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Course: EE6601 / Advanced Wafer Processing ocessing

School: School of Electrical and Electronic Engineering

Lithography 3 – Lithography Technology

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Lithography Technology – Lesson Overview

Lithography technology:

- Lithography equipment
- Resolution and its critical parameters
- Mask and reticle

Lithography Equipment

Lithography Equipment – Aligners

调整

Aligners

Single Exposure:

- Contact Aligner
- Proximity Aligner

Multiple Exposure:

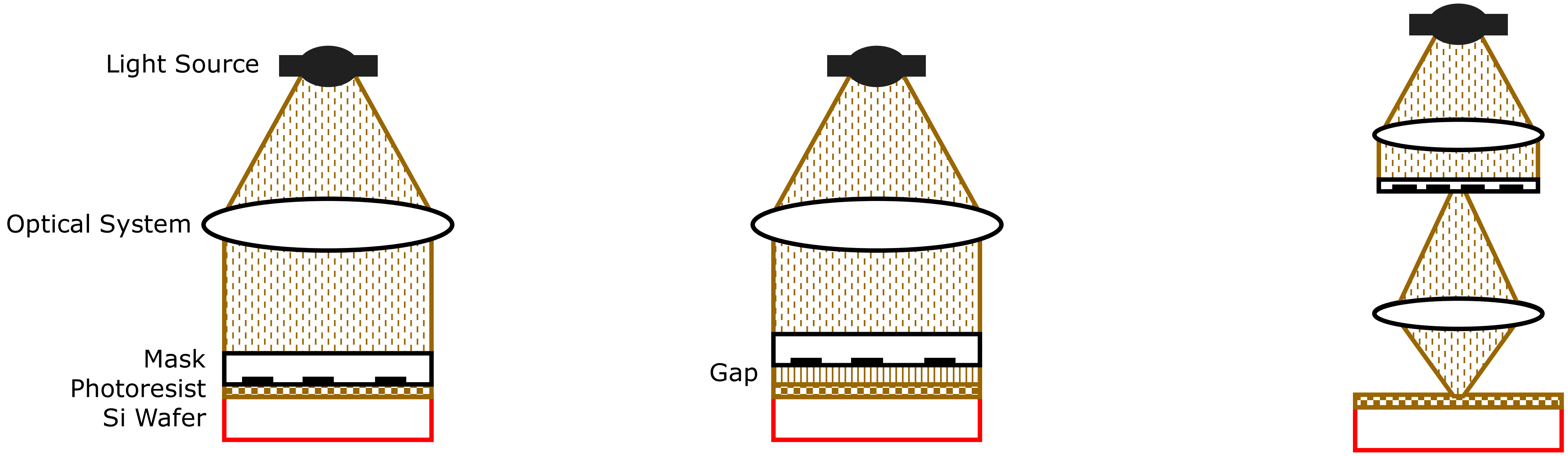
Step-and-Repeat Aligner
(Stepper)

UV Exposure - Printing

UV exposure is sometimes known as “printing” because it “prints” the desired pattern onto the substrate using UV source.

