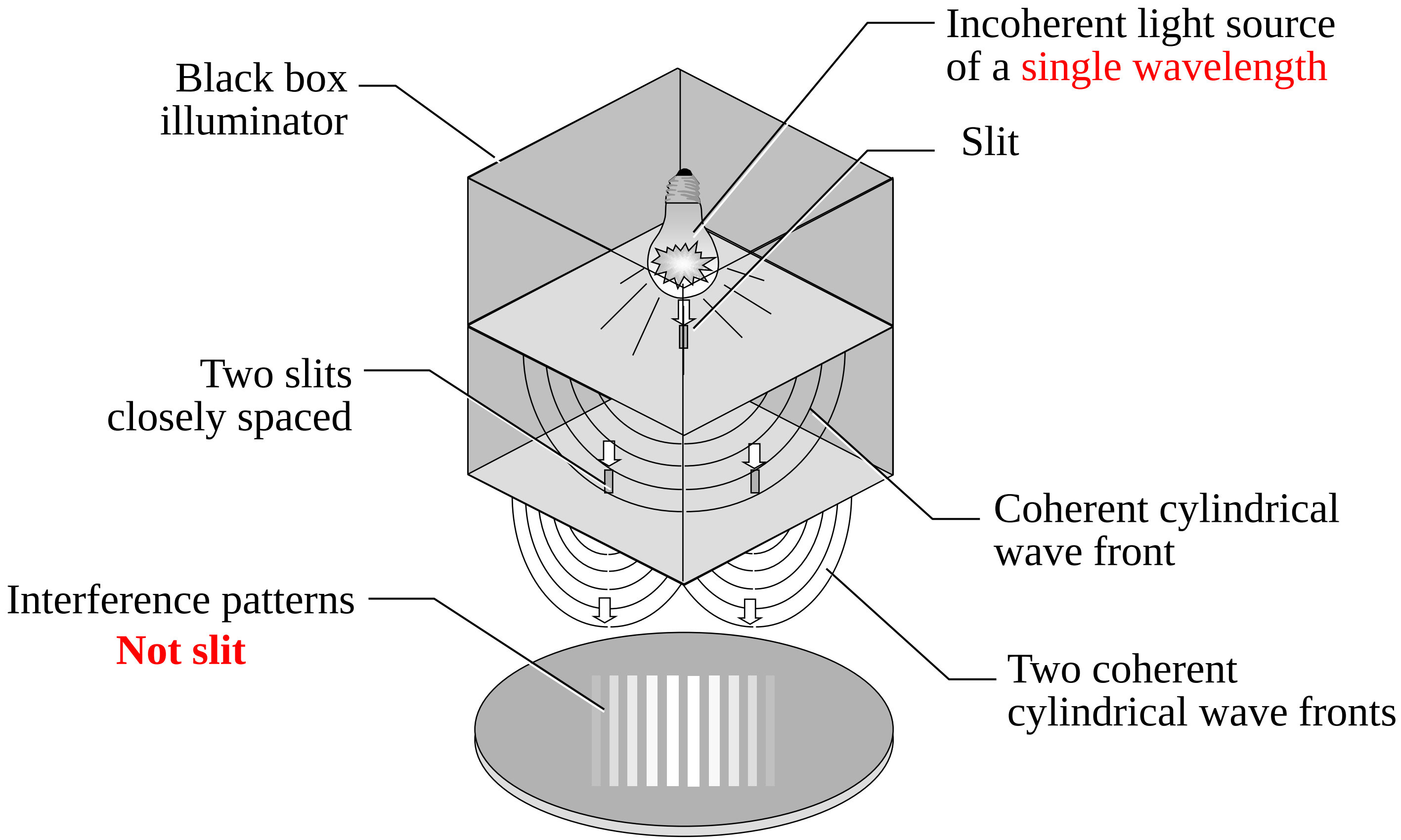
Excimer Laser Sources for Semiconductor Photolithography

Material	Wavelength (nm)	Max. Output (mJ/pulse)	Frequency (pulses/sec)	Pulse Length (ns)	CD Resolution (μm)
KrF	248	300 – 1500	500	25	$\leq$ 0.25
ArF	193	175 – 300	400	15	$\leq$ 0.18
F_2	157	6	10	20	$\leq$ 0.15

- An excimer is an exotic [異質] molecule formed from an atom of a noble gas and halogen, such as argon fluoride (ArF), where the molecule exists only in a quasi-stable, excited state
- Excimer= excited dimer [二聚體]
- Move to 193 nm: optical material have undesirable absorbance and are more sensitive to laser damage

Table 14.3

Spatial Coherence



- Spatial coherence is controlled through optics to minimize interference patterns that can be formed in the image

Figure 14.10

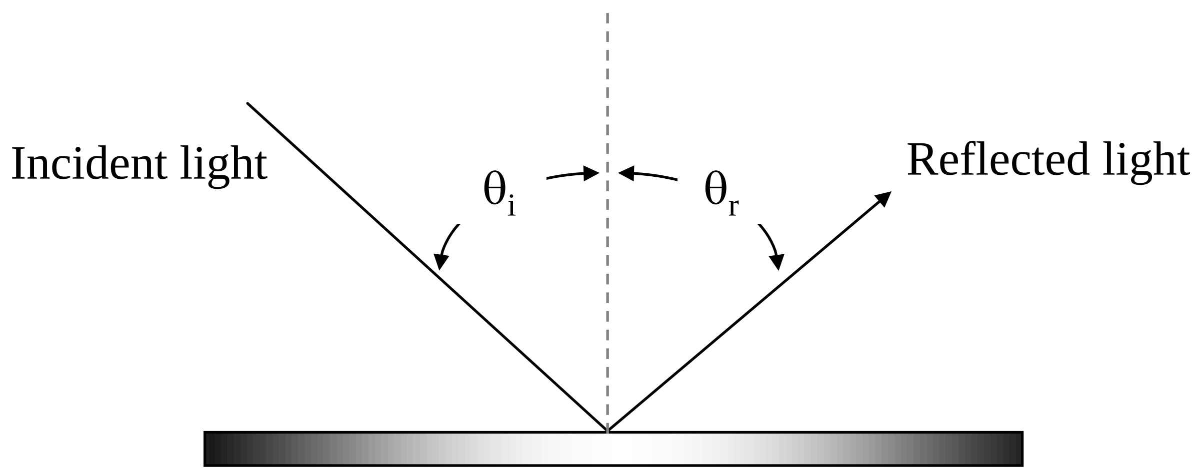
Optical Lithography

Optics

- Reflection of Light
- Refraction of Light
- Lens
- Diffraction
- Numerical Aperture, NA
- Antireflective Coating

Law of Reflection

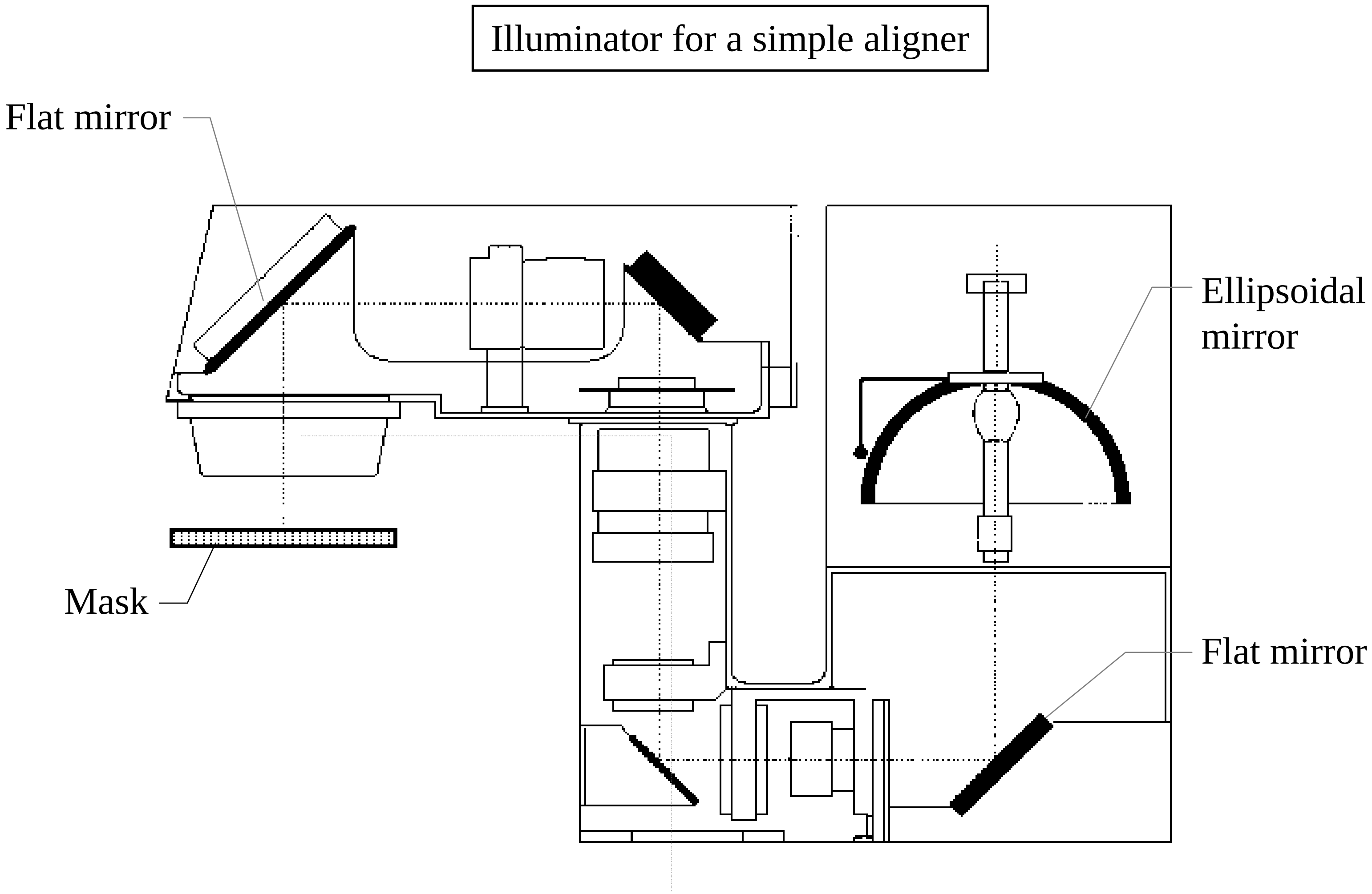
The angle of incidence of a light wavefront with a plane mirror is equal to the angle of reflection.



Law of Reflection: $\theta_i = \theta_r$

Figure 14.11

Application of Mirrors



Used with permission from Canon USA

Figure 14.12

Refraction of Light Based on Two Mediums

- Snell's Law: $\sin \theta_i = n \sin \theta_r$
- Index of refraction, $n = \sin \theta_i / \sin \theta_r$

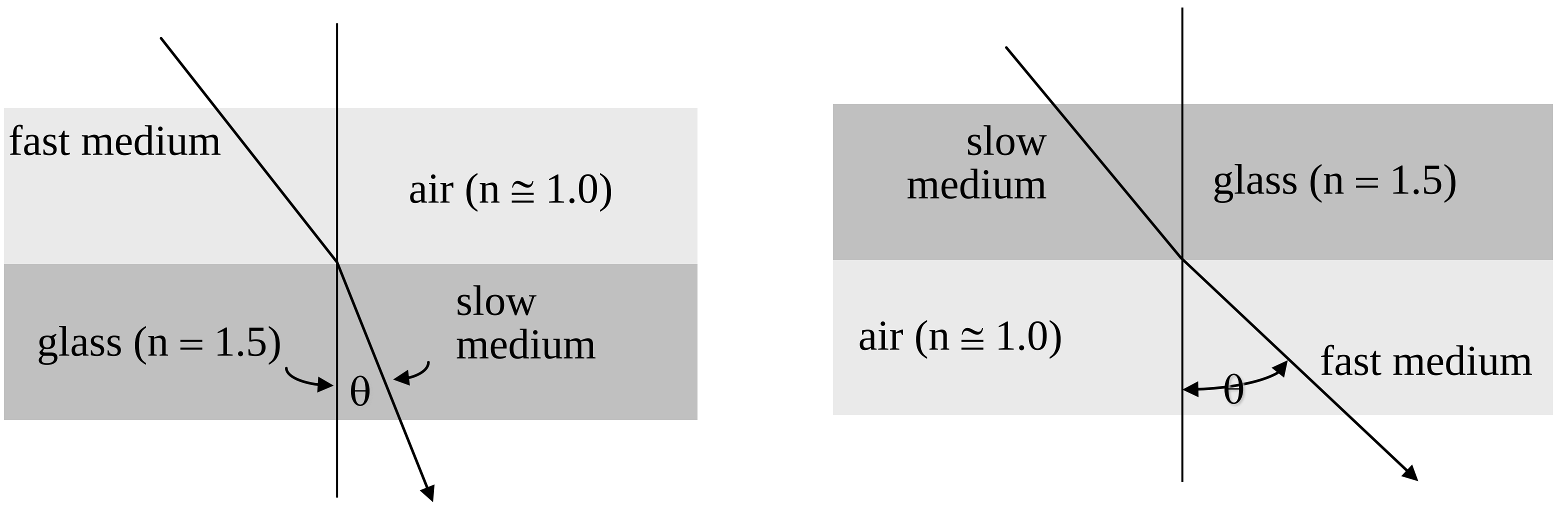


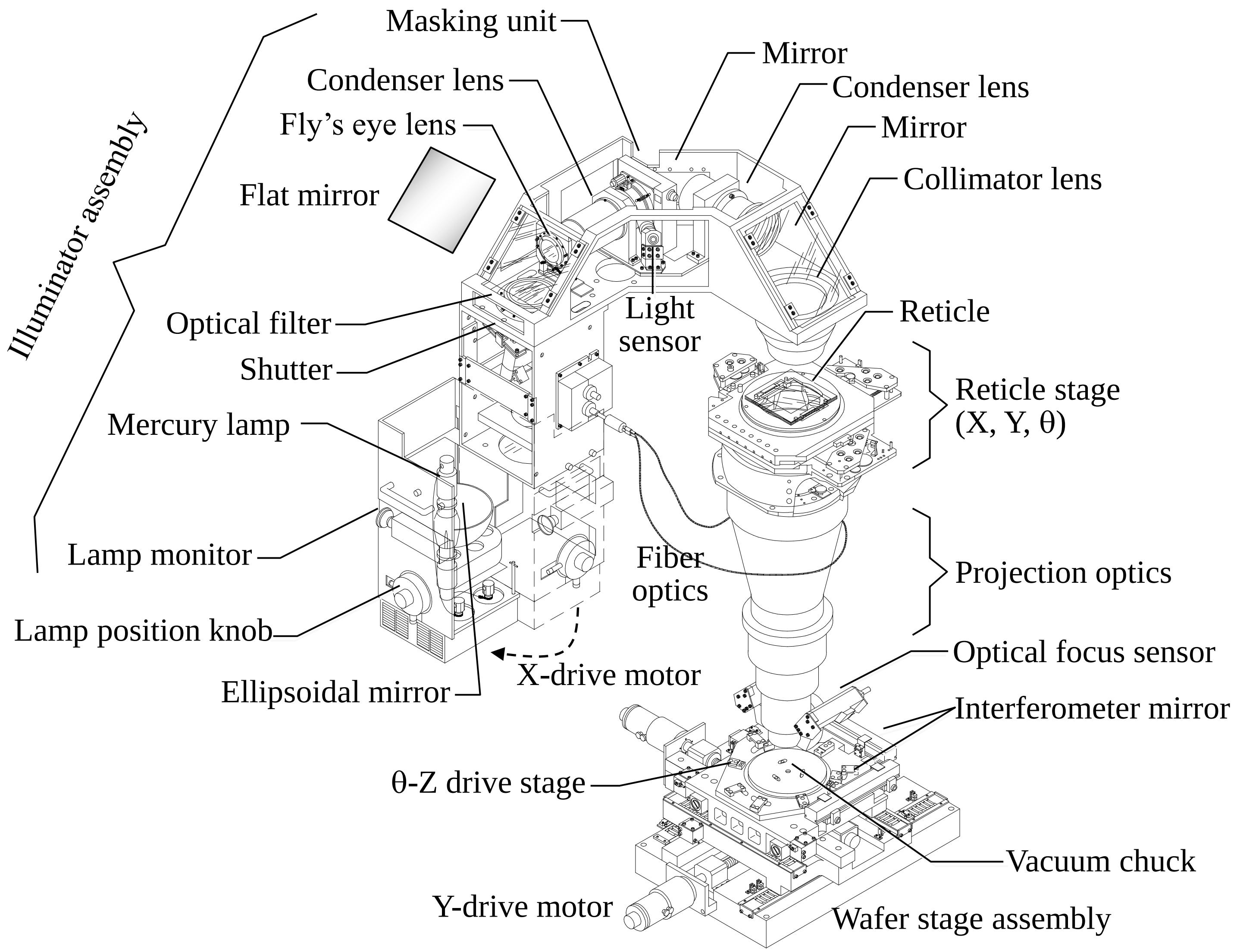
Figure 14.13

Absolute Index of Refraction for Select Materials

Material	Index of Refraction (n)
Air	1.000293
Water	1.33
Fused Silica (Amorphous Quartz)	1.458
Diamond	2.419

Table 14.4

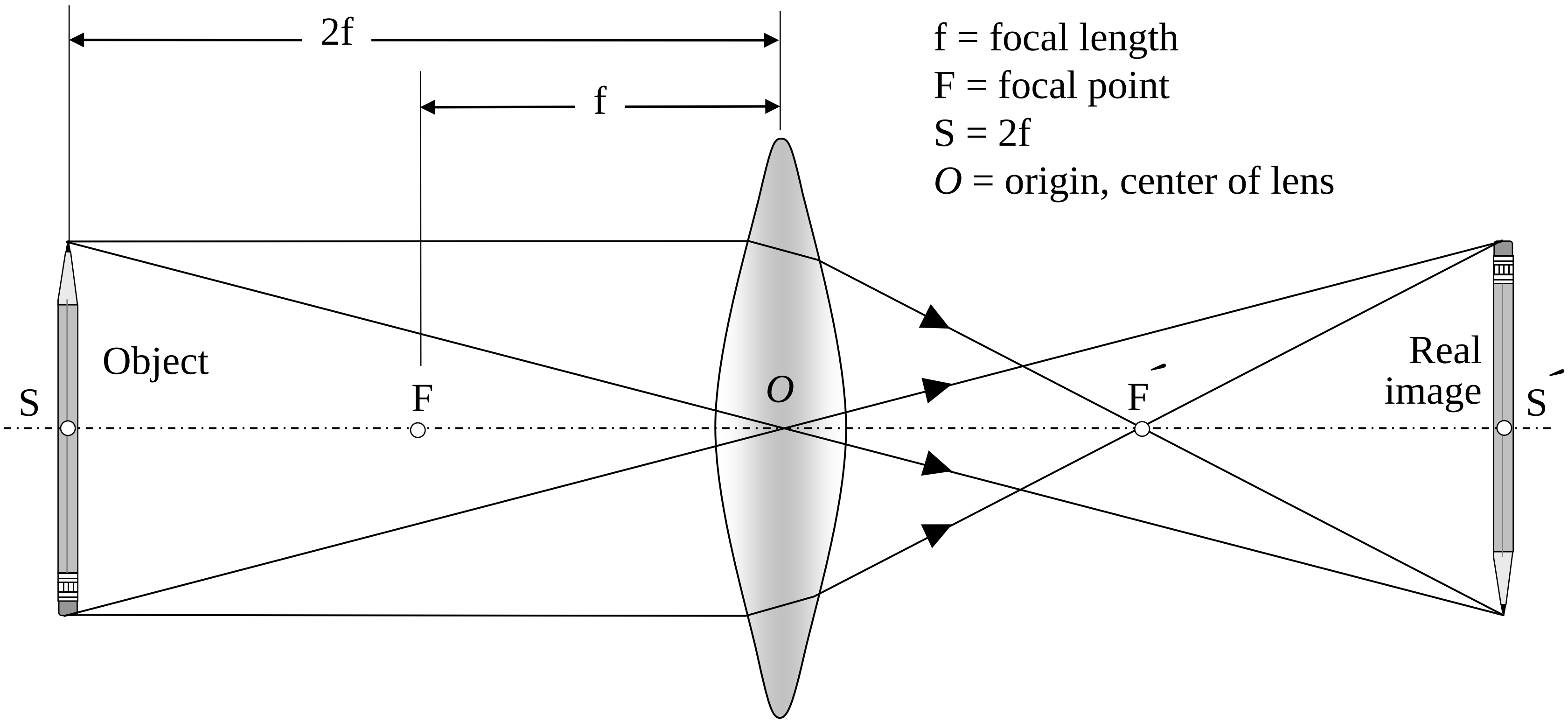
Optical System of Lenses



Used with permission from Canon U.S.A., FPA-2000 i1 exposure system

Figure 14.14

Converging Lens with Focal Point



- Lenses and refractive optics in photolithography steppers and scanner system play a critical role in achieving the resolution needed to achieve the CD linewidths