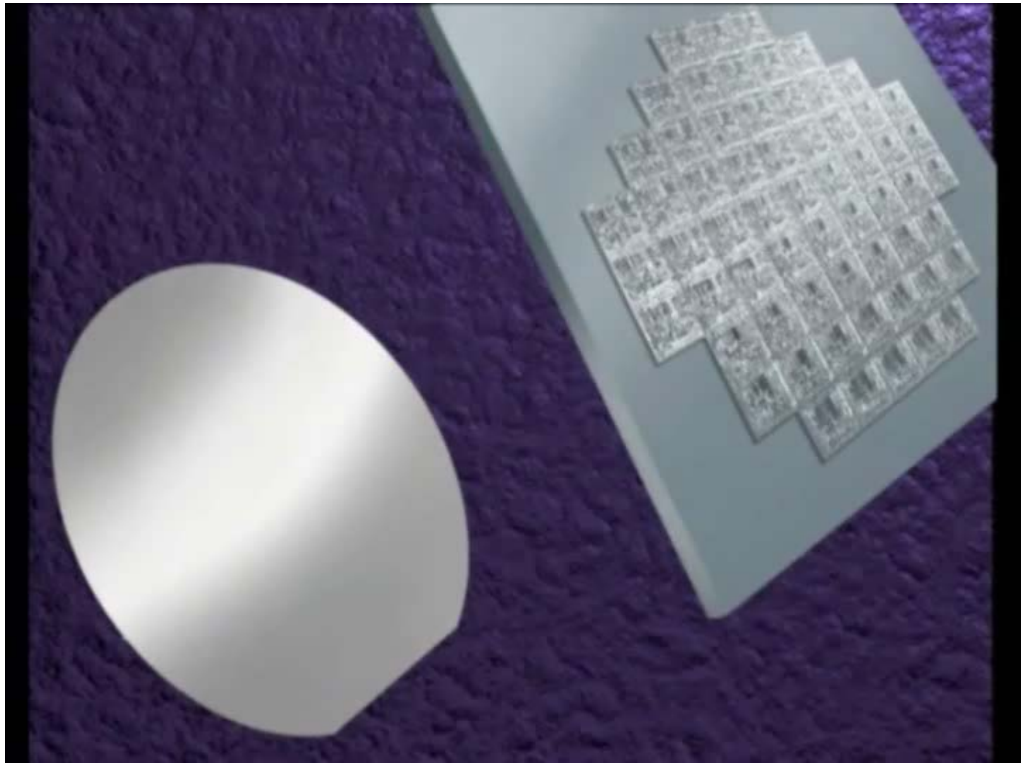
Three Basic UV Exposure Methods

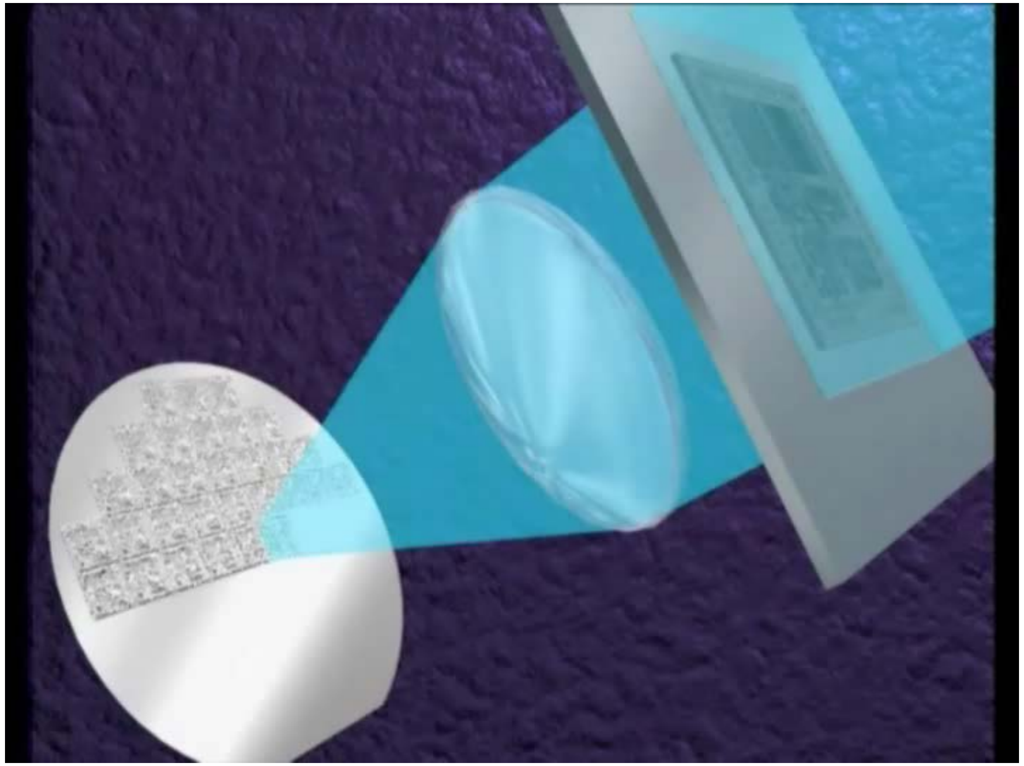
Single Exposure | **Single Exposure** | **Multiple Exposures**



Contact Printing | **Proximity Printing** | **Projection Printing**

Lithography Equipment: Single and Multiple Exposure





Single Exposure

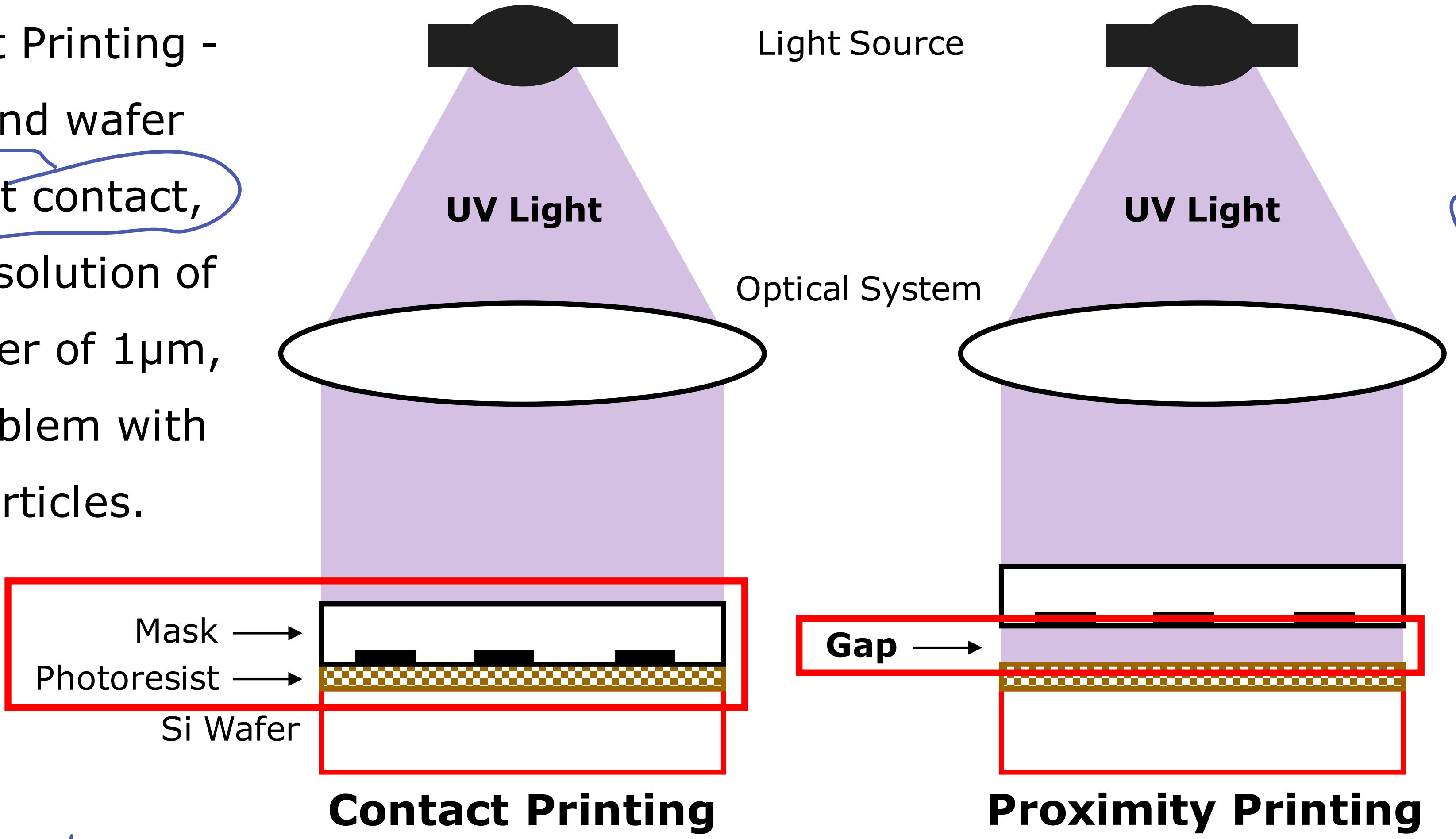
- Contact Aligner/ Printer
- Proximity Aligner/ Printer

Multiple Exposure

- Step-and-Repeat Aligner (Stepper)

Contact and Proximity Aligners

Contact Printing - mask and wafer in direct contact, high resolution of the order of 1μm, the problem with dust particles.