Figure 14.15

Diverging Lens with Focal Point

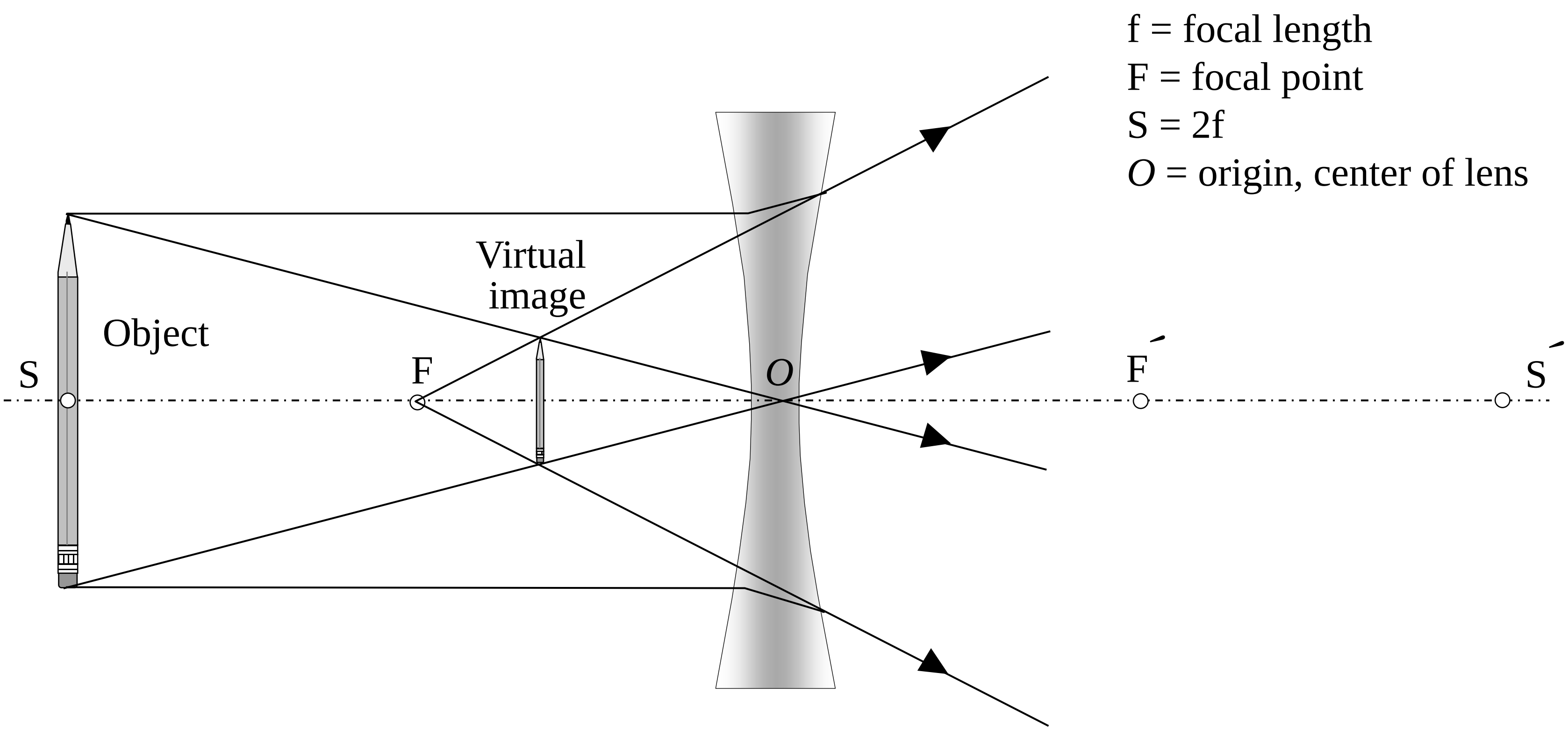


Figure 14.16

Laser-Induced Lens Compaction

- Lenses have traditionally been made of glass
- For 248-nm, fused silica is used, less light absorption
- CaF_2 is used for 193-nm
- Lens compaction is a structural rearrangement of the lens material that cause densification of the lens material
- It is not well understood, but it occurs to the total cumulative laser beam exposure and peak power density
- Lenses are of the finest quality materials and workmanship.
- Deviation from the ideal lens behavior are referred to as aberrations

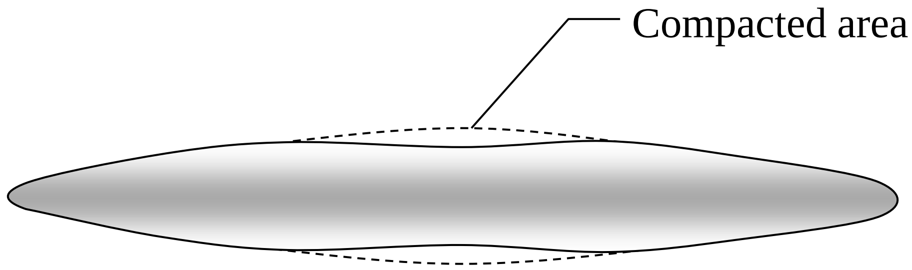


Figure 14.17

Interference Pattern from Light Diffraction at Small Opening

- Light travels in straight lines.
- Diffraction occurs when light hits edges of objects.
- Diffraction bands, or interference patterns, occur when light waves pass through narrow slits.

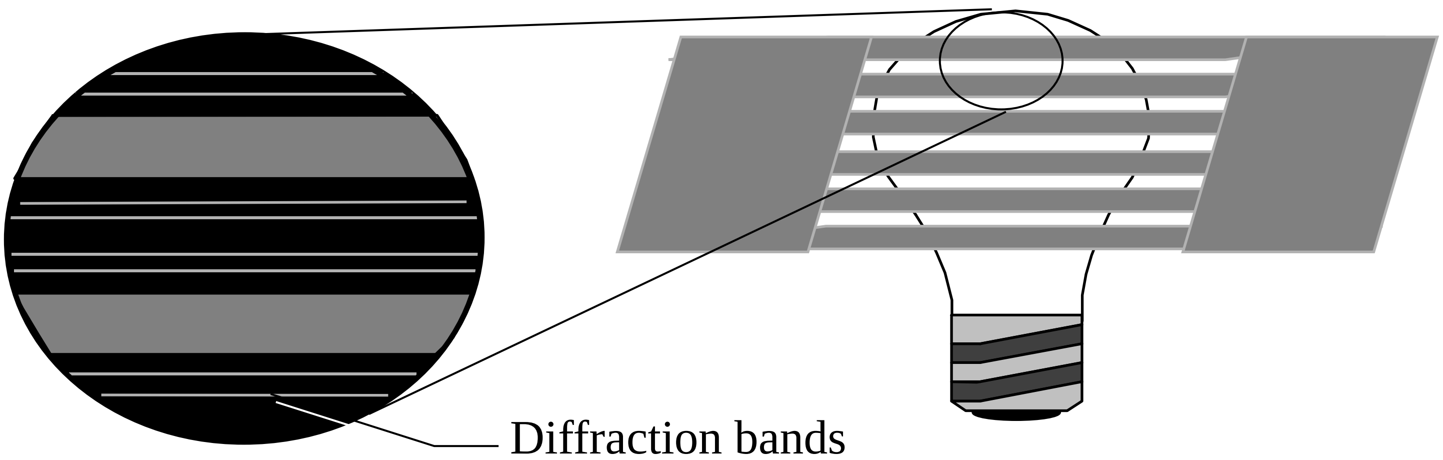
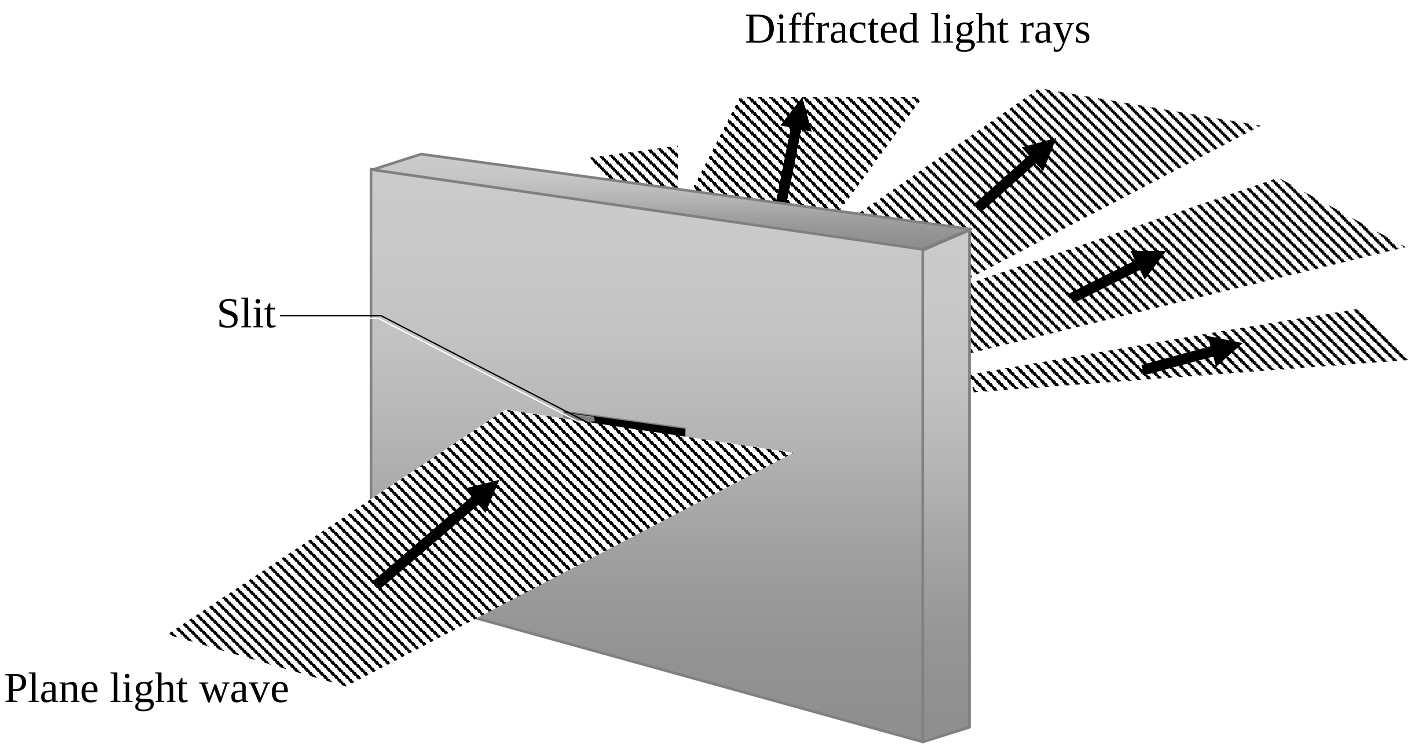


Figure 14.18

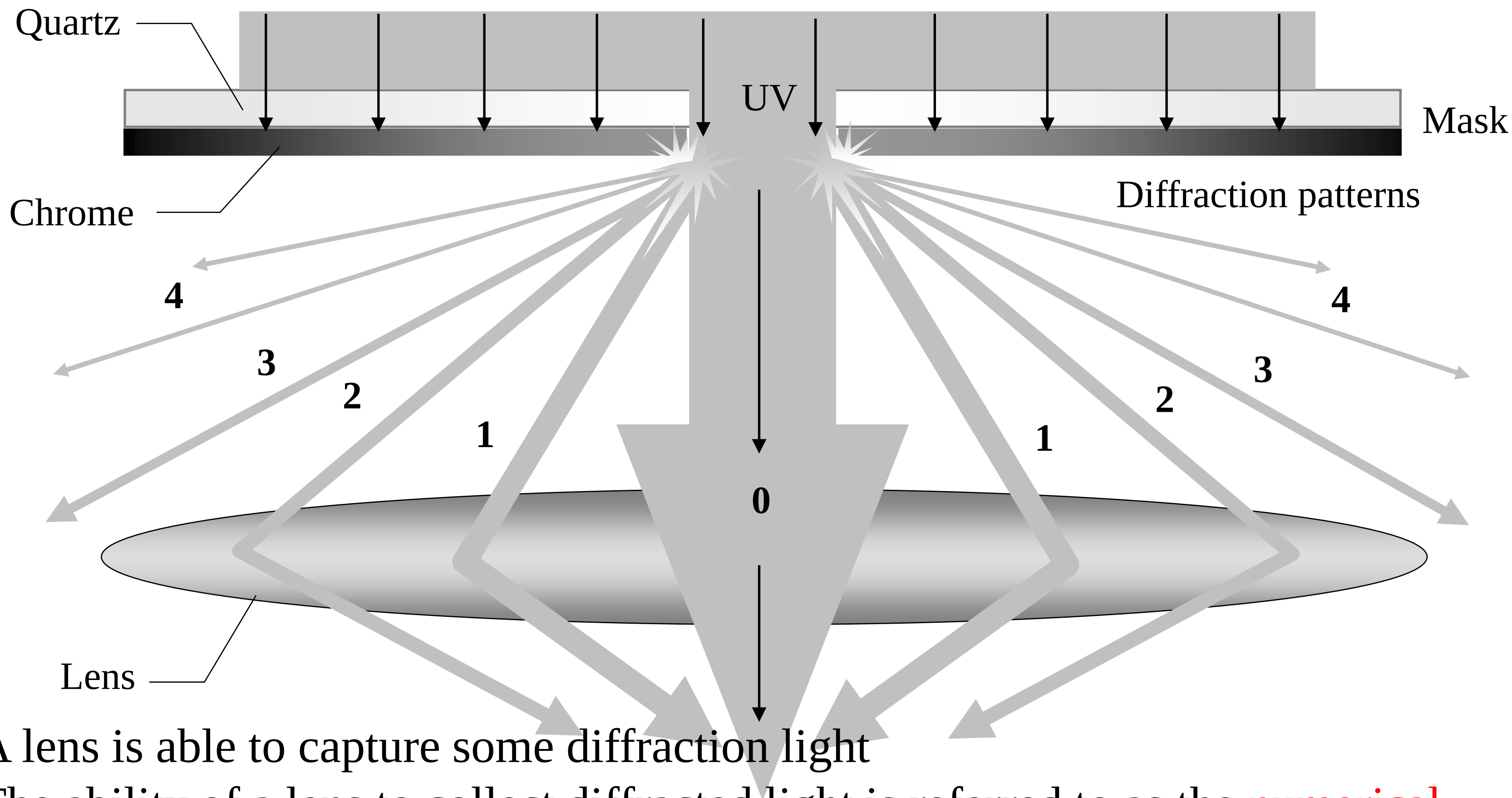
Diffraction in a Reticle Pattern



- Light diffraction is a concern in photolithography because of the extremely small patterns of sharp edges and narrow spaces on reticles
- The problem is worse in small holes, such as small contact opening.
- The interference patterns caused by diffraction can make small contact holes and small line difficult to print.

Figure 14.19

Lens Capturing Diffracted Light



- A lens is able to capture some diffraction light
- The ability of a lens to collect diffracted light is referred to as the numerical aperture (NA) of the lens
- With an increased NA, more of the diffracted light can be converged to a single point for imaging
- However, increasing the radius of the lens to increase the NA also means more complicated and costly optical systems

Effect of Numerical Aperture on Imaging

NA= radius of lens/ focal length of lens
High NA capture more diffracted light

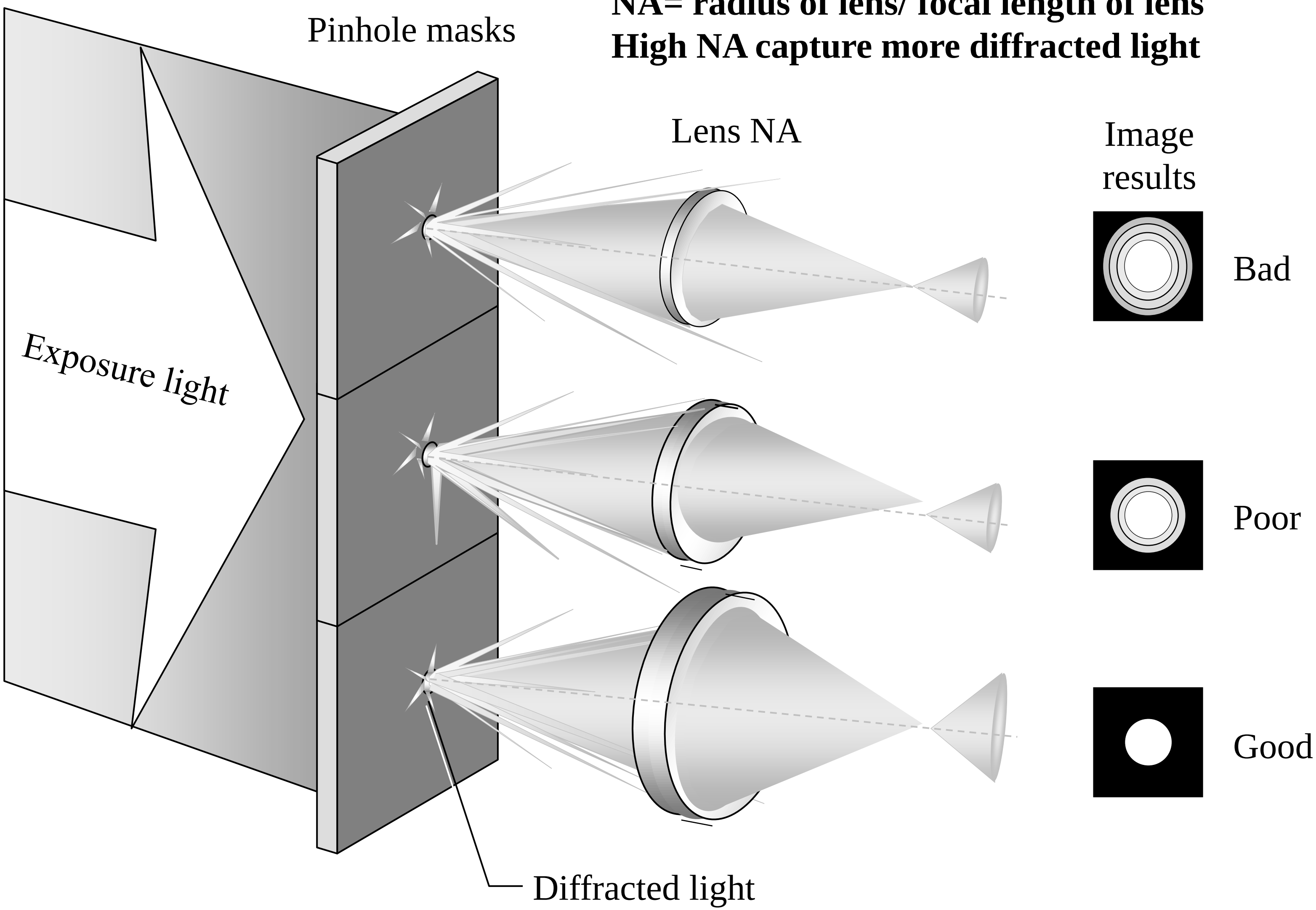


Figure 14.21

Typical NA Values for Photolithography Tools

Type of Equipment	NA Value
Scanning Projection Aligner with mirrors (1970s technology)	0.25
Step-and-Repeat	0.60 – 0.68
Step-and-Scan	0.60 – 0.68

- $NA = (n)\sin\theta_m \approx (n)\dfrac{radius\ of\ lens}{focal\ lenght\ of\ lens}$
- For an air or vacuum medium, the NA value must be less than or equal to 1

Table 14.5

Photoresist Reflective Notching Due to Light Reflections

- If the underlying film is reflective, as with metal and poly-Si, then light rays reflect off damage the adjacent resist
- Two problems: reflective notching and standing wave

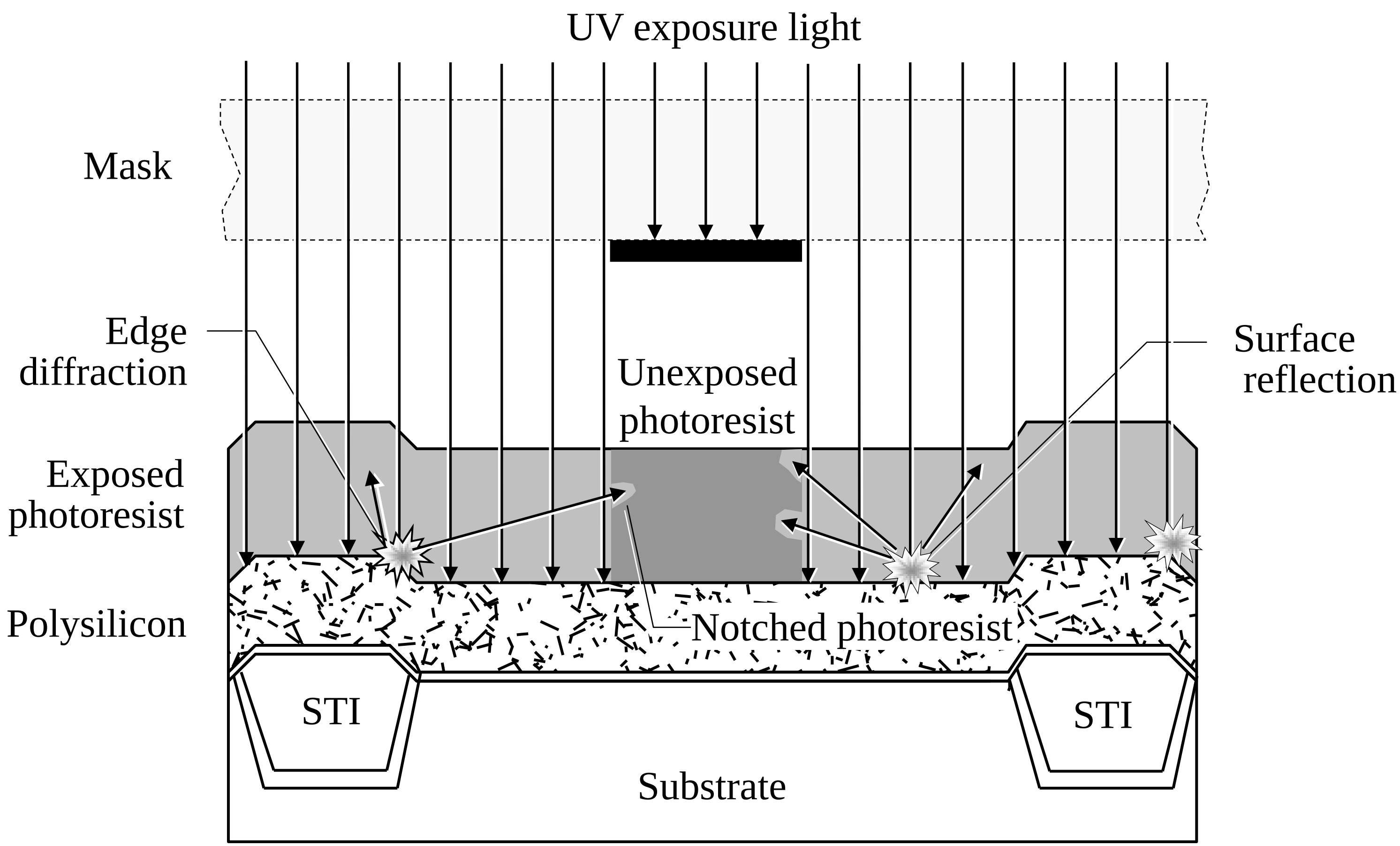
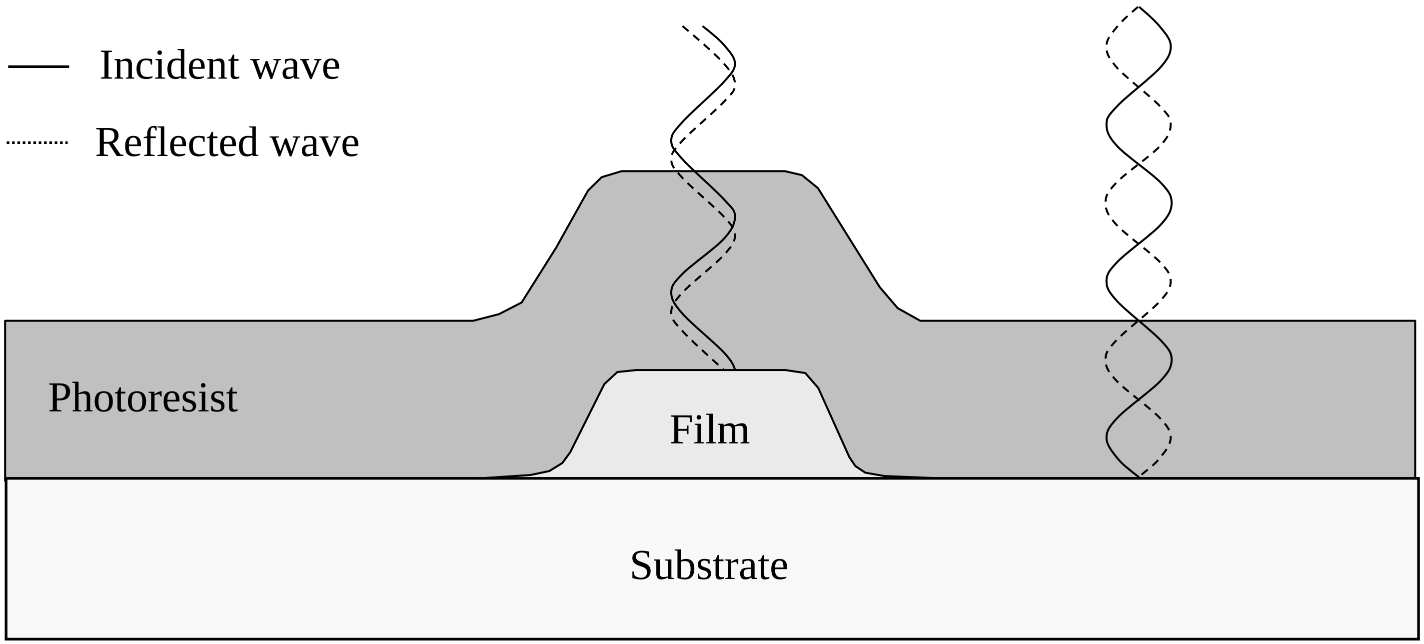


Figure 14.22

Incident and Reflected Light Wave Interference in Photoresist

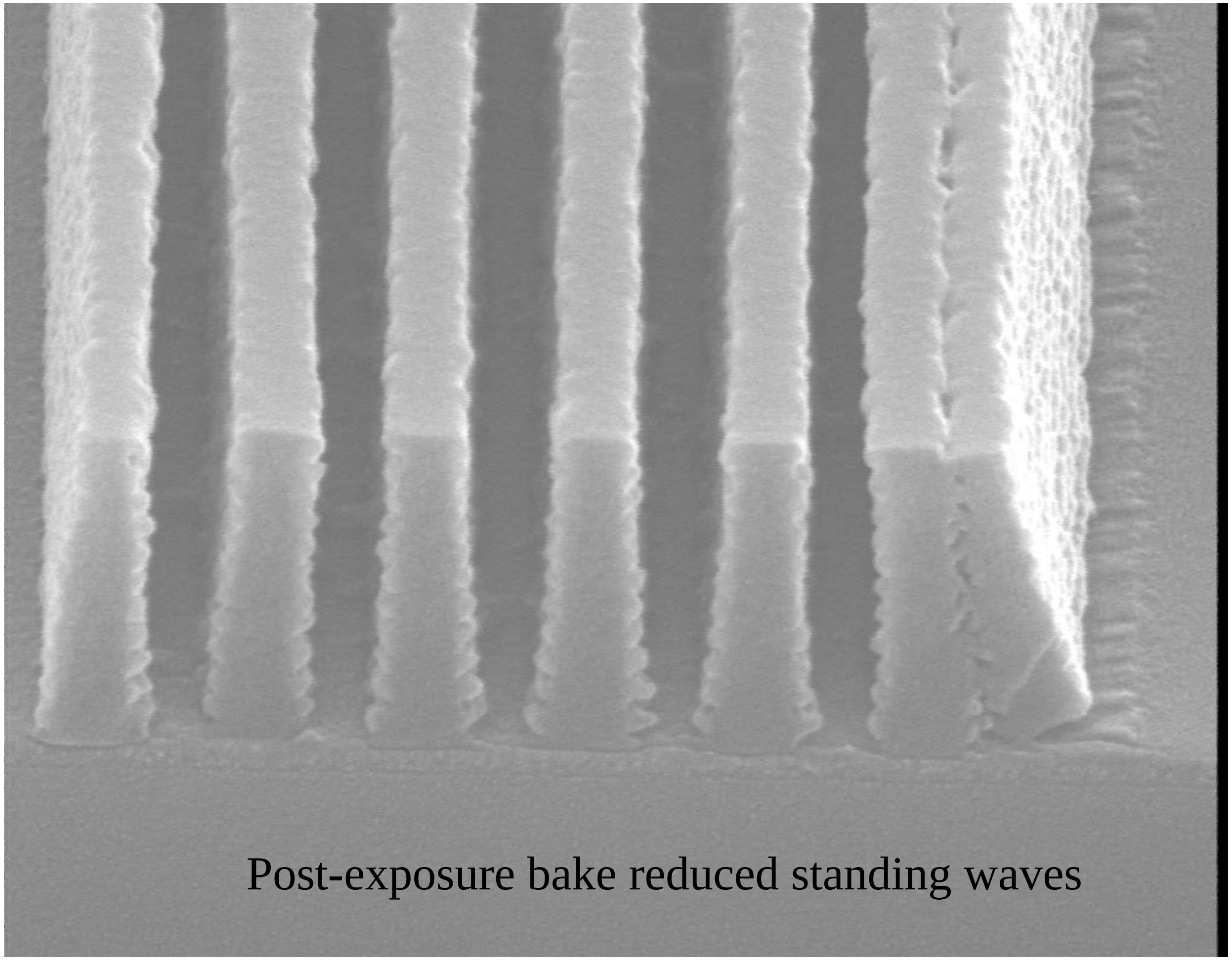
- Standing waves represent interface between the incident light waves and reflected light waves, which causes nonuniform exposure along the thickness of the PR
- Wafer surface are more reflective at the shorter DUV



Standing waves cause nonuniform exposure along the thickness of the photoresist film.

Figure 14.23

Effect of Standing Waves in Photoresist



Photograph courtesy of the Willson Research Group, University of Texas at Austin

Photo 14.1

Antireflective Coating to Prevent Standing Waves

- ARC capable of suppressing 99% of the substrate-reflected light
- The use of antireflective coatings, dyes, and filters can help prevent interference
- PEB between exposure and development can reduce the extent of standing wave stiration in conventional i-line resist
- PEB redistributes the PAC in the resist and allows for straighter resist sidewall profiles by reducing standing waves

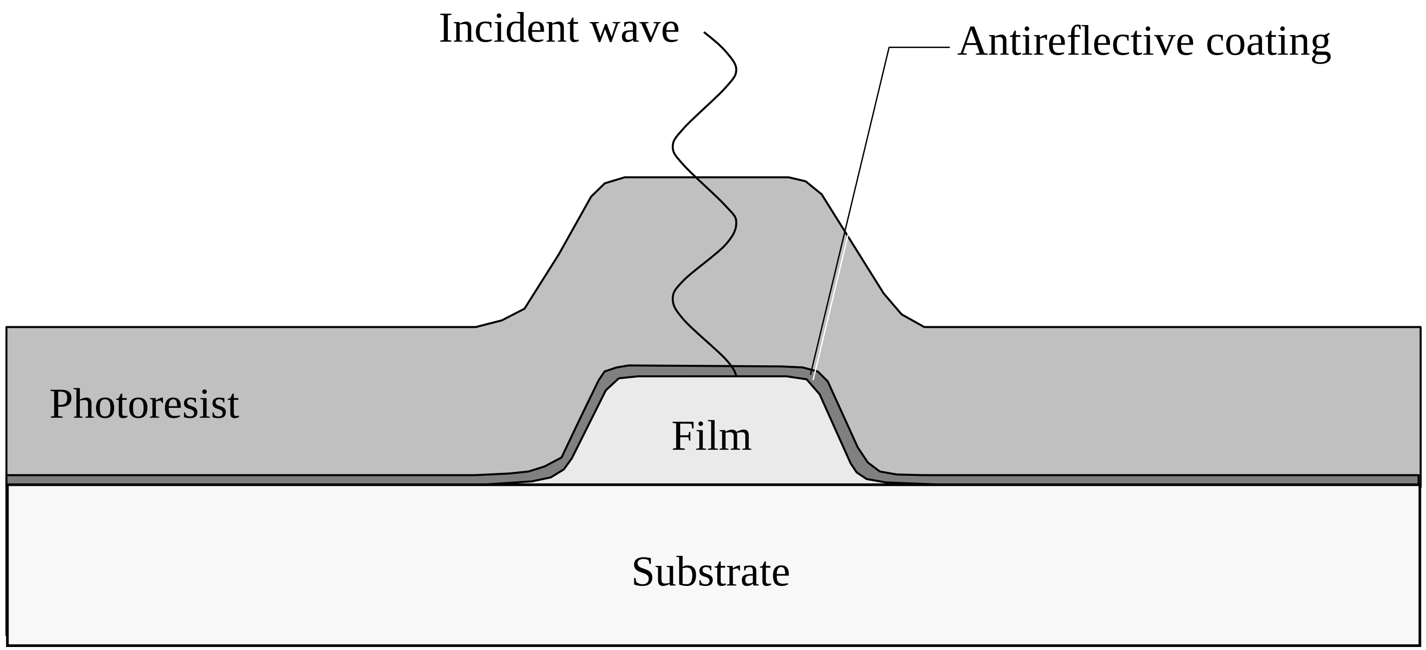


Figure 14.24

Light Suppression with Bottom Antireflective Coating

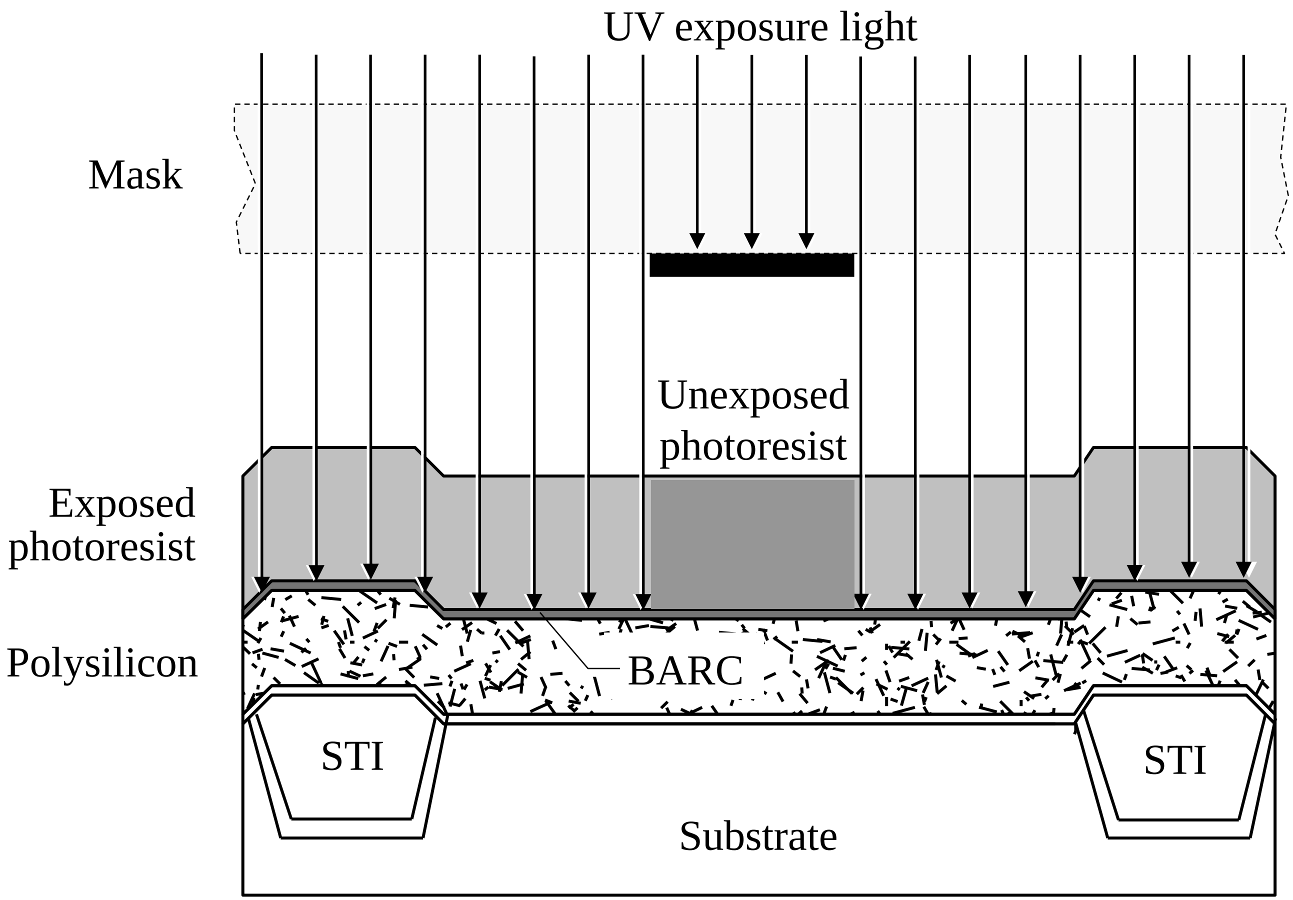
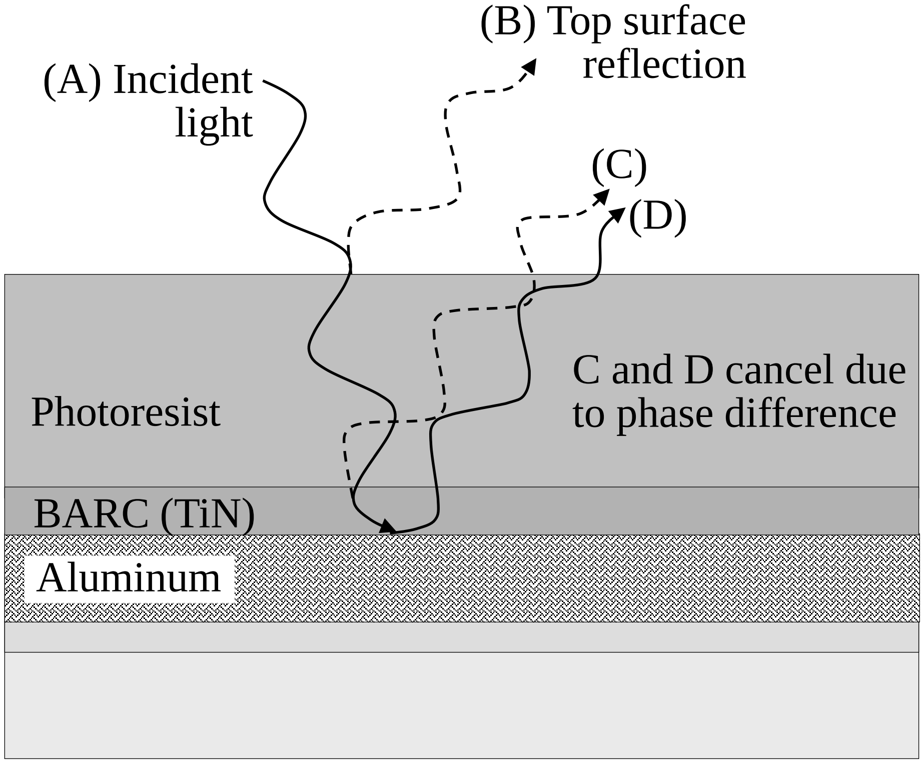


Figure 14.25

BARC Phase-Shift Cancellation of Light

- BARC is the most effective method in reducing reflections
- BARC material is an organic or inorganic dielectric material that is applied to the wafer before the photoresist
- Organic BARC: by absorbing , spin as PR
- Inorganic BARC: by phase-shift cancellation of specific wavelengths based on reflective index, film thickness, and other parameters
- TiN used as a diffusion barrier, and is also a good antireflective coating. It is left on the wafer surface and becomes a part of the device