Proximity Printing - mask and wafer in close proximity (a small gap of 10-50μm between mask and wafer), less damage by dust particles, the low resolution of the order of 2-5μm due to the fringe.

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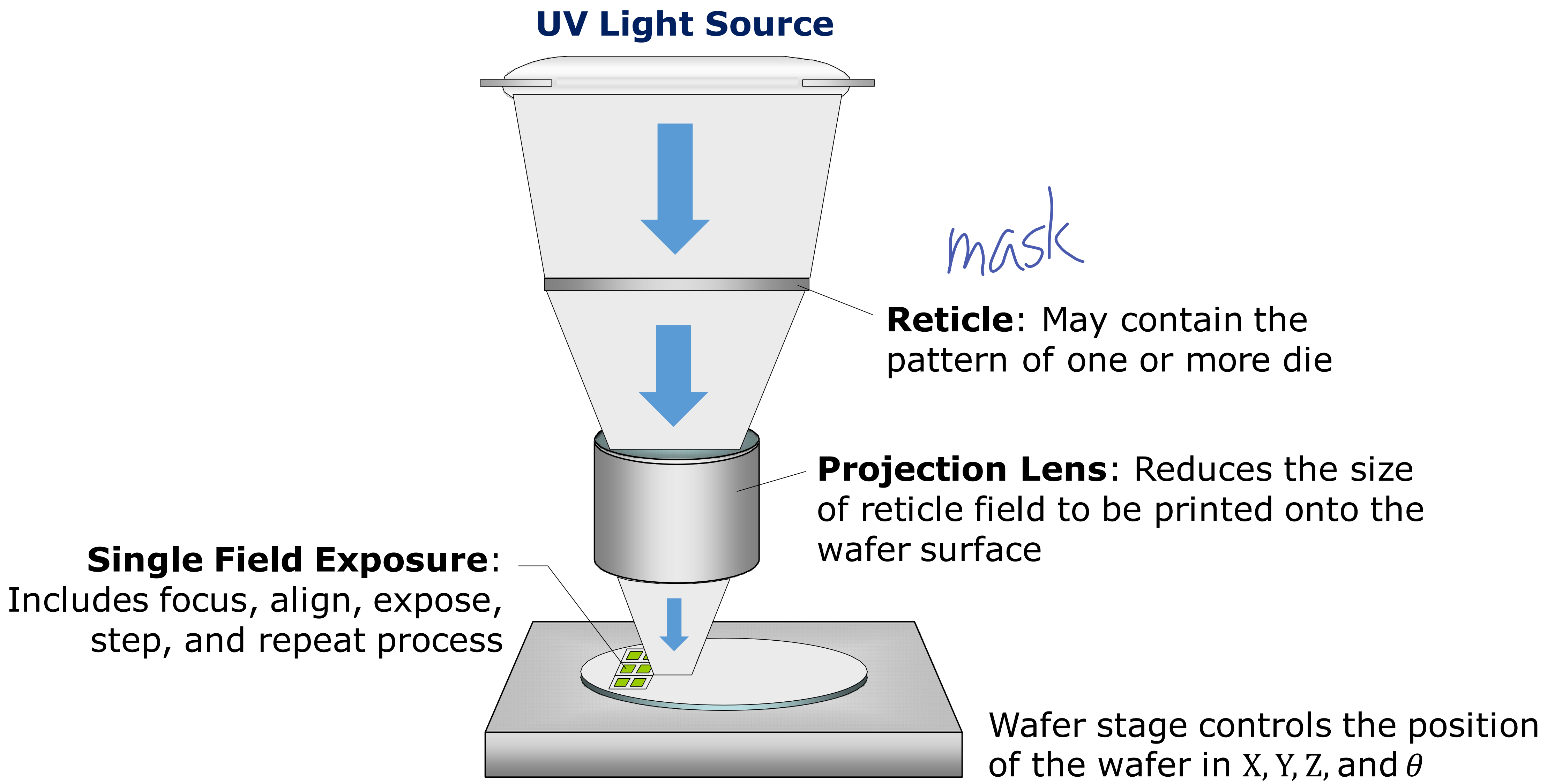
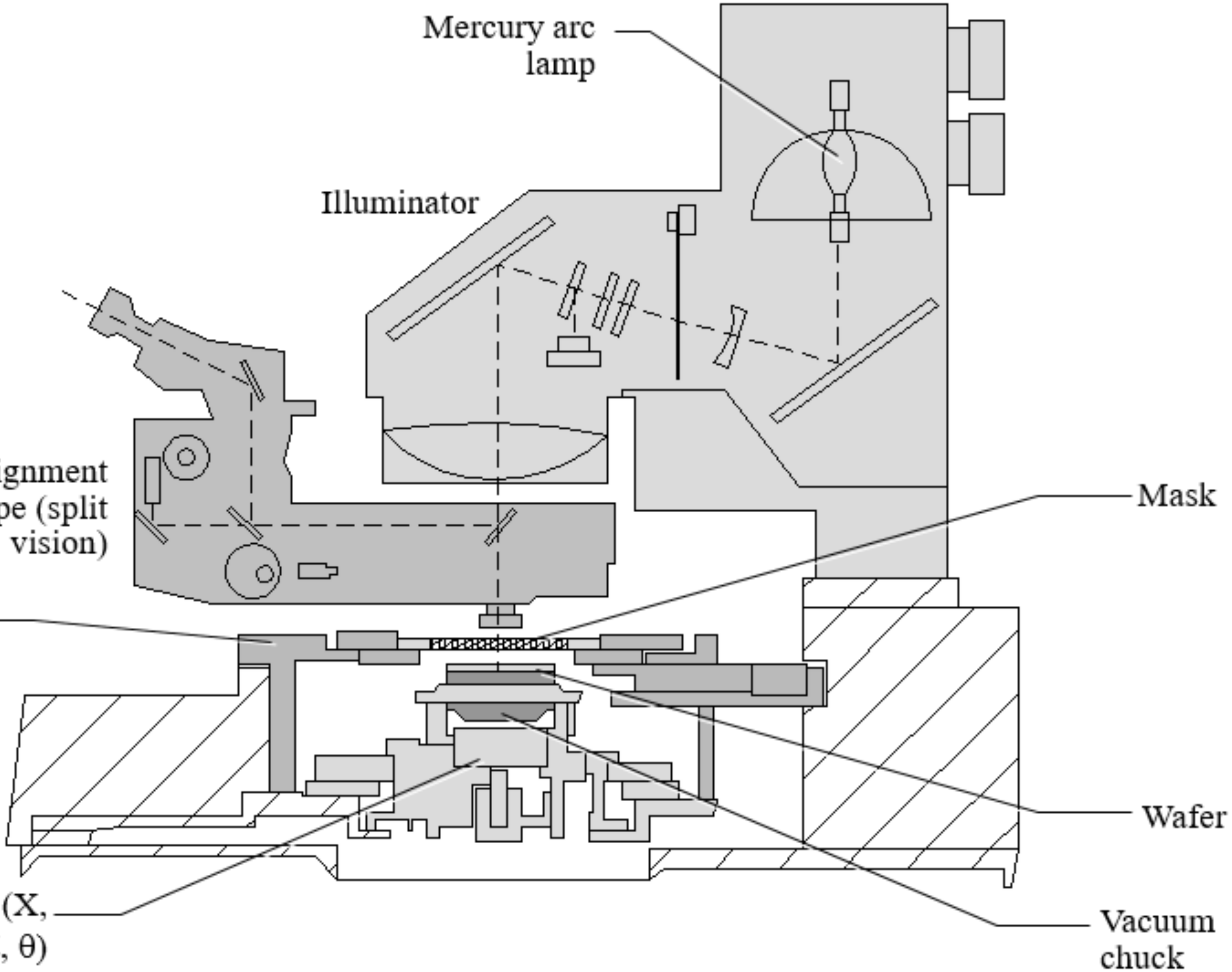
Prevents Dust Particles