Top Antireflective Coating

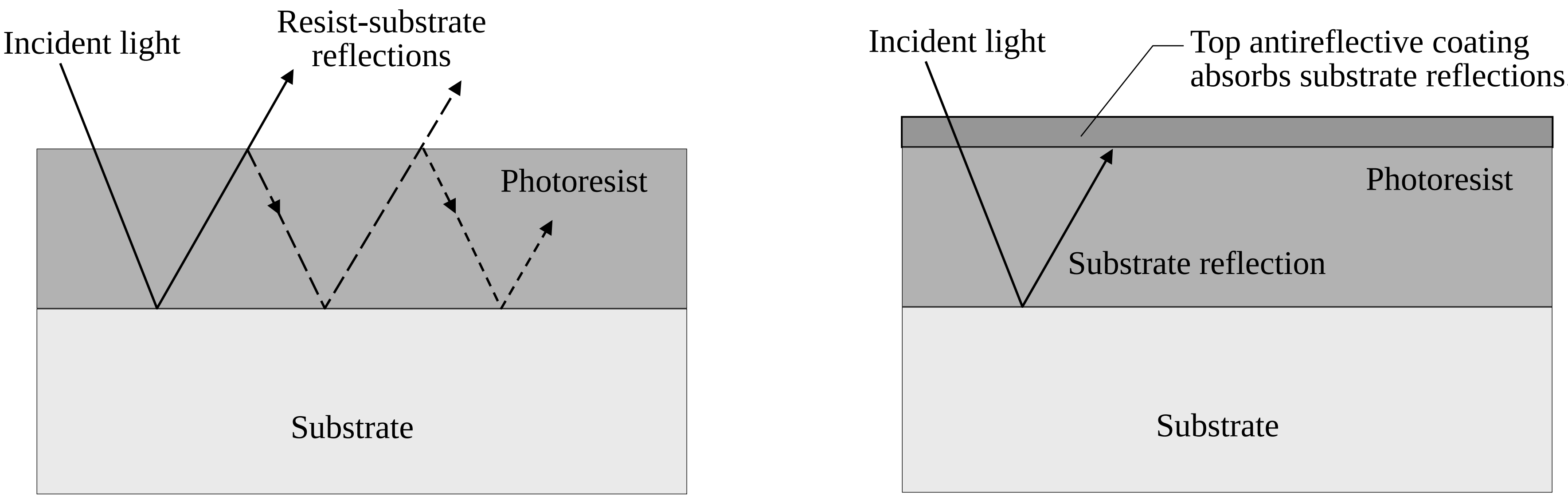


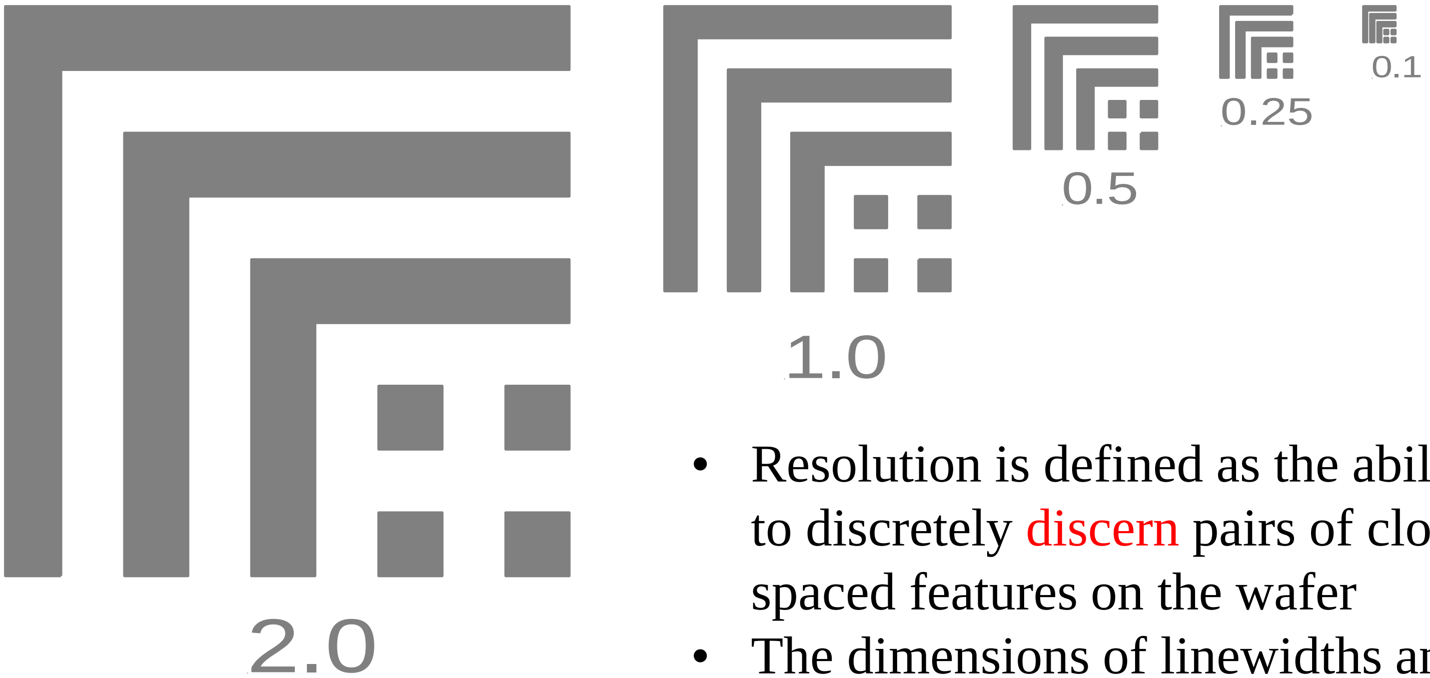
Figure 14.27

Optical Lithography

Resolution

- Calculating Resolution
- Depth of Focus
- Resolution Versus Depth of Focus
  - Surface Planarity

Resolution of Features

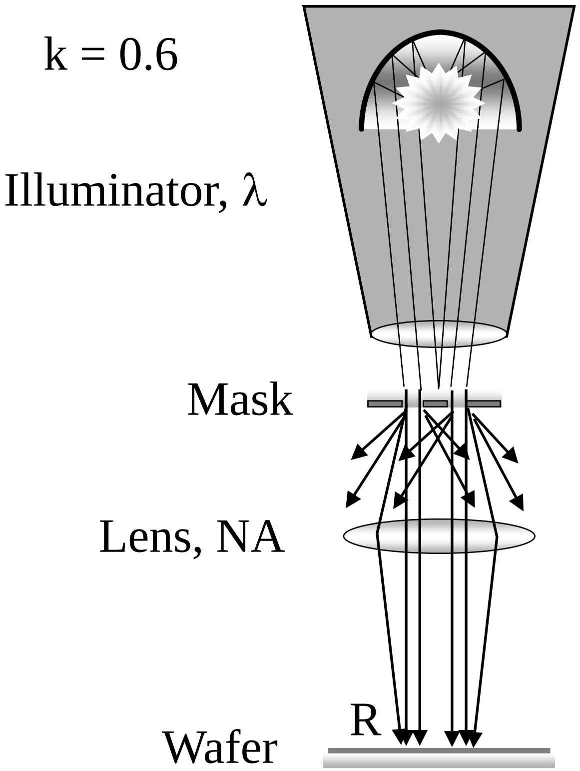


- Resolution is defined as the ability to discretely discern pairs of closely spaced features on the wafer
- The dimensions of linewidths and spaces must be equal. As feature sizes decrease, it is more difficult to separate features from each other.

Figure 14.28

Calculating Resolution for a given λ, NA and k

- *k* represents process factors of the optical system and can affect resolution, there are practical limitations to decreasing *k* much below 0.6
- Using phase-shift masks (PSM) or optical proximity correction (OPC) to reduce *k*



$$R = \frac{k\,\lambda}{NA}$$

	λ	NA	R
i-line	365 nm	0.45	486 nm
	365 nm	0.60	365 nm
DUV	193 nm	0.45	257 nm
	193 nm	0.60	193 nm

Figure 14.29

Depth of Focus (DOF)

- The range around the focal point over which the image is continuously in focus is called the depth of focus
- Center of focus: where the best imaging occurs
- DOF is the range above and below the center of focus where the exposure energy is relatively constant

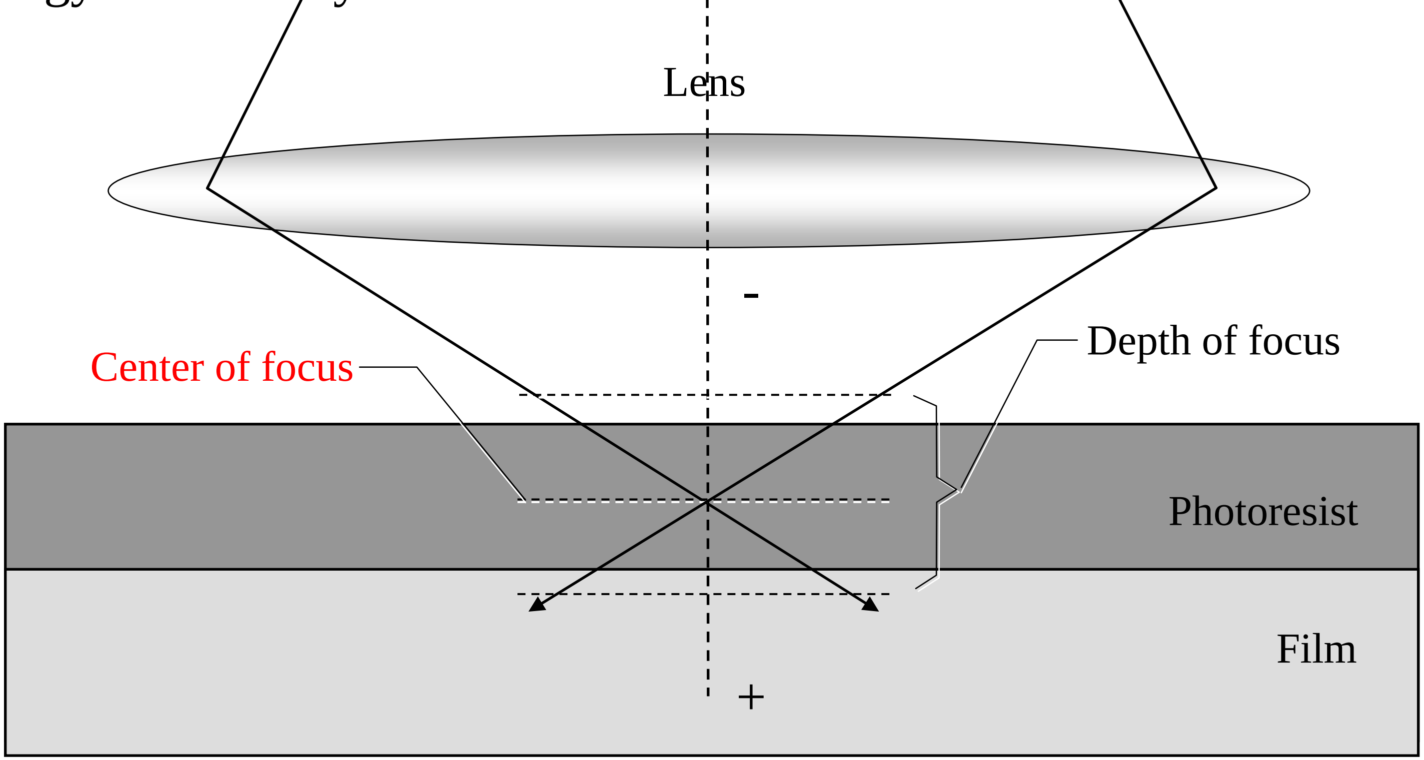
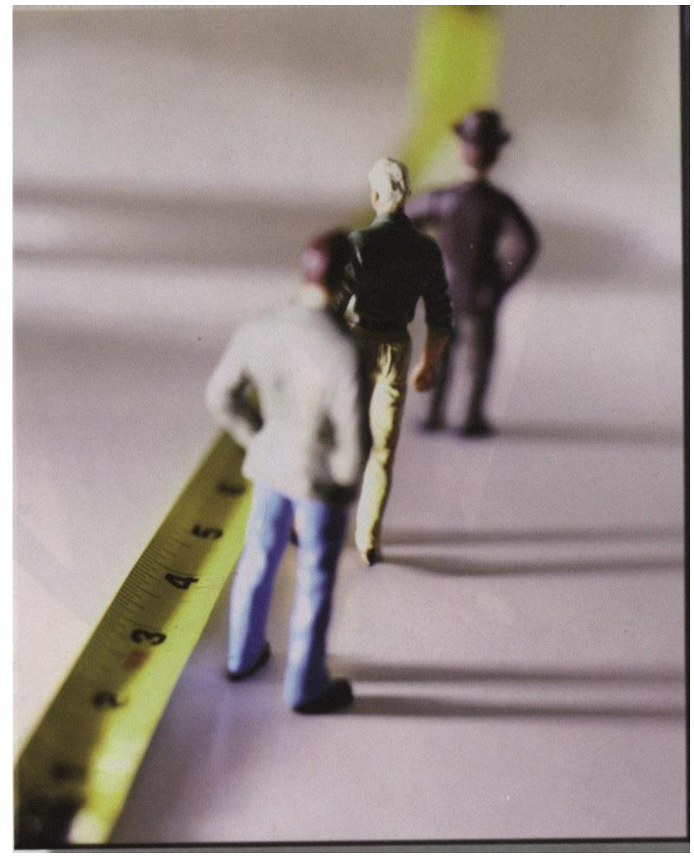
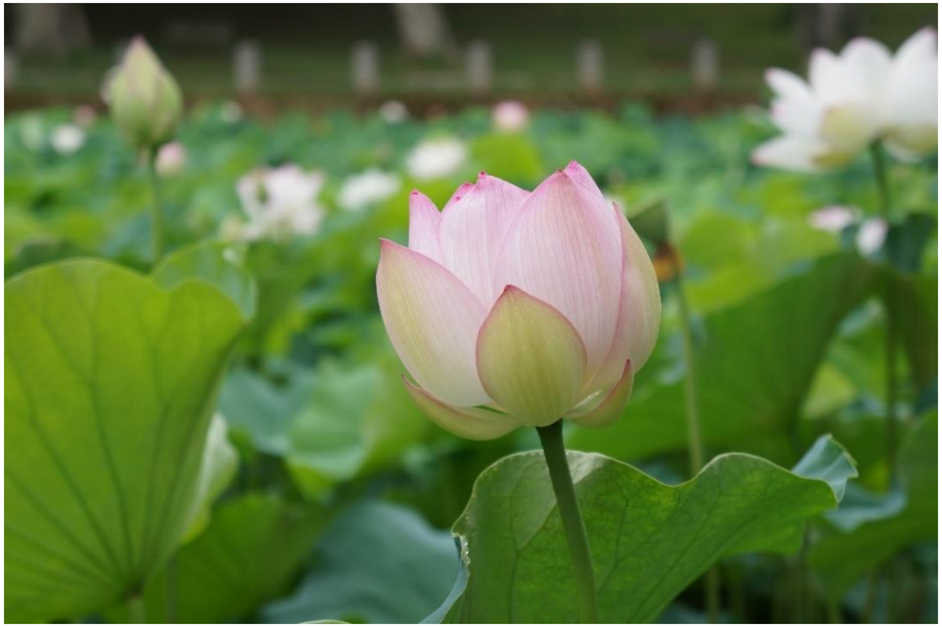


Figure 14.30

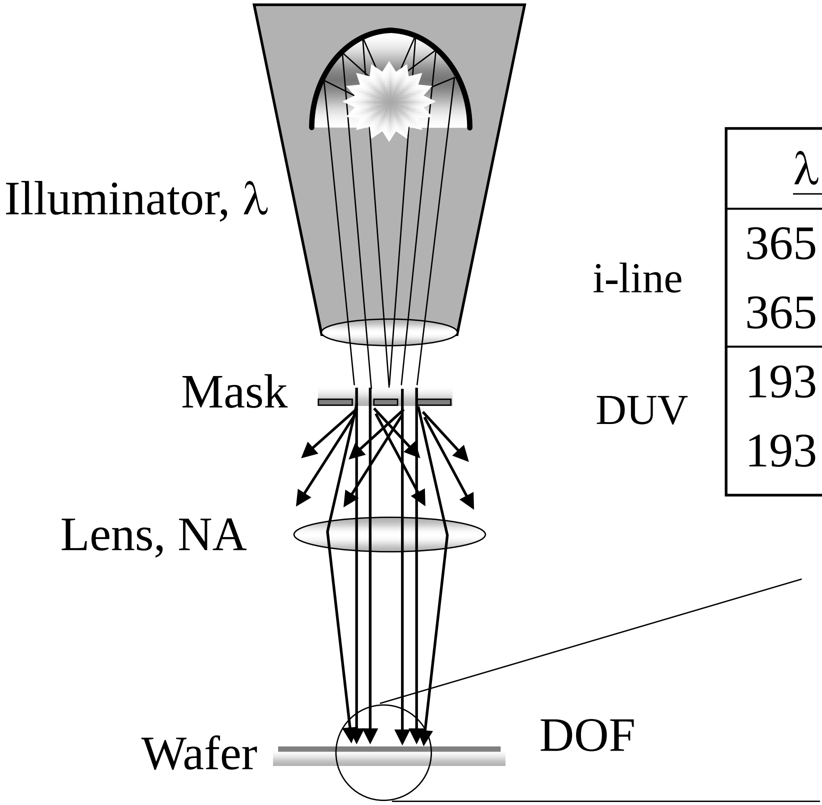
Depth of Focus



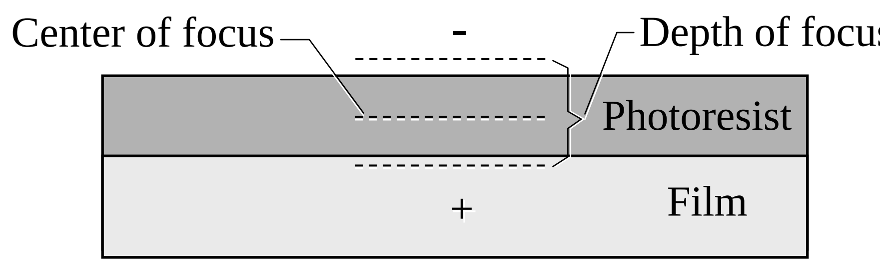


Resolution Versus Depth of Focus for Varying NA

$$DOF = \frac{\lambda}{2(NA)^2}$$



	λ	NA	R	DOF
i-line	365 nm	0.45	486 nm	901 nm
	365 nm	0.60	365 nm	507 nm
DUV	193 nm	0.45	257 nm	476 nm
	193 nm	0.60	193 nm	268 nm



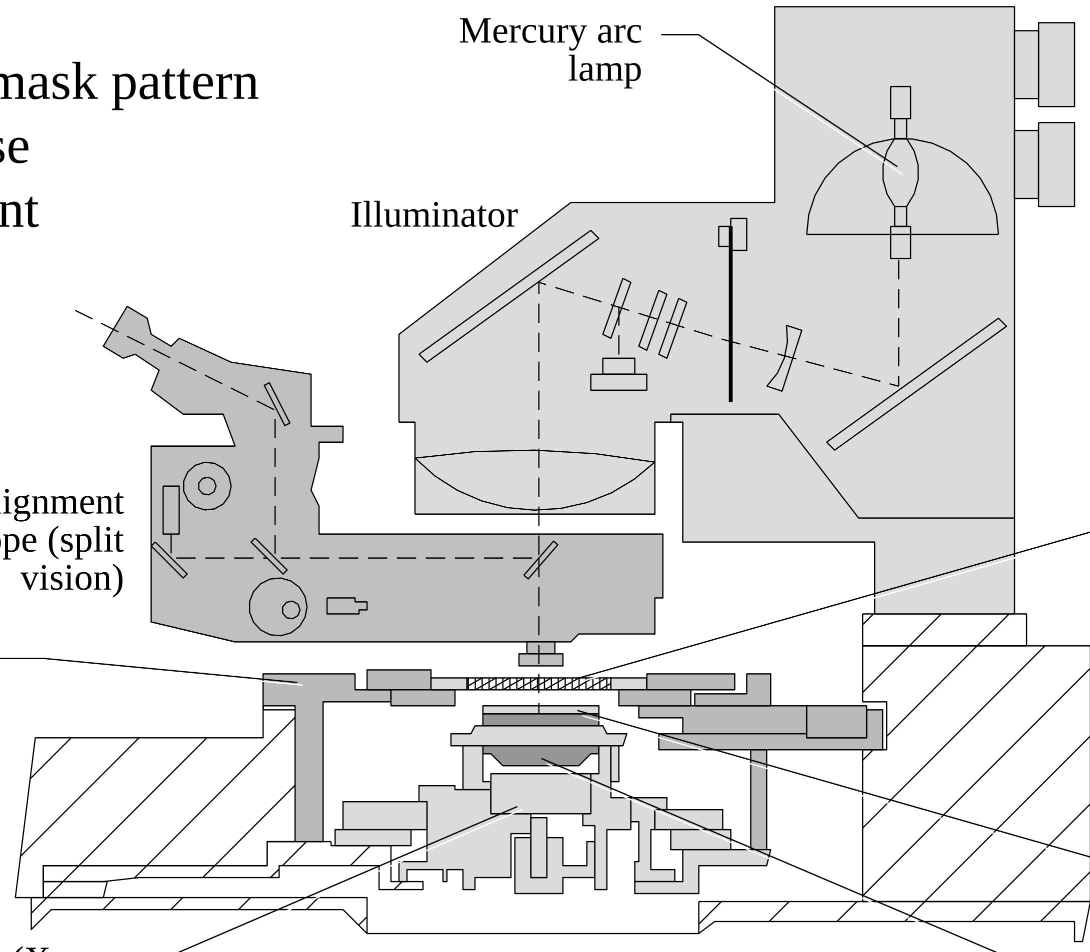
- 30 cm for handheld cameras, 1 μm for stepper
- But high NA, high R, and low DOF → CMP
- CMP makes possible the reduction of the DOP to achieve a higher pattern resolution

Photolithograhy Equipment

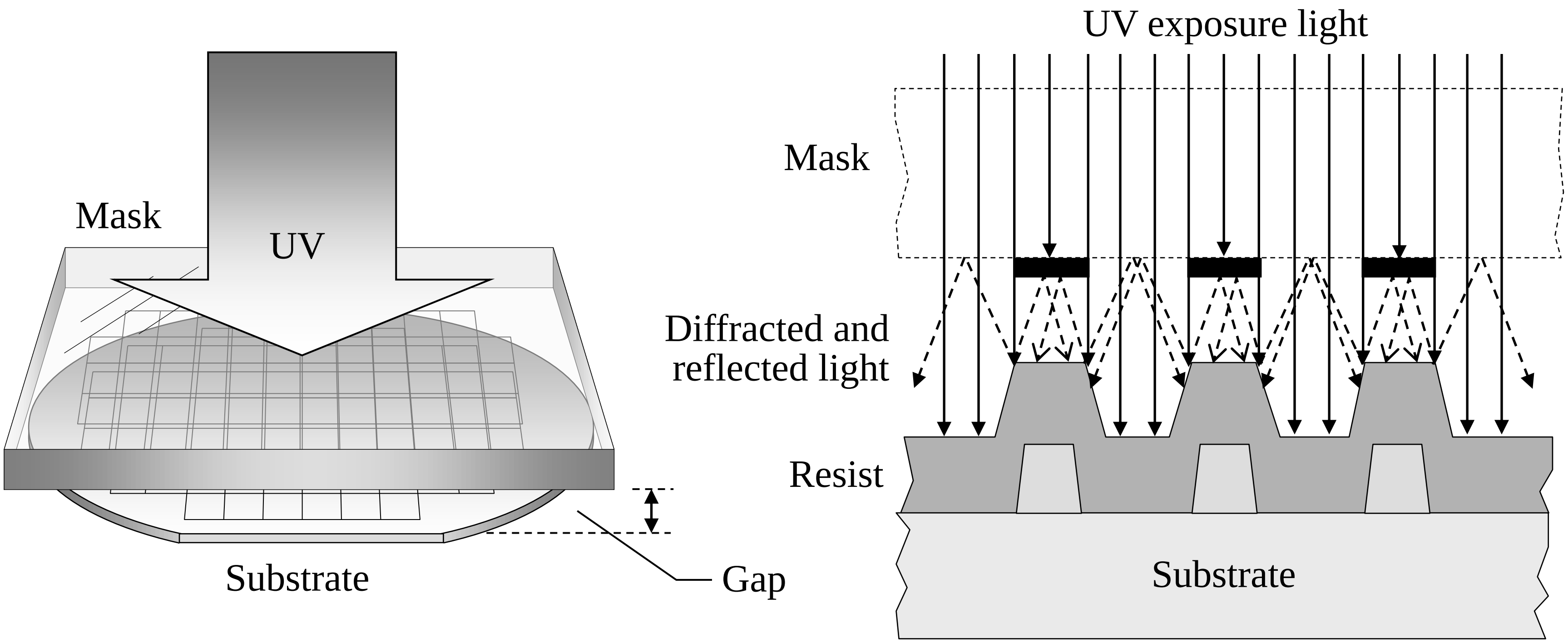
- Contact Aligner
- Proximity Aligner
- Scanning Projection Aligner (scanner)
- Step-and-Repeat Aligner (stepper)
- Step-and-Scan System

Contact/Proximity Aligner System

- Linewidth 0.4 μm is possible
- Contamination on mask
- Overlay accuracy
- But good image: mask pattern and wafer are close
- Operator dependent



Edge Diffraction and Surface Reflectivity on Proximity Aligner

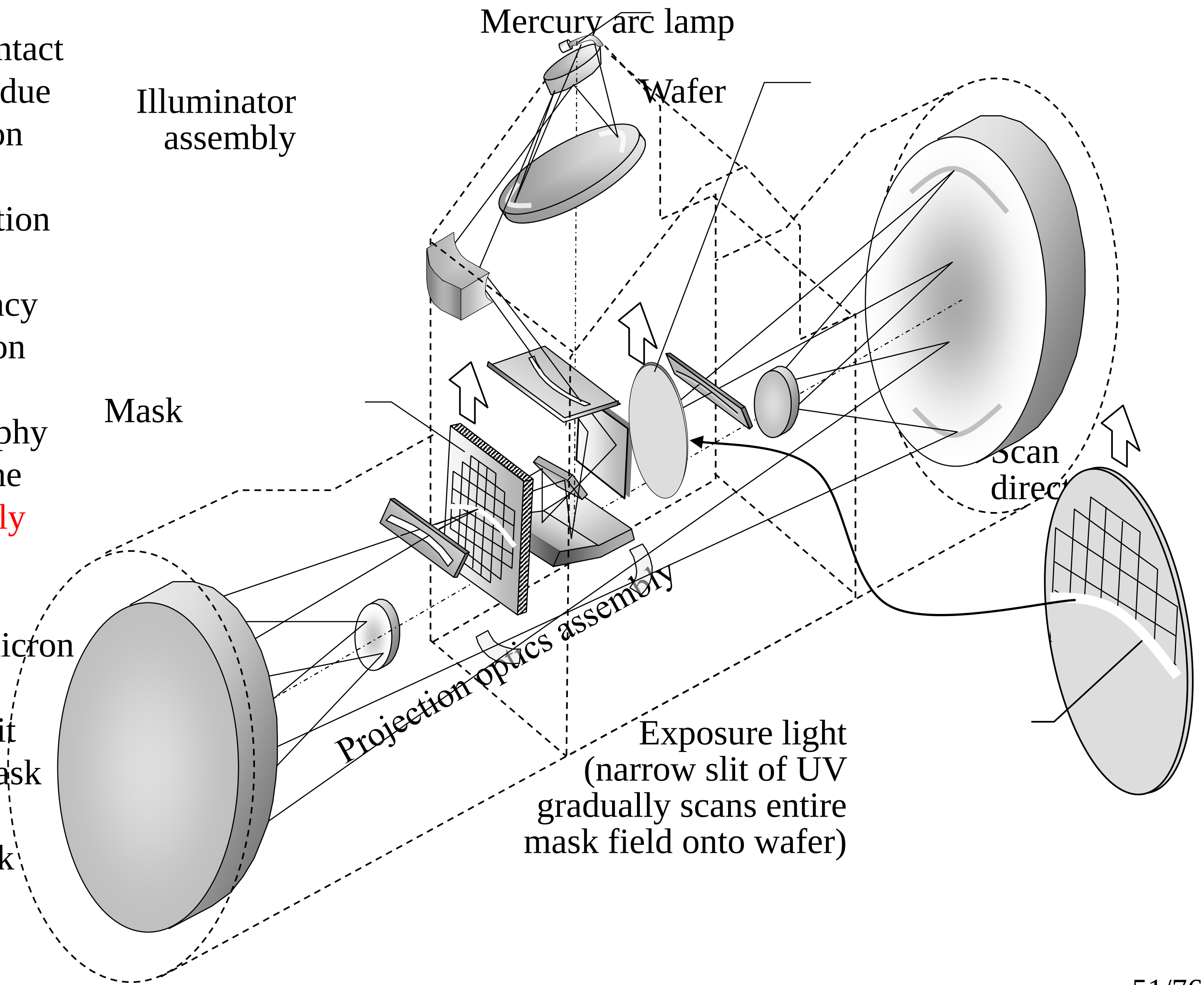


- It suitable for linewidth 2 to 4 μm
- 2.5~ 25 μm the gap
- Diffraction of light on edges results in reflections from underside of mask causing undesirable resist exposure

Figure 14.33

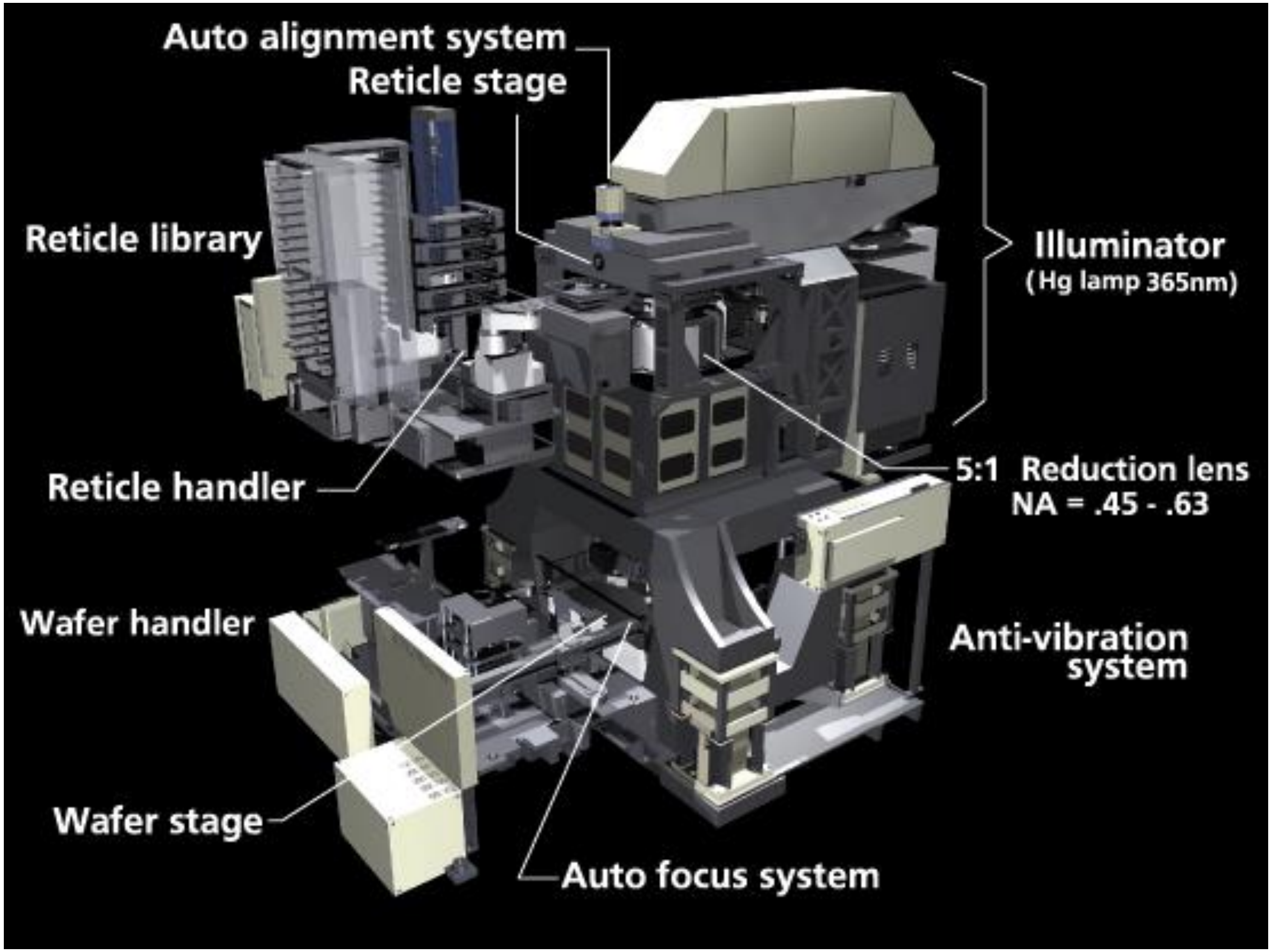
Scanning Projection Aligner

- Move away from contact or near contact alignment system due to its contamination problems, edge diffraction, resolution limitations, and operator dependency
- Scanning projection aligners were the dominant lithography exposure tool in the late 1970s and early 1980s.
- Suitable > 1μm
- 1X mask, as submicron feature sizes were introduced, made it difficult for the mask maker to have no defects in the mask



Step-and-Repeat Aligner (Stepper)

- Step-and-repeat (stepper) is the mainstay of the 1990s microlithography equipment
- Steppers have dominated IC fabrication since the later 1980s, down to 0.35 μm
- A stepper uses a reticle, which contains the pattern in an exposure field corresponding to one or more die



Stepper Exposure Field

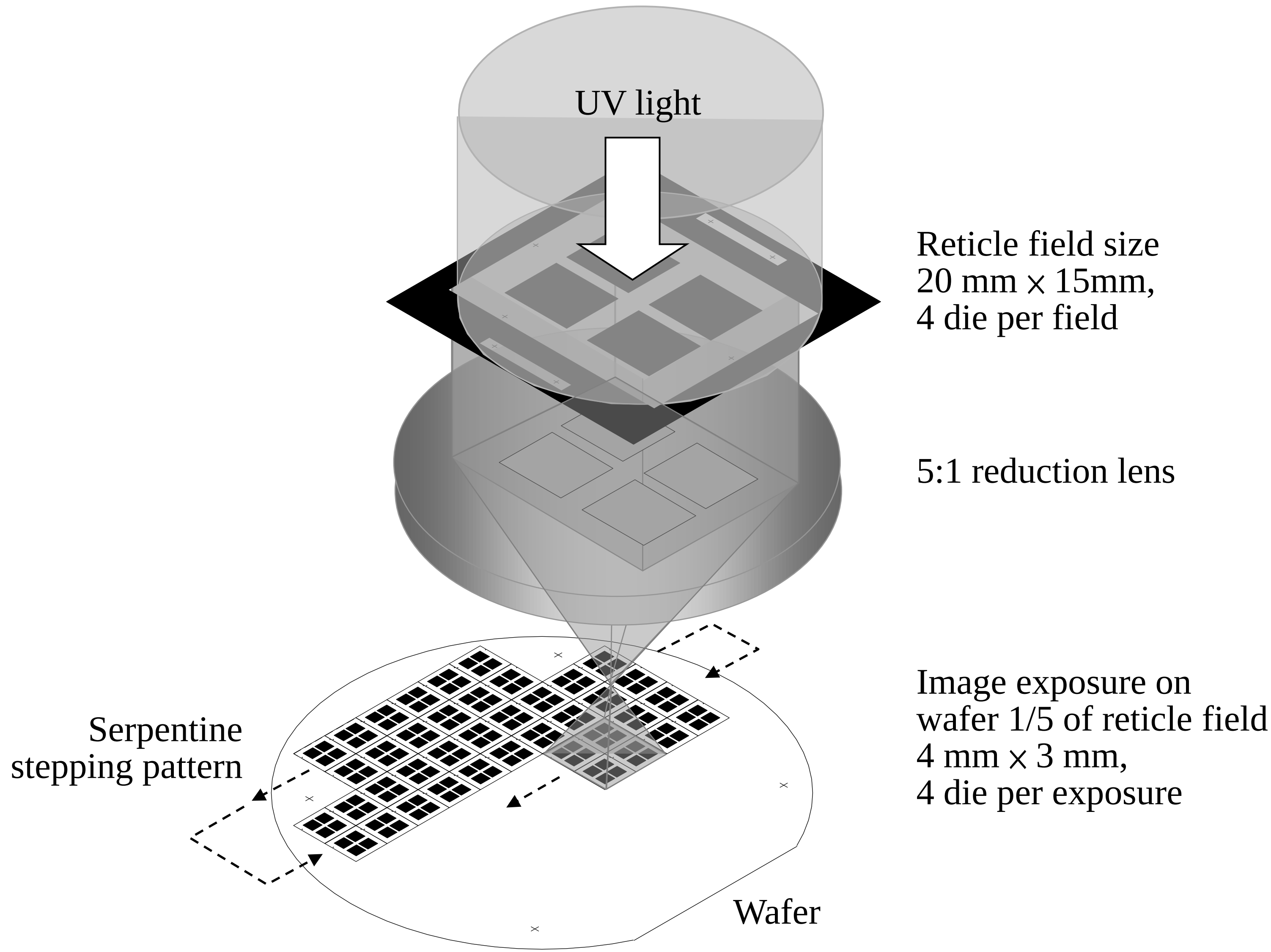
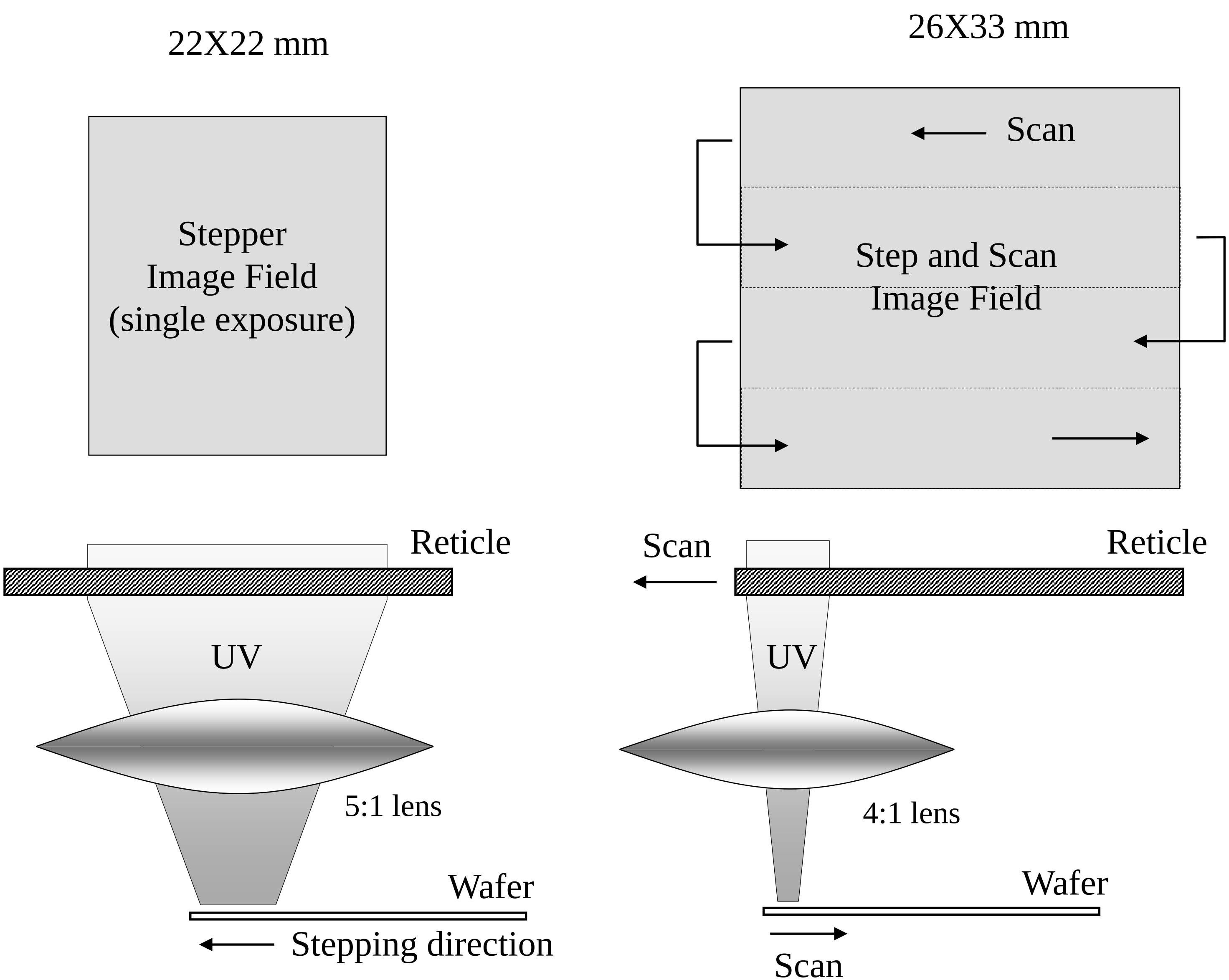


Figure 14.36

Step-and-Repeat Aligner

- Advantage: its ability to use a reduction lens
- The reticles are sized 4X, 5X and 10X larger than the actually image to be patterned
- Makes it easier to fabricate the reticle because the features on the reticles are five times larger than the final image on the wafer
- Because the stepper exposes only a small portion of the wafer at one time, compensations for variations in wafer flatness and geometry can be easily performed
- Large lens is costly, limits the field size to 22x22 mm