have a small Gap

Multiple Exposure: Step and Repeat Printing

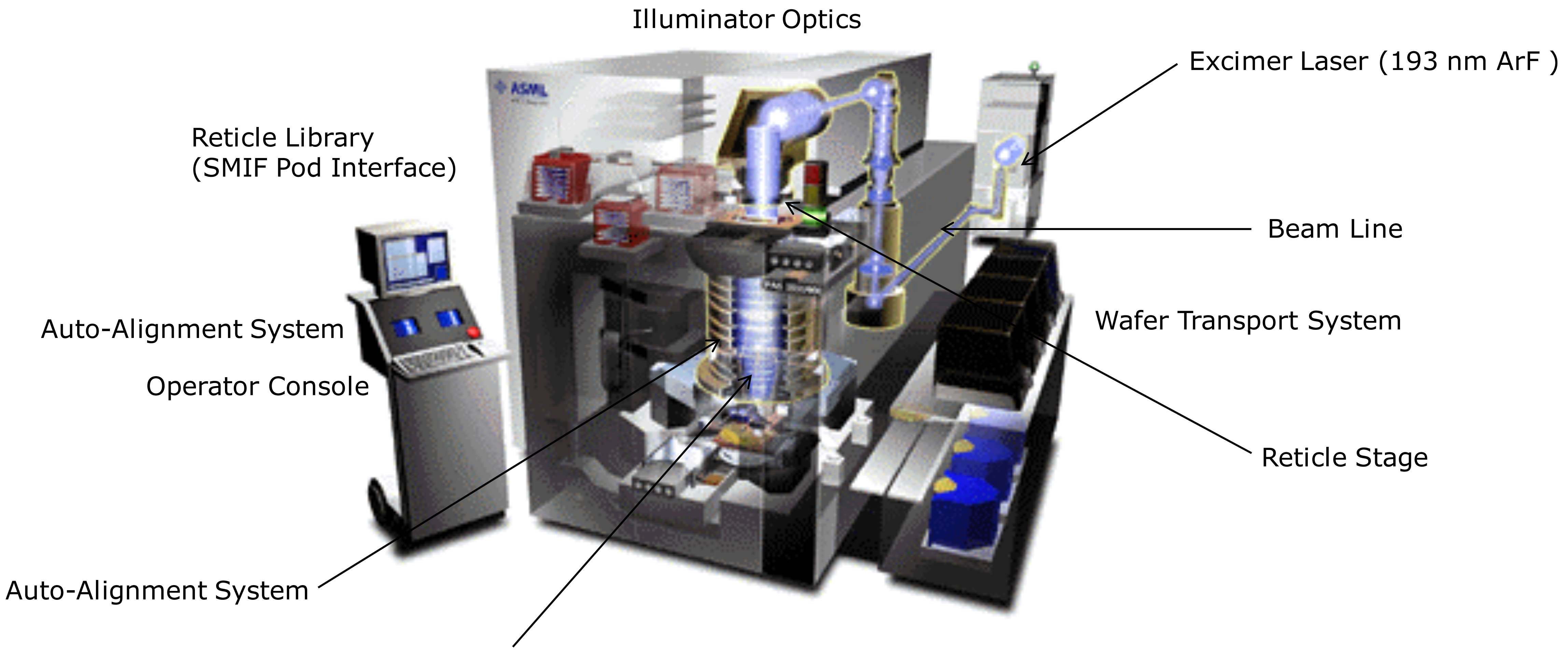


Contact/ Proximity Aligner



Used with permission from Canon USA,

Step-and-Repeat Projection Aligner



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Resolution and its Critical Parameters

Resolution

The ability of an optical system to distinguish closely spaced objects.