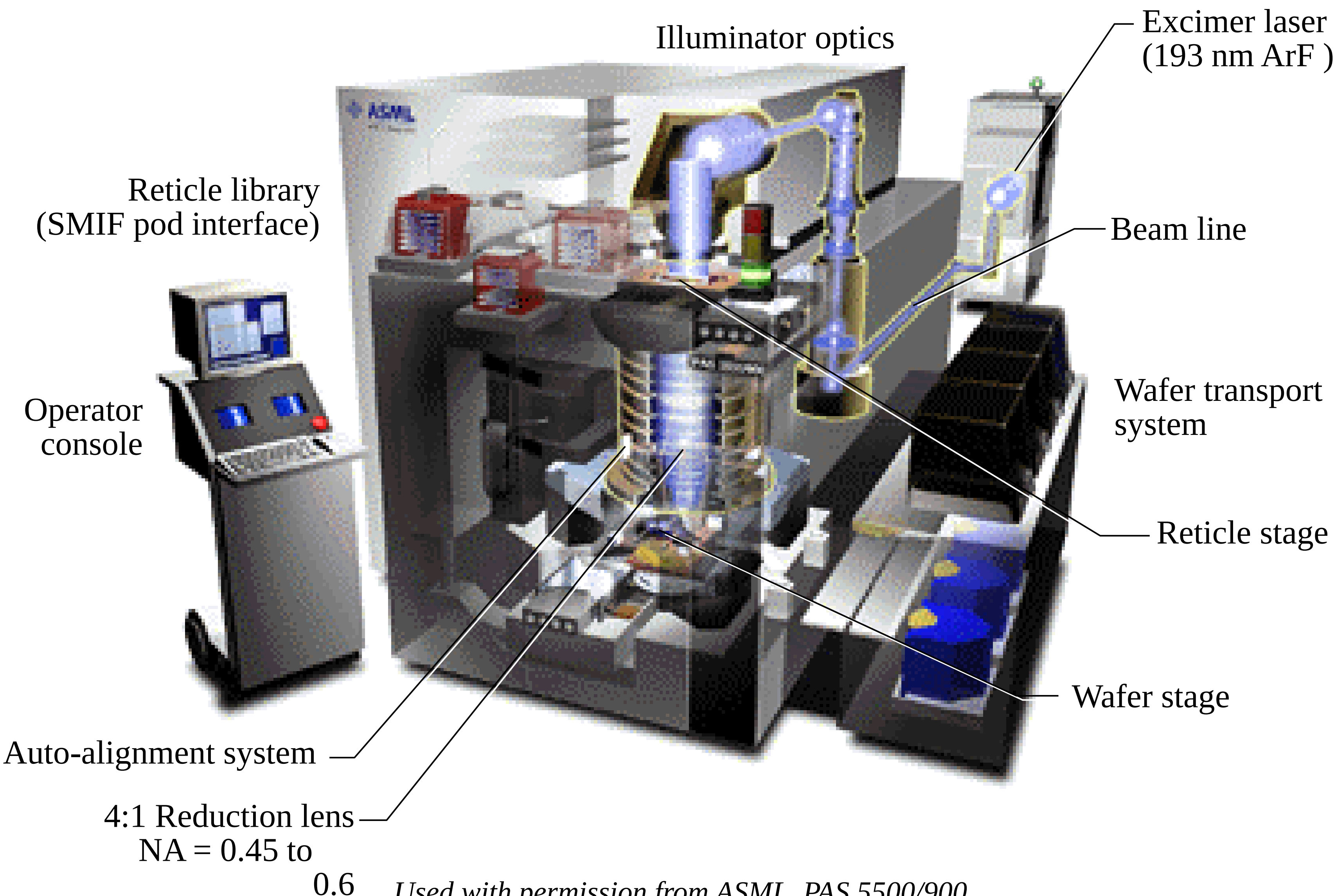
Wafer Exposure Field for Step-and-Scan



Scanner

- Step-and-scan is a hybrid tool that combines the technology from scanning project aligners and step-and –repeat stepper by using a reduction lens to scan the image of a large exposure field onto a portion of the wafer
- The lens field only has to be a narrow slit as in the older full-wafer scanning projection aligners
- The optical system can now be designed for much smaller field, permitting a smaller lens system
- Another advantage: adjust focus throughout a scan, permitting compensation for lens defects and changes in wafer flatness
- The major challenge is mechanical tolerance control (within one few tens of nanometer) due to the motion of the stage controls for the reticle and wafer

Step and Scan Exposure System

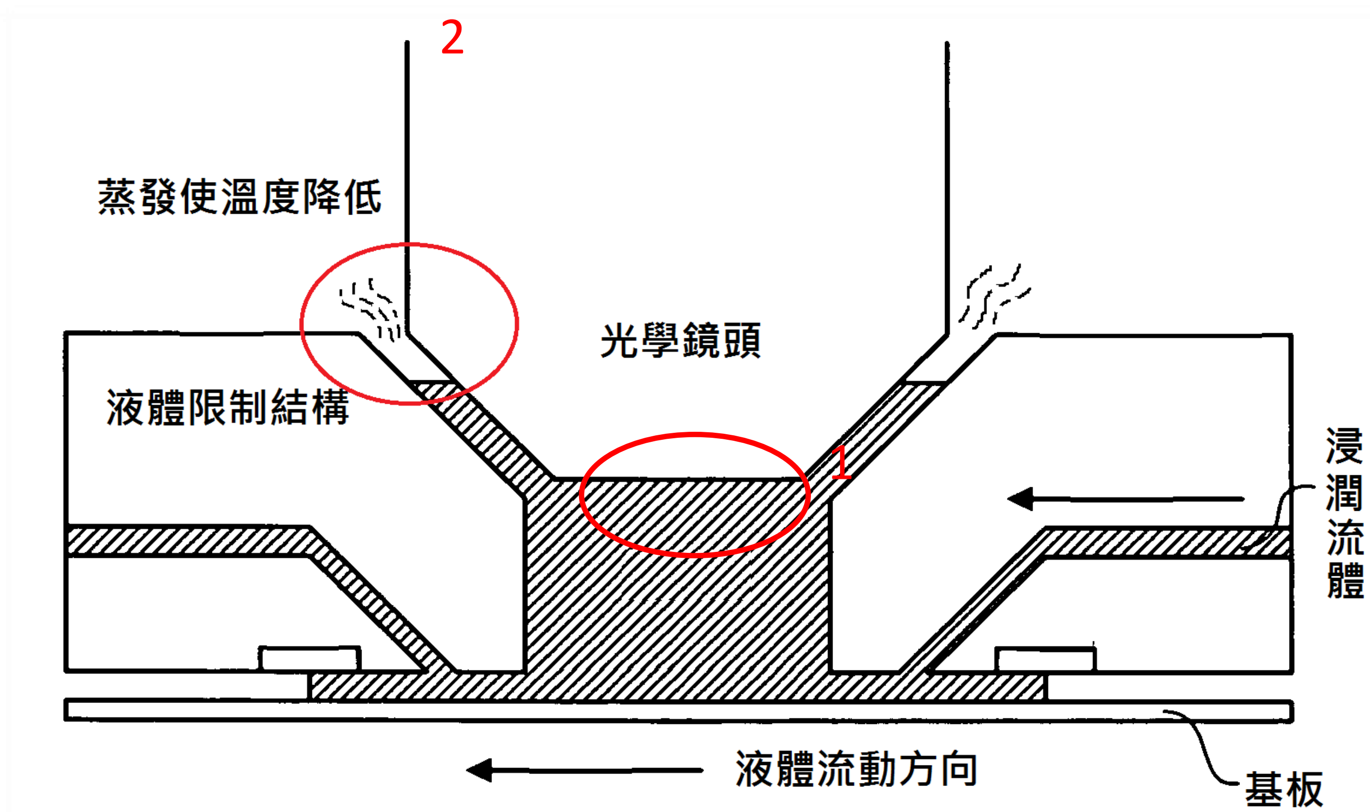


Used with permission from ASML, PAS 5500/900

Figure 14.38

浸潤微影設備示意圖

- $NA = (n)\sin\theta_m \approx (n)\dfrac{radius\ of\ lens}{focal\ lenght\ of\ lens}$
- For an air or vacuum medium, the NA value must be less than or equal to 1



來源：美國專利公告號US 8711323B2

Reticles

- Comparison of Reticle Versus Mask
- Reticle Materials
- Reticle Reduction and Size
- Reticle Fabrication
- Sources of Reticle Damage

Comparison of Reticle Versus Mask

Parameter	Reticle (Pattern for Step-and-Repeat Exposure)	Mask (Pattern for 1:1 Mask-Wafer Transfer)
Critical Dimension	Easier to pattern submicron dimensions on wafer due to larger pattern size on reticle (e.g., 4:1, 5:1).	Difficult to pattern submicron dimensions on mask and wafer without reduction optics.
Exposure Field	Small exposure field that requires step-and-repeat process.	Exposure field is entire wafer.
Mask Technology	Optical reduction permits larger reticle dimensions – easier to print.	Mask has same critical dimensions as wafer – more difficult to print.
Throughput	Requires sophisticated automation to step-and-repeat across wafer.	Potentially higher (not always true if equipment is not automated).
Die alignment & focus	Adjusts for individual die alignment & focus.	Global wafer alignment, but no individual die alignment & focus.
Defect density	Improved yield but no reticle defect permitted. Reticle defects are repeated for each field exposure.	Defects are not repeated multiple times on a wafer.
Surface flatness	Stepper compensates during initial global pre-alignment measurements or during die-by-die exposures.	No compensation, except for overall global focus and alignment.

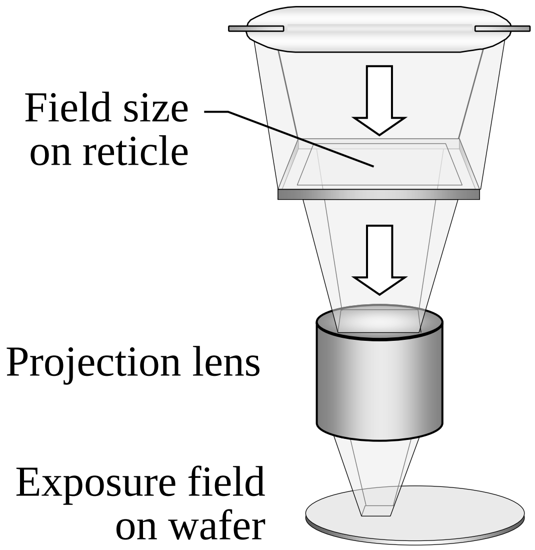
Table 14.6

Photolithography Reticle

- Fused silica is the most expensive material: low thermal expansion, stable with change in temperature, and high optical transmission and no defects on surface
- Opaque material: chromium (Cr) ~ 100 nm + 20 nm (ARC)

Photograph courtesy of Advanced Micro Devices

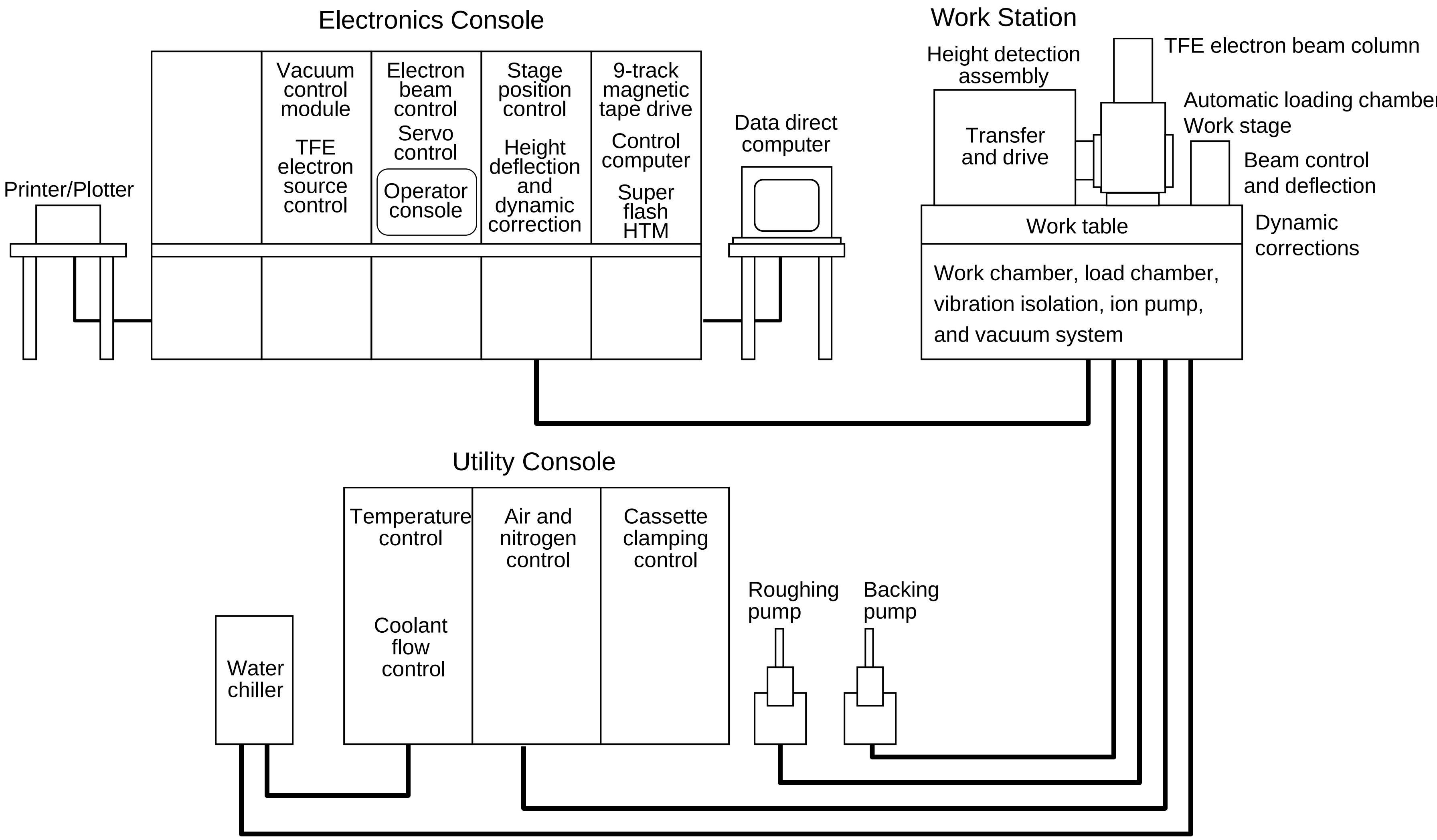
Comparison of Reticle Reduction Versus Exposure Field



Lens Type	**10:1**	**5:1**	**4:1**	**1:1**
Reticle Field Size (mm)	100 x 100	100 x 100	100 x 100	30x30
Exposure Field on Wafer (mm)	10x10	20 x20	25 x 25	30 x 30
Die per Field of Exposure (assume 5mm x 5mm die size)	4	16	25	36

Figure 14.39

Principles of Electron Beam Lithography

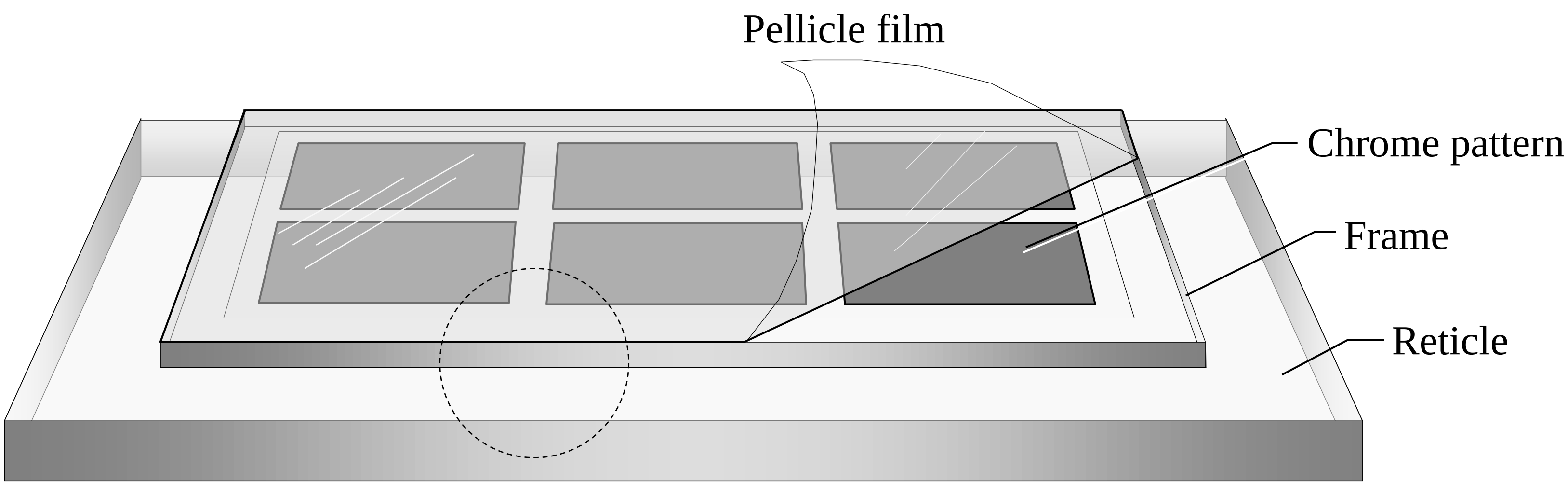


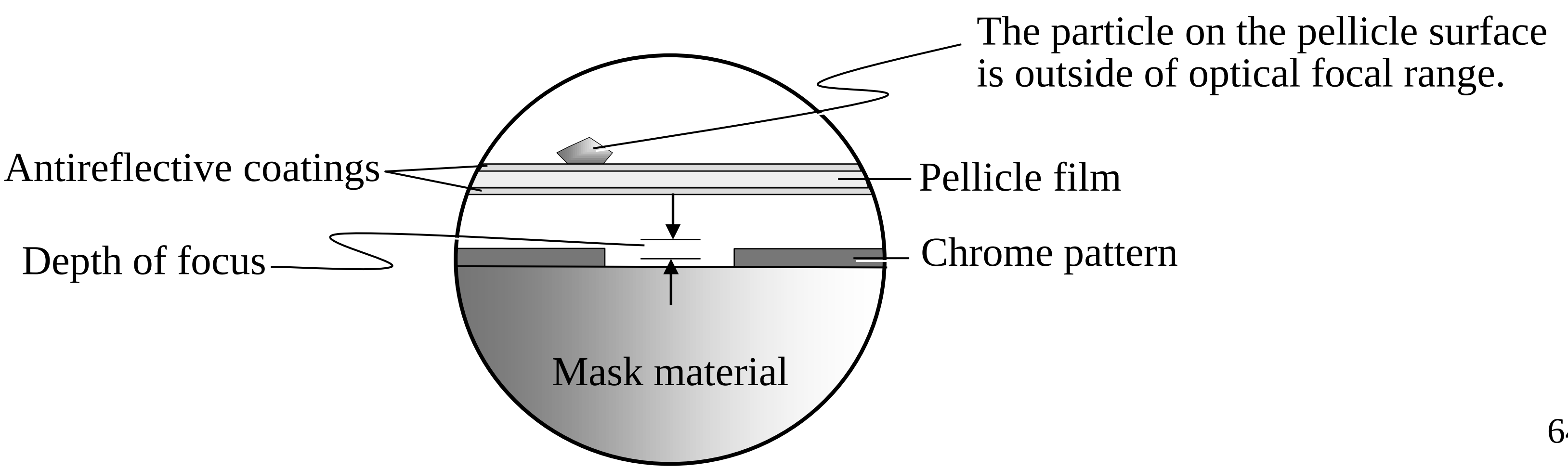
CD: 20nm （Positive resist, thickness < 100nm) , 100nm（Positive resist, thickness = 300nm）

Figure 14.40

Pellicle on a Reticle

- The pellicle is 5-10 mm above the mask surface.
- Particle is far removed from the focal plane and is invisible to the projection optics





Optical Enhancement Techniques

- Phase-Shift Mask (PSM)
- Optical Proximity Correction (OPC)
- Off-Axis Illumination
- Bias

Phase-Shifting Mask

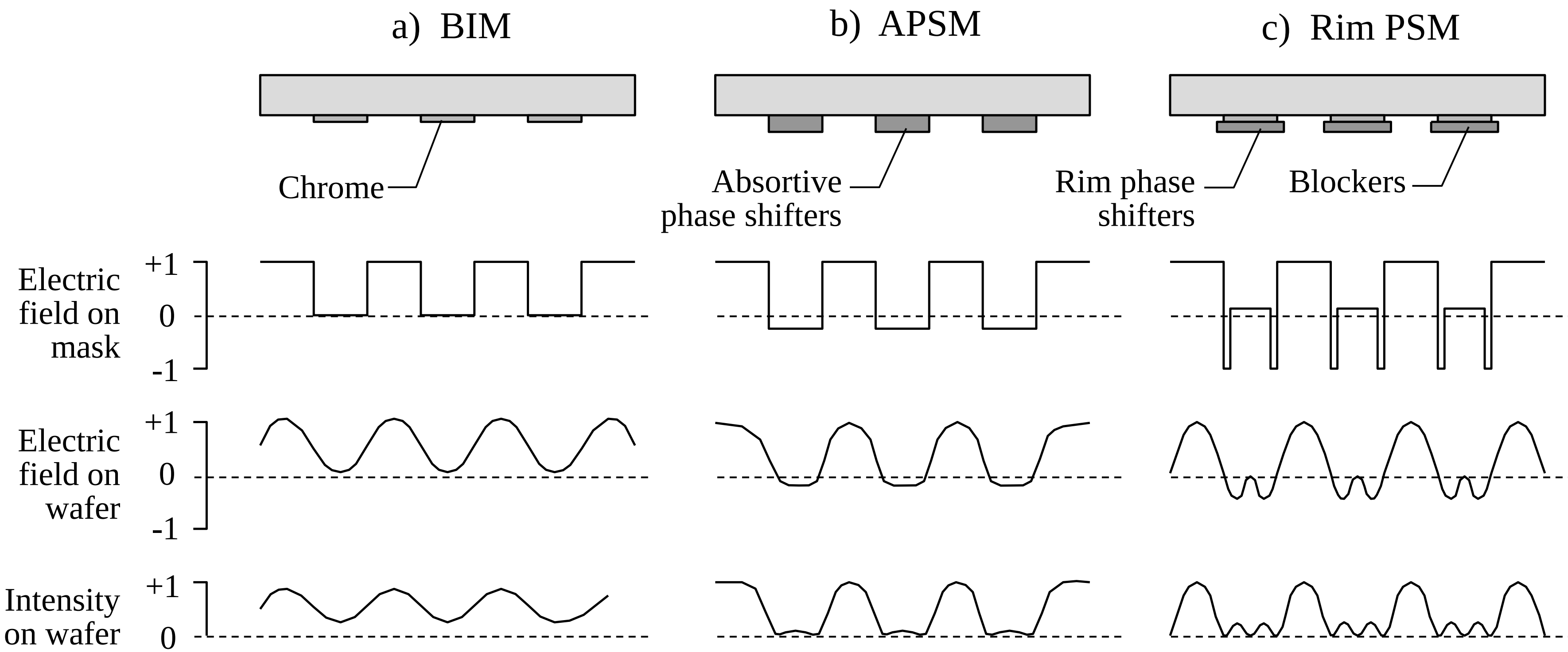


Figure 14.42

Optical Proximity Effects

- Because of optical proximity effects due to light diffraction and interference between closely spaced features on the reticle, the width of lines are affected by other nearby features