More challenging to distinguish small pattern.

Minimum Linewidth/ Resolution for Proximity Aligner

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- Resolution is the minimum linewidth achievable by the lithography equipment. ↓ good
- Minimum linewidth (Resolution) for the proximity printer:

$W_{min} \approx \sqrt{k_1 \lambda g}$

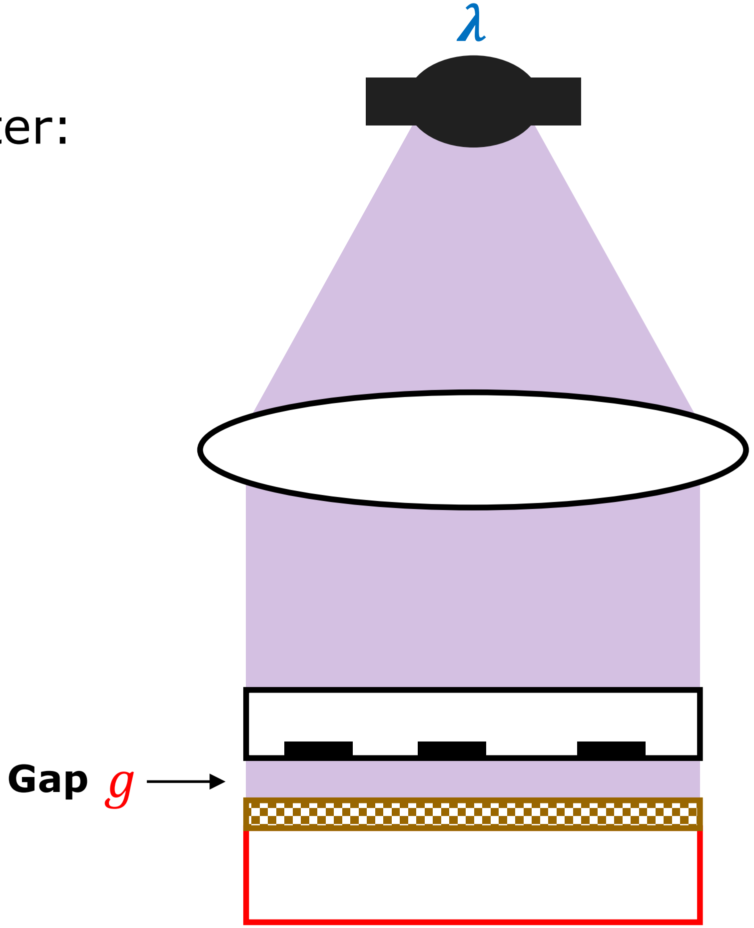
k_1 = Constant

λ = Wavelength of the exposure source

g = Gap between the mask and the wafer surface (in the range of **µm**)

k_1 factor has no well-defined physical meaning. It is an experimental parameter, depends on the lithography system and resist properties. Typical values are close to 1.

Proximity Aligner



Proximity Printing

Pause and read carefully

Practice Question 1

Determine the maximum allowable proximity gap for near and deep UV sources as a function of the feature size. ($k_1 = 1$)

Near UV: $\lambda = 0.405\ \mu m$ **Deep UV:** $\lambda = 0.248\ \mu m$ (Linewidth) $W_{min} \approx \sqrt{k_1 \lambda g}$

Pause and try out this question

Linewidth (µm)	**Maximum Gap for Near UV Source (µm)**	**Maximum Gap for Deep UV Source (µm)**
2.5	15.43	25.2
2.0	9.88	16.13
1.0	2.47	4.03
0.5	0.62	1.01

- As **feature size decreases**, **the maximum allowable gap decreases**.
- A **light source of lower wavelength** is better to overcome the above constraints in the maximum allowable gap.

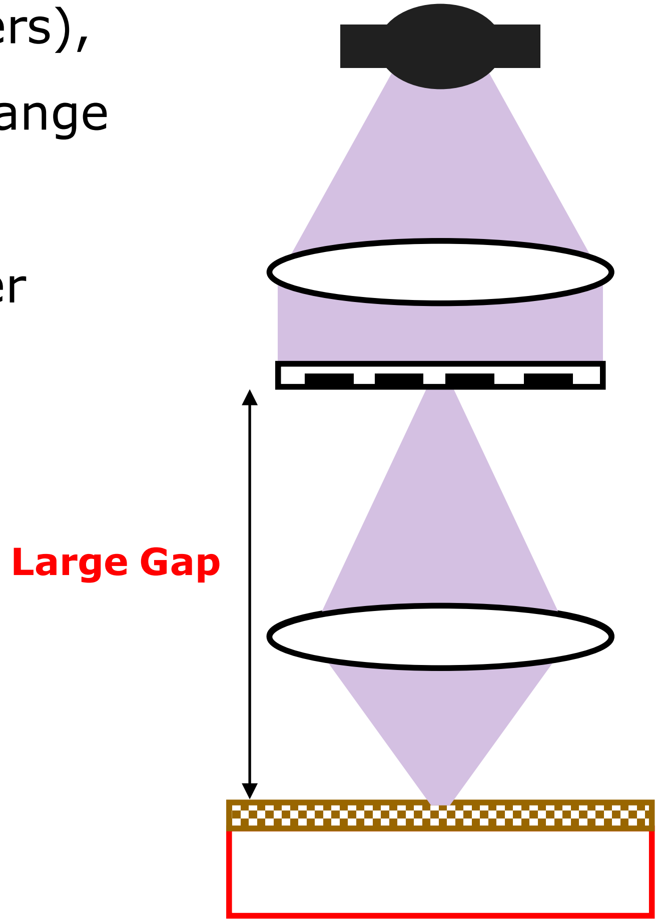
Minimum Linewidth/ Resolution for Projection Aligner

- In projection aligner (also called step-and-repeat aligners), the gap between mask and wafer is very large (in the range of cm).
- Minimum linewidth (resolution) for the projection printer can be calculated using:

$$W_{min} \approx k_1 \frac{\lambda}{NA}$$

Where *NA* is called the numerical aperture.

high resolution



Projection Printing

Pause and read carefully

Numerical Aperture

- The numerical aperture (NA) of an optical system is a measure of the ability to collect light, which is a measure of the light gathering power.
- Numerical Aperture, (NA) can be defined as:

high = good

$$NA = n \sin\theta$$

Where n = refraction index (the medium in which the system is immersed, in this $n = 1$ for air), and θ = one half the angle of acceptance of the objective lens.

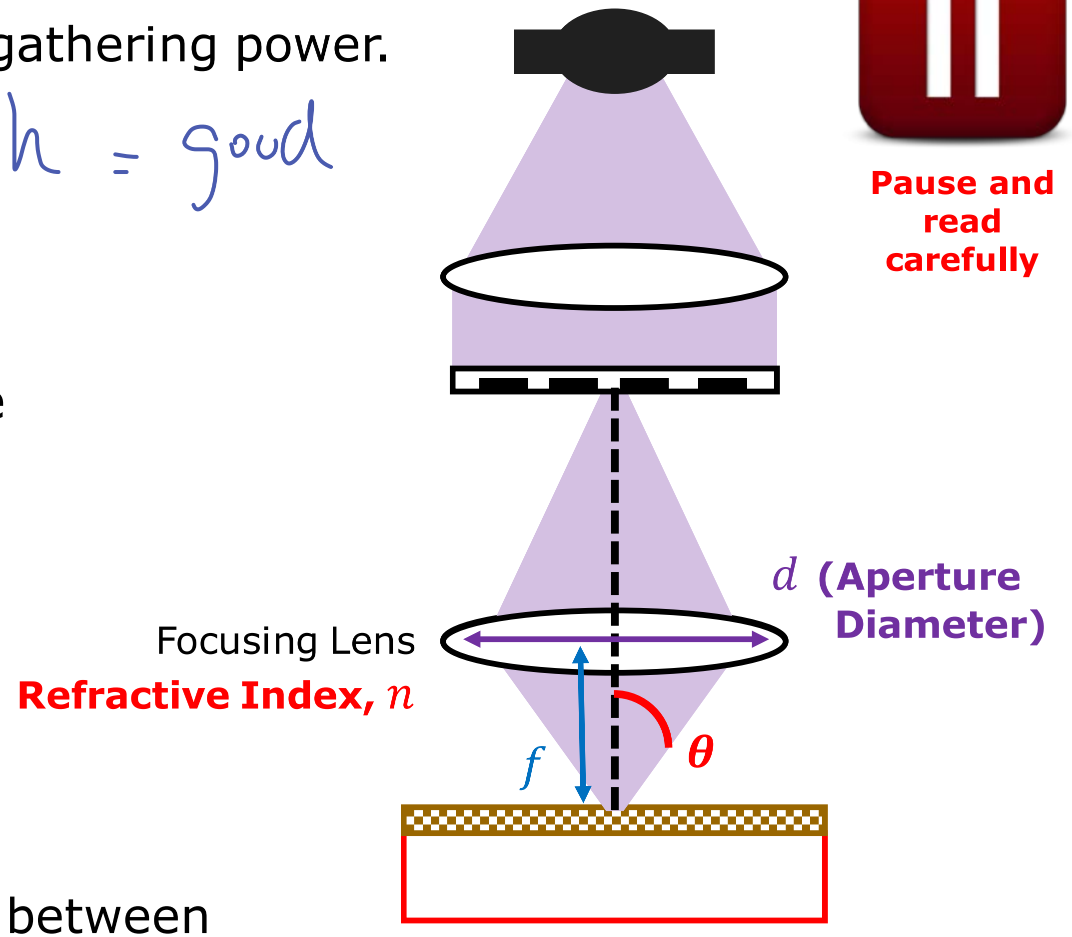
When $n = 1$, the NA can be defined as

$$NA = \sin\theta \approx \tan\theta = \frac{d/2}{f} = \frac{d}{2f}$$

$\tan\theta \simeq \sin\theta$ since θ is less than 12°

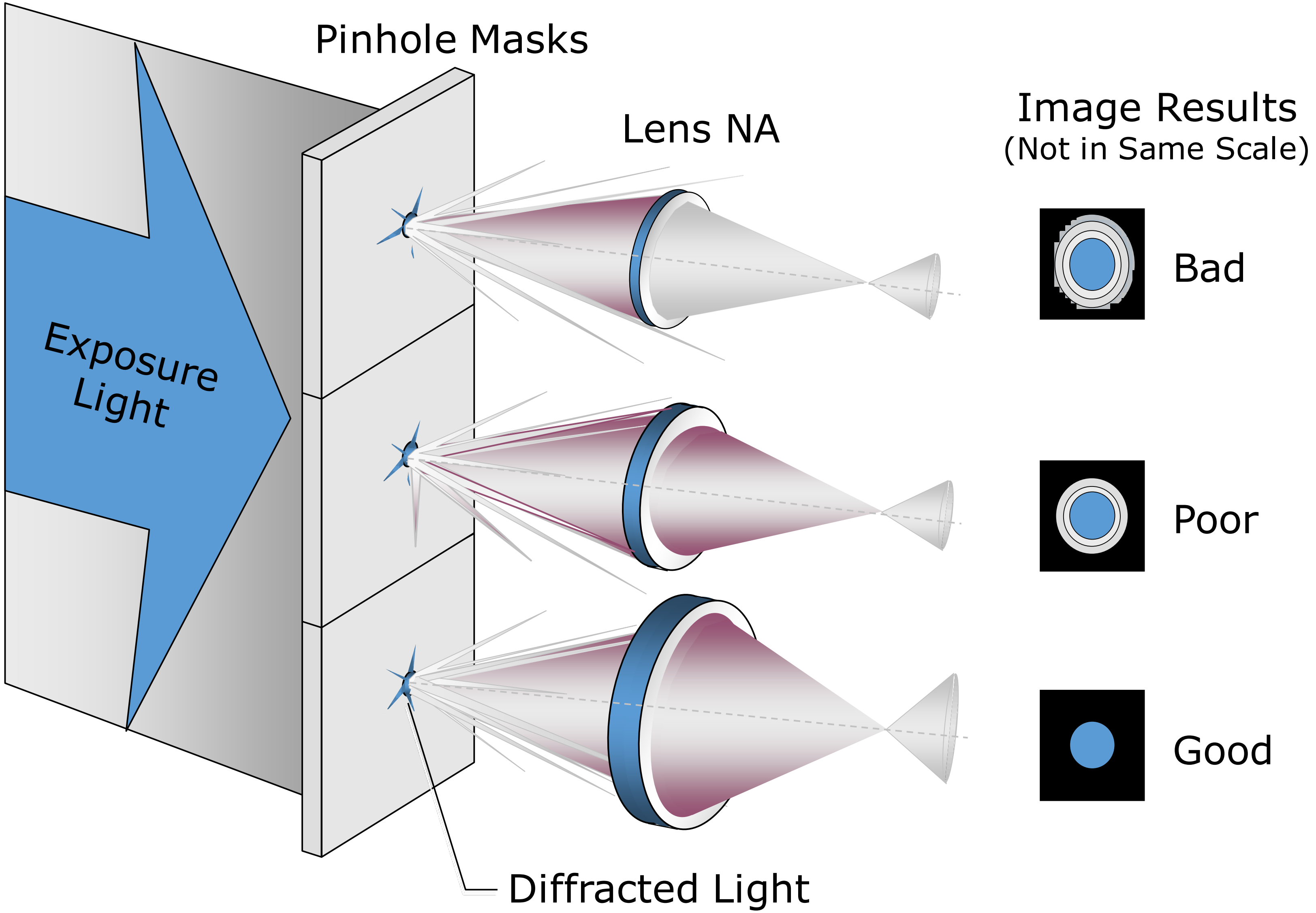
NA for projector objective is also the geometrical ratio between aperture and focal length.

Pause and read carefully



Projection Printing

Effect of Numerical Aperture on Imaging



Typical *NA* Values for Photolithography Tools

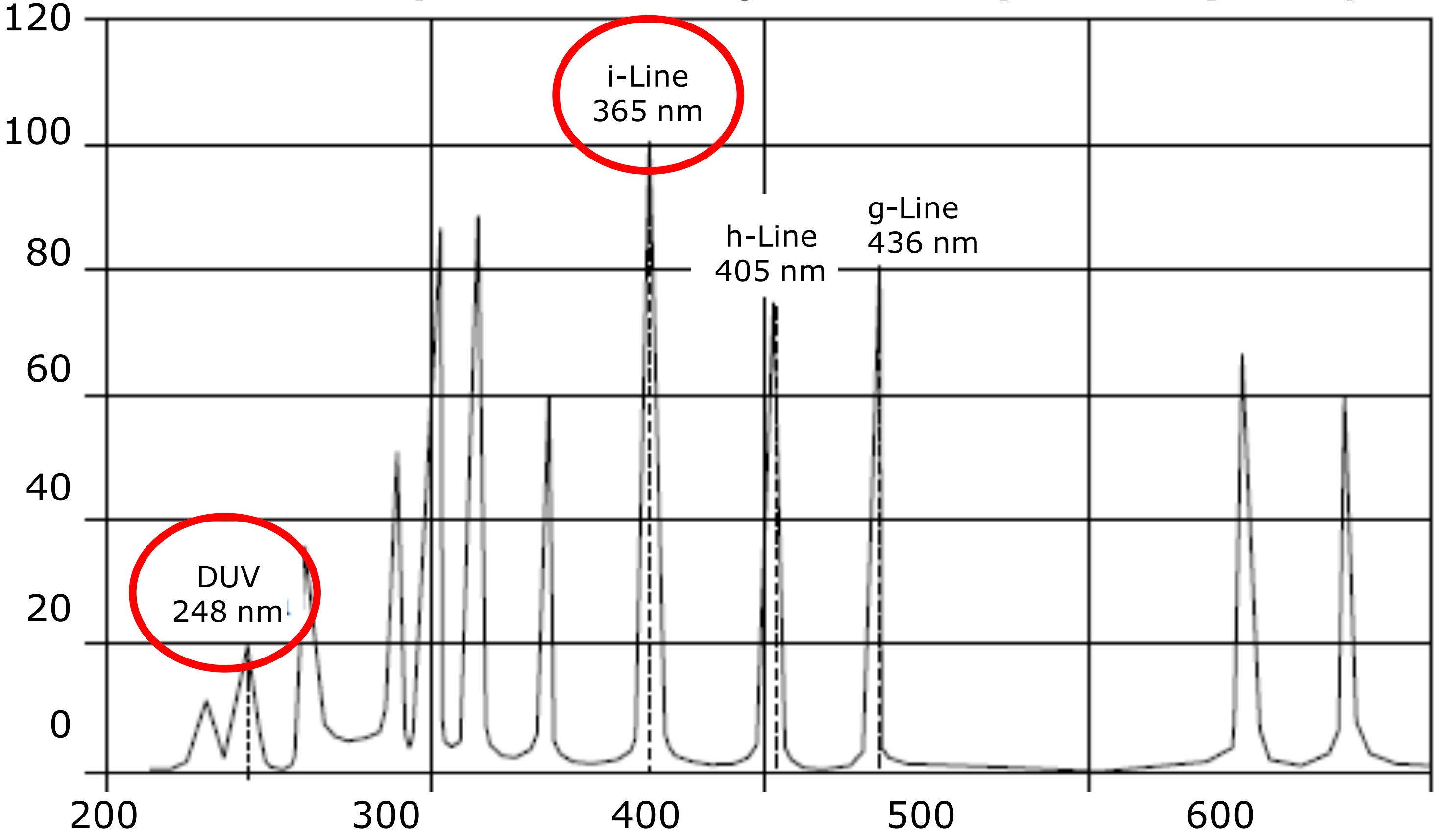
Type of Equipment	***NA* Value**
Step-and-Repeat	0.60 - 0.68