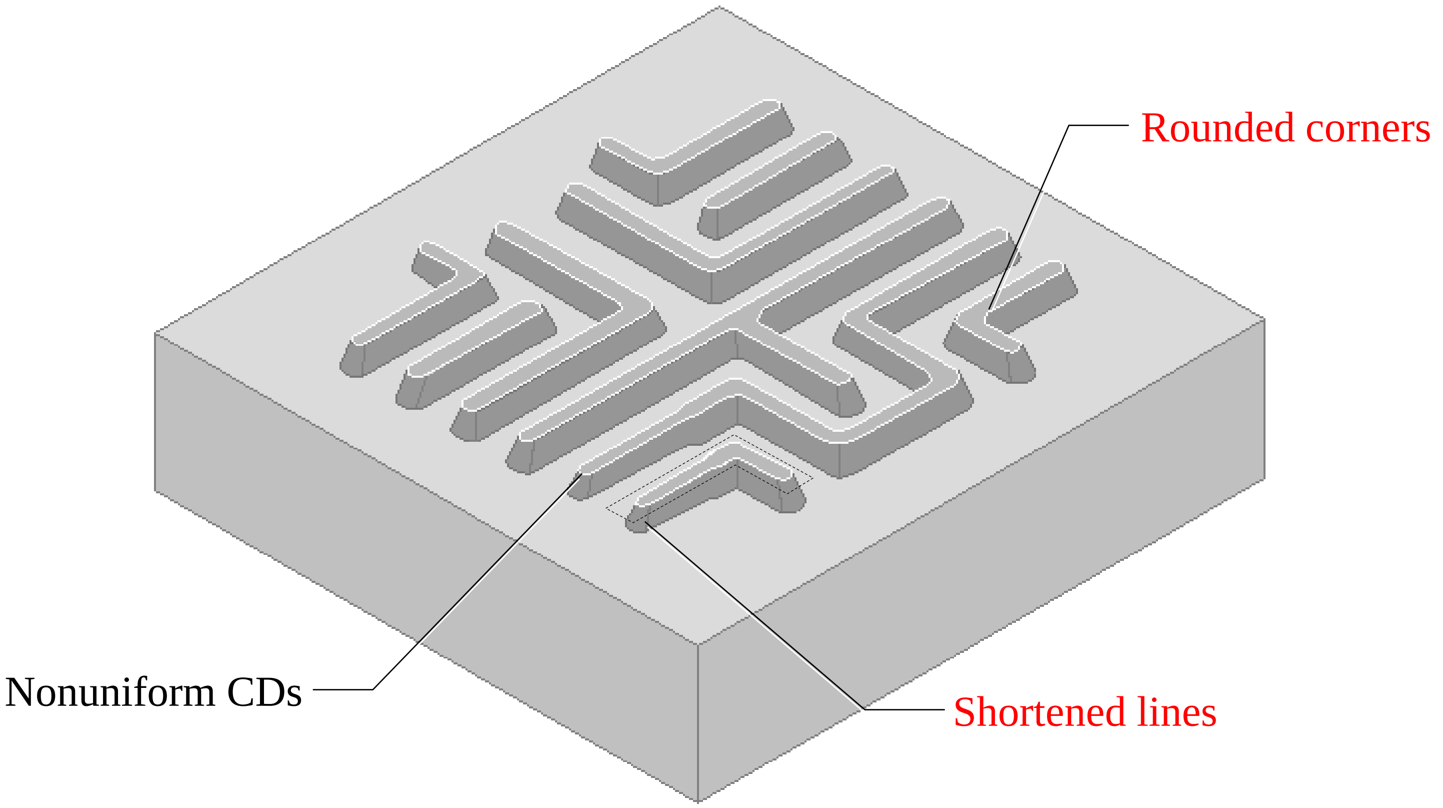
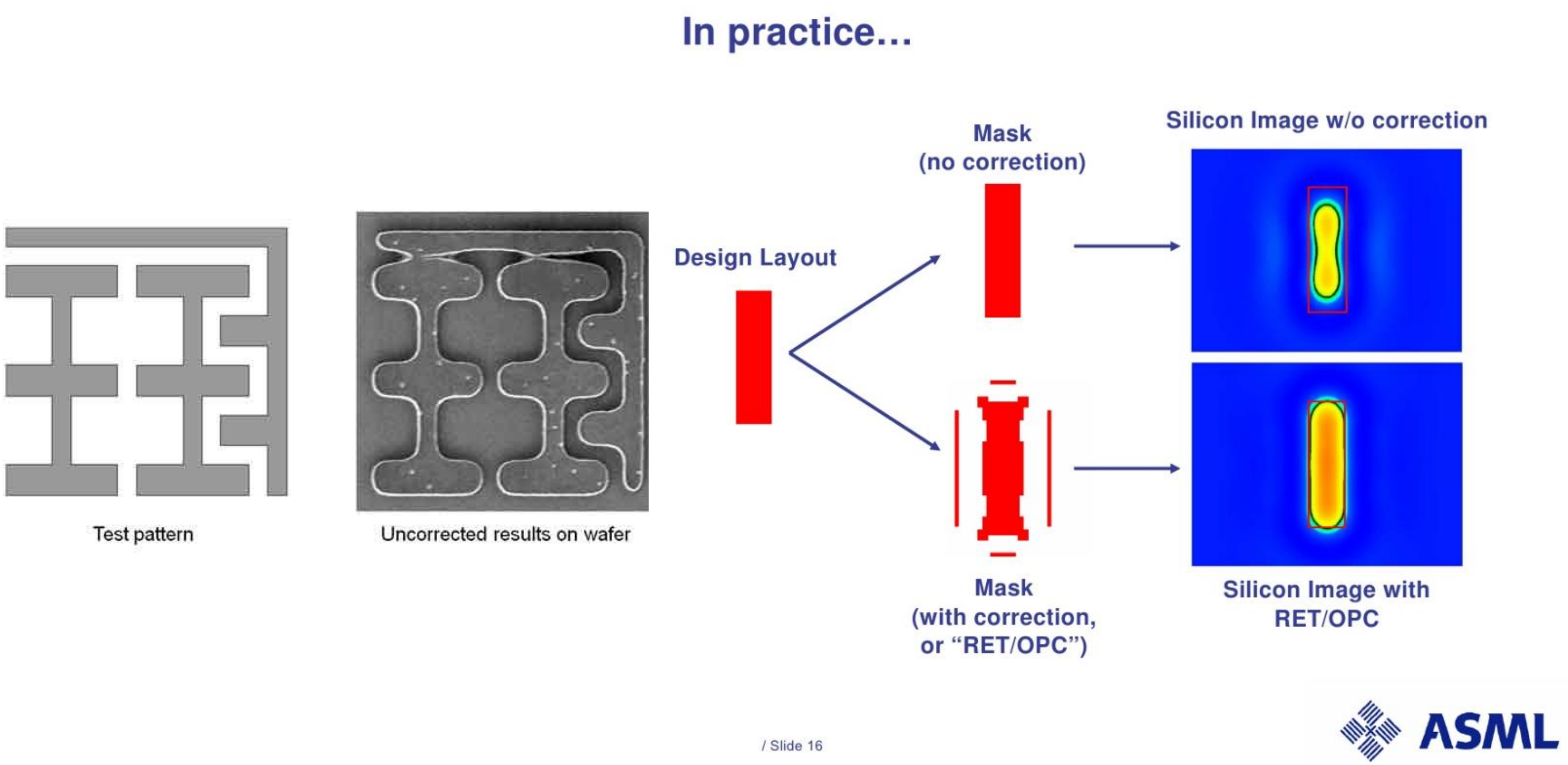


Figure 14.43

OPC

- It is possible to introduce selective image size biases into the reticle pattern to compensate for optical proximity effects



Off-Axis Illumination

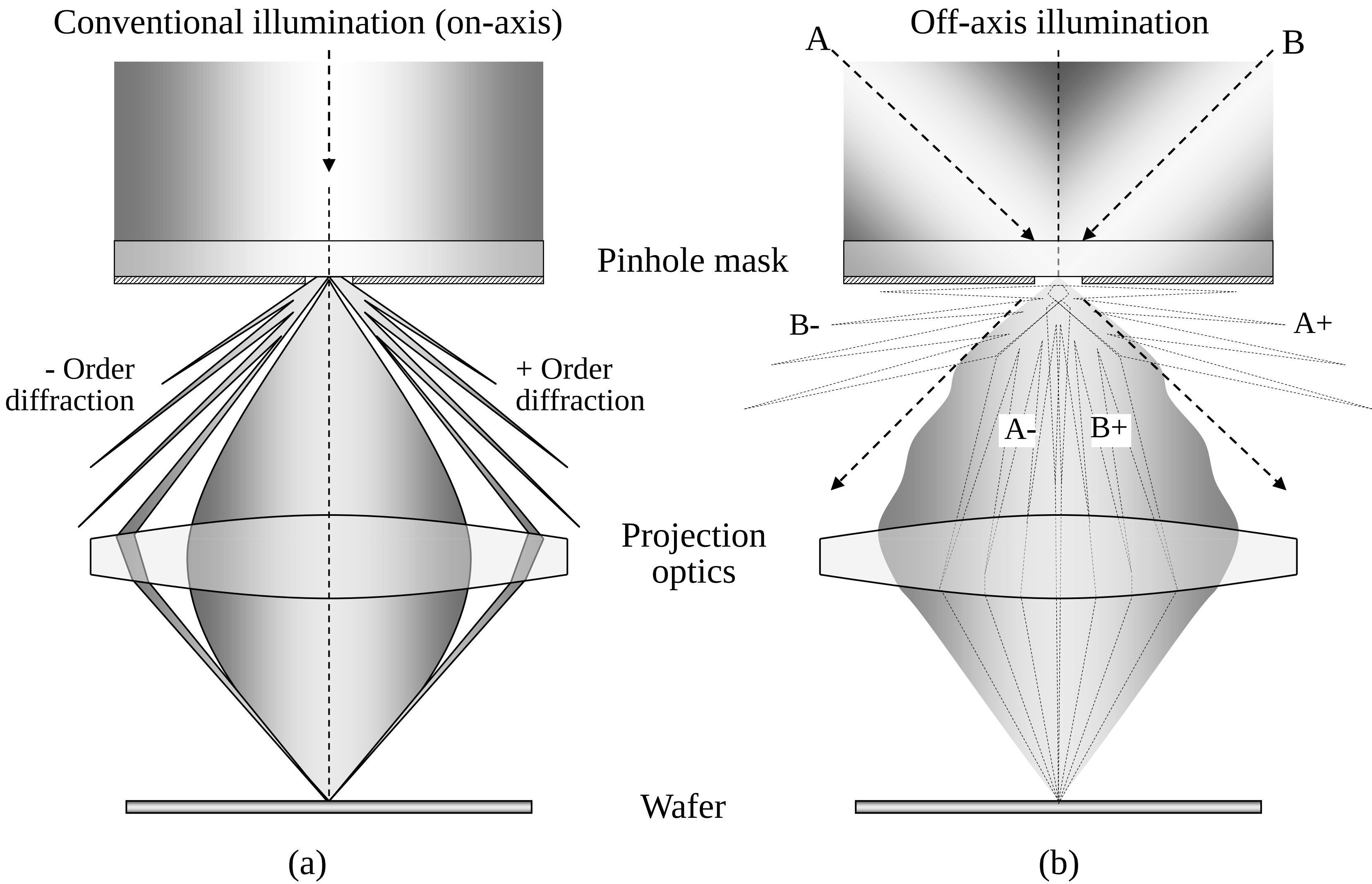
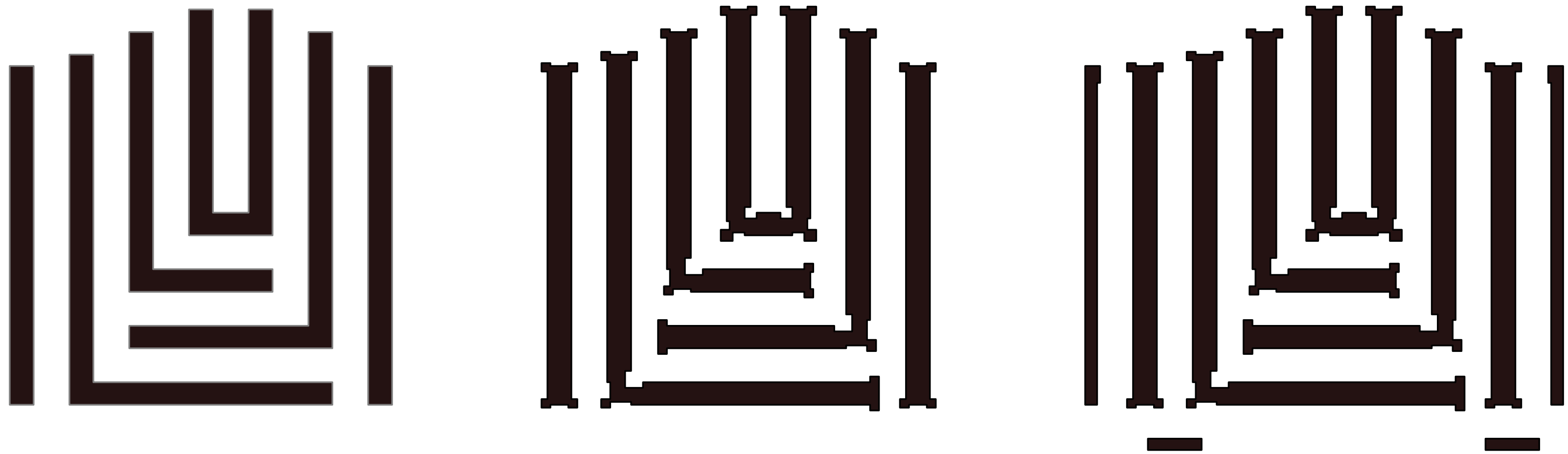


Figure 14.44

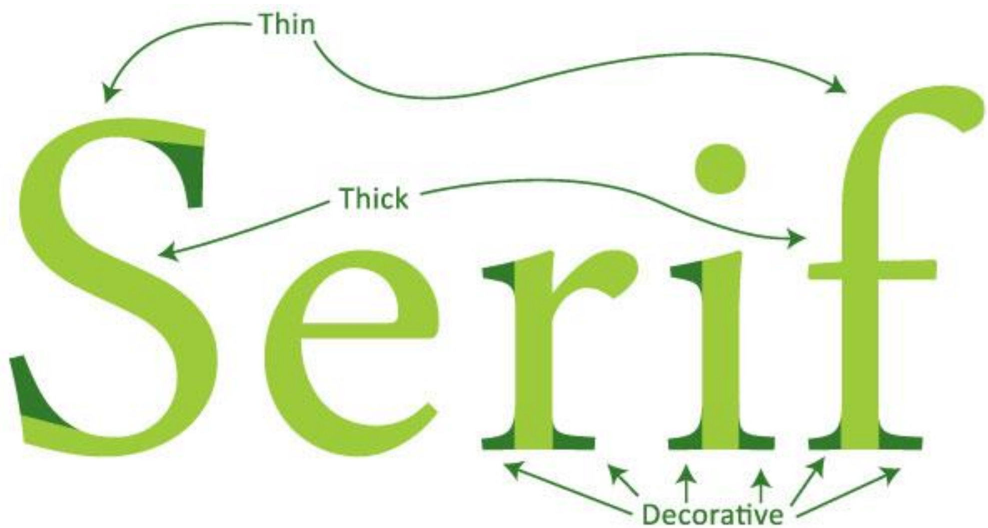
Serifs [襯線] to Minimize Rounding of Contact Corners



(a) Uncorrected design

(b) Corrected with feature biasing

(c) Feature assisting technique



Double Patterning

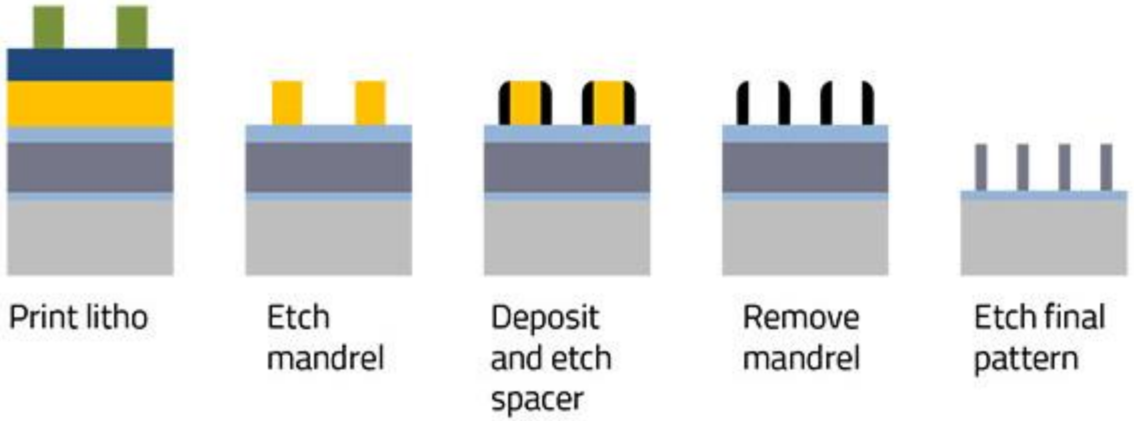


Fig. 1: Self-aligned spacer avoids mask misalignment. Source: Lam Research

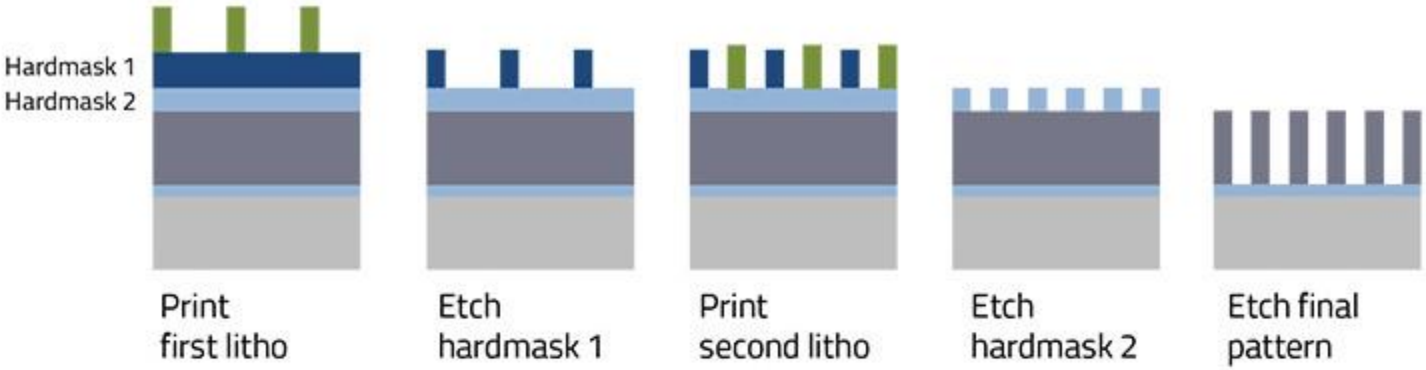


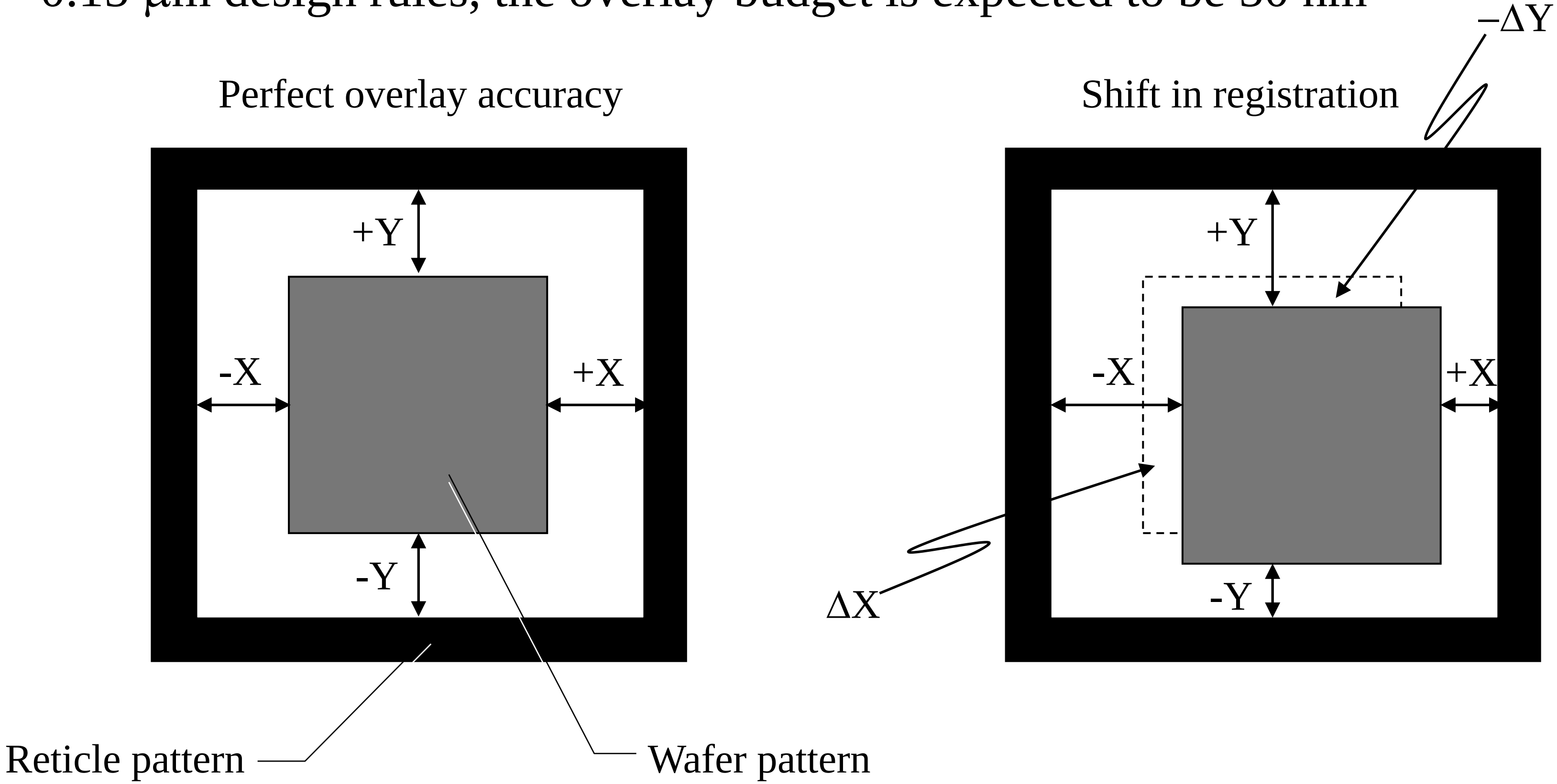
Fig. 2: Double patterning increases density. Source: Lam Research

Alignment

- Baseline Compensation
- Overlay Accuracy
- Alignment Marks
- Types of Alignment

Overlay Budget

- How accurately each successive pattern is matched to the previous layer is known as registration (or overlay accuracy)
- Overlay budget describes the maximum relative displacement between a patterned layer and the previous defined layer
- In general, the overlay budget is about one-third of the critical dimension., for 0.15 μm design rules, the overlay budget is expected to be 50 nm



Grid of Exposure Fields on Wafer

- A grid is the particular path that the photo tool follows to step across the wafer and exposure the individual fields

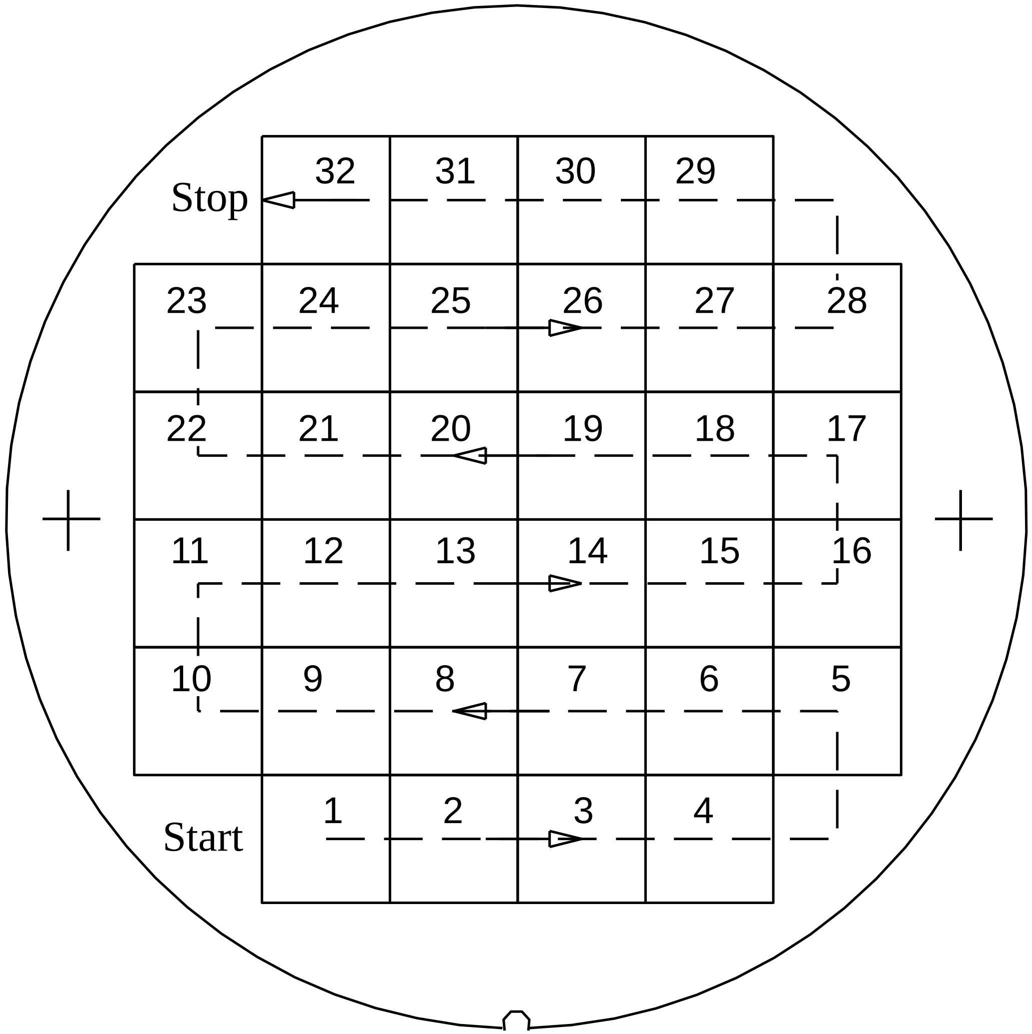
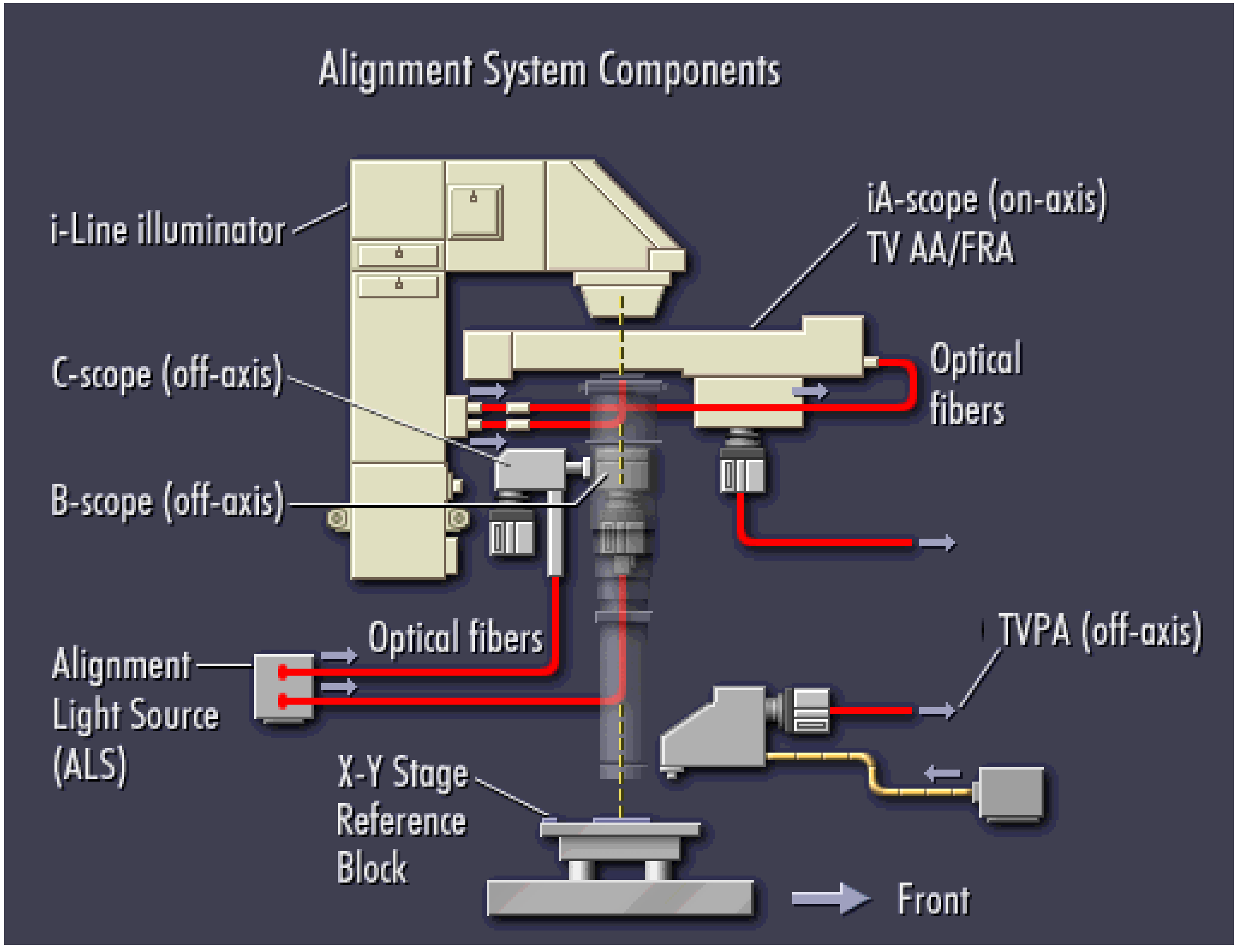


Figure 14.47

Step-and-Repeat Alignment System

- The tool's alignment system includes alignment marks on both the reticle and wafer, an alignment detection system, and the electromechanical positioning devices such as motors and drive mechanisms



Alignment Marks

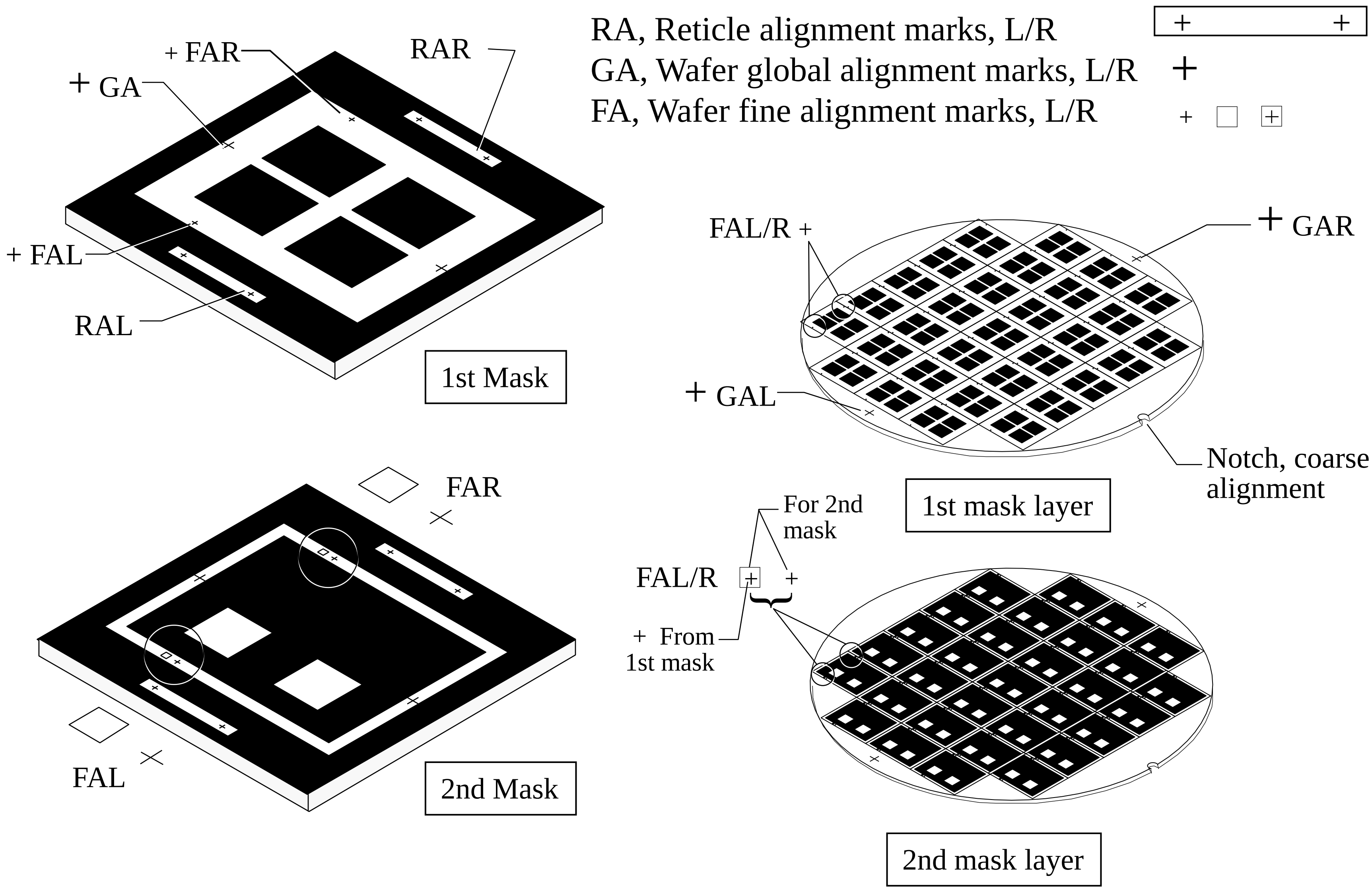
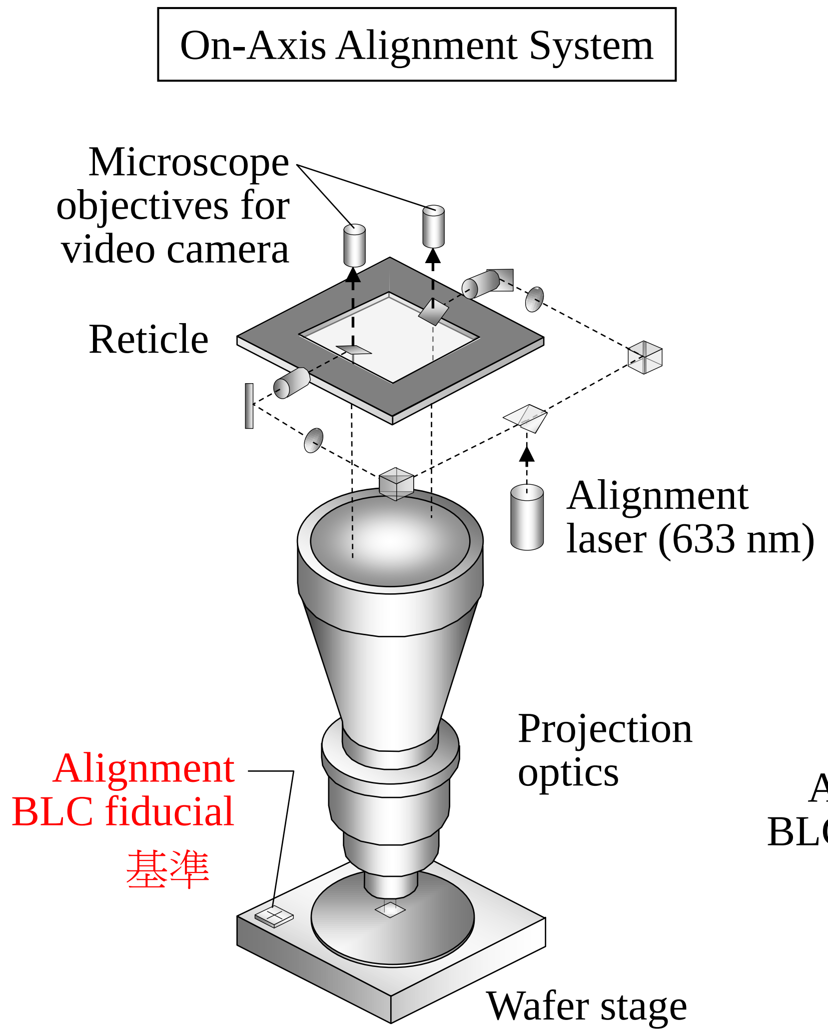
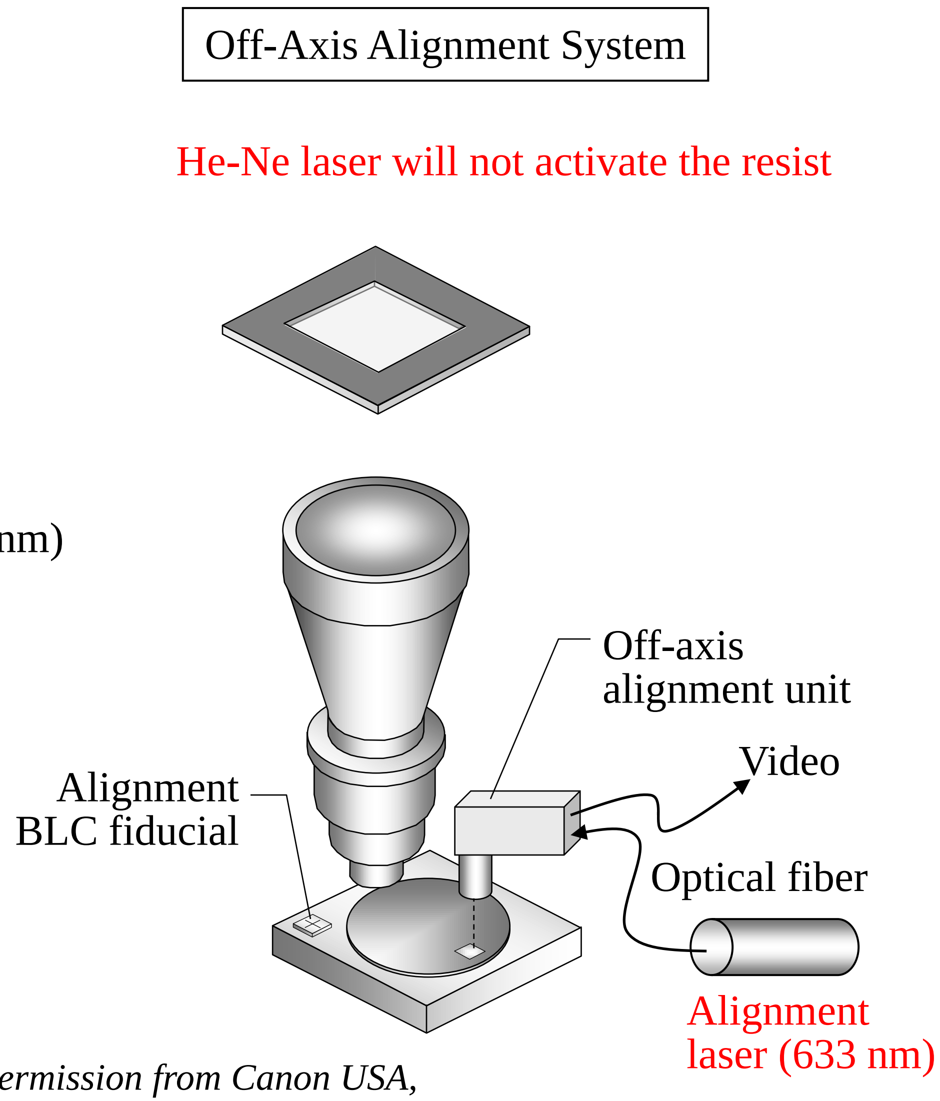


Figure 14.49

On-Axis Versus Off-Axis Alignment System





Used with permission from Canon USA, redrawn after FPA-2000i1 schematics

Figure 14.50

Environmental Conditions

- Temperature
  - controlled within a tenth of a degree
- Humidity:
  - resist adhesion
- Vibration
  - Isolated by large shock absorbers
- Atmospheric Pressure
  - Change reflective index
- Particle Contamination
  - Low particle generation

Comparison of Photo Tools (Refer to Table 14.7)

- Models by Manufacturer
- Wavelength (nm)
- Type of Aligner
- Illumination Type
- Exposure Field Size (mm)
- Resolution (μm)
- Overlay Accuracy (nm)

Step-and-Scan Aligner

Photograph courtesy of Silicon Valley Group Lithography, Micrascan II

Photo 14.3