Practice Question 2

A step-and-repeat aligner has an *NA* value of 0.6. By assuming $k_1=1$, which of the followings is/ are the most suitable UV source(s) to achieve resolution of **0.62 µm**?

Pause and try this carefully

Emission Spectrum of High-Intensity Mercury Lamp

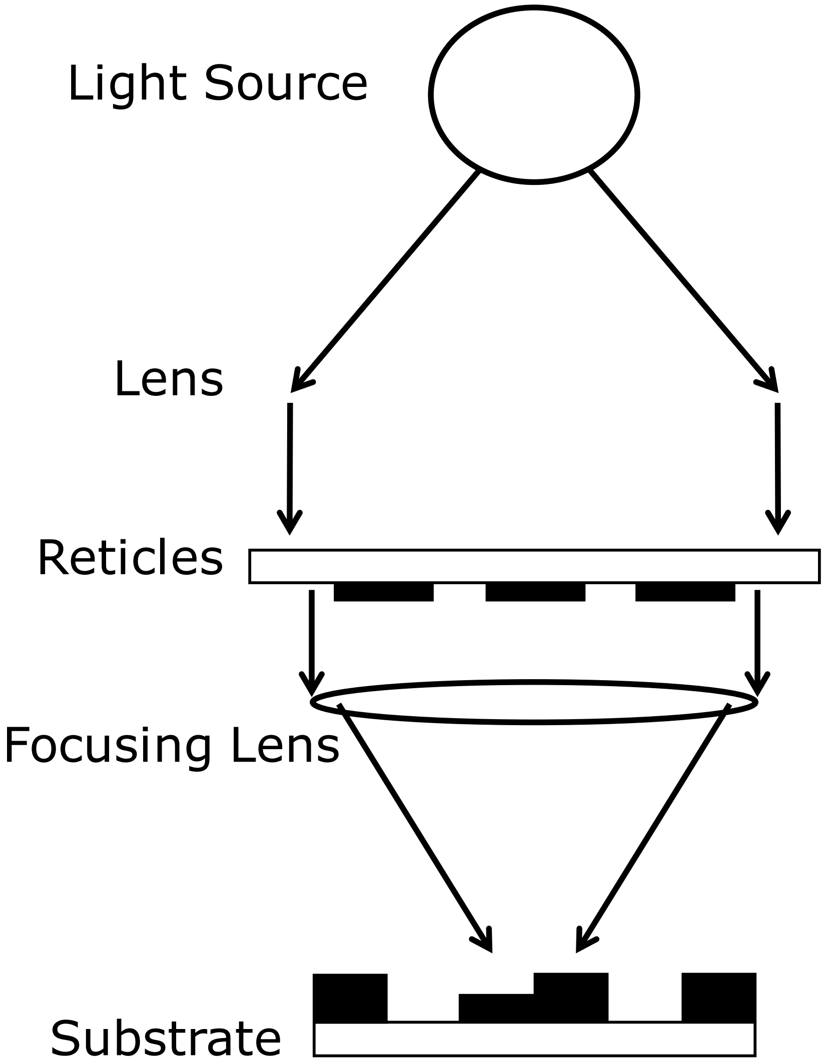


maller better

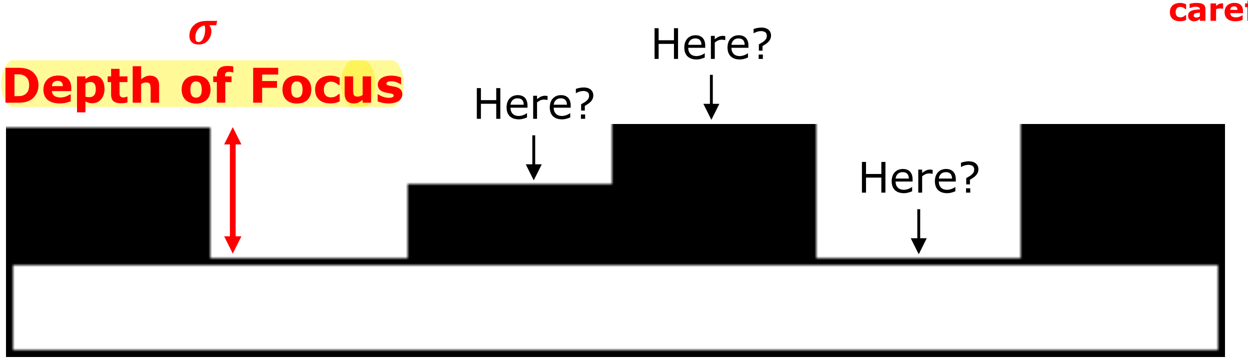
$$W_{min} \approx k_1 \frac{\lambda}{NA}$$

- The obtained λ value is 372 nm. UV sources with wavelengths smaller than 372 nm can be used. Both i-line and DUV can achieve such resolution.
- DUV has a lower intensity.
- Excimer laser which has a higher intensity can be used.

Lithography on Uneven Surface



Where should be focused?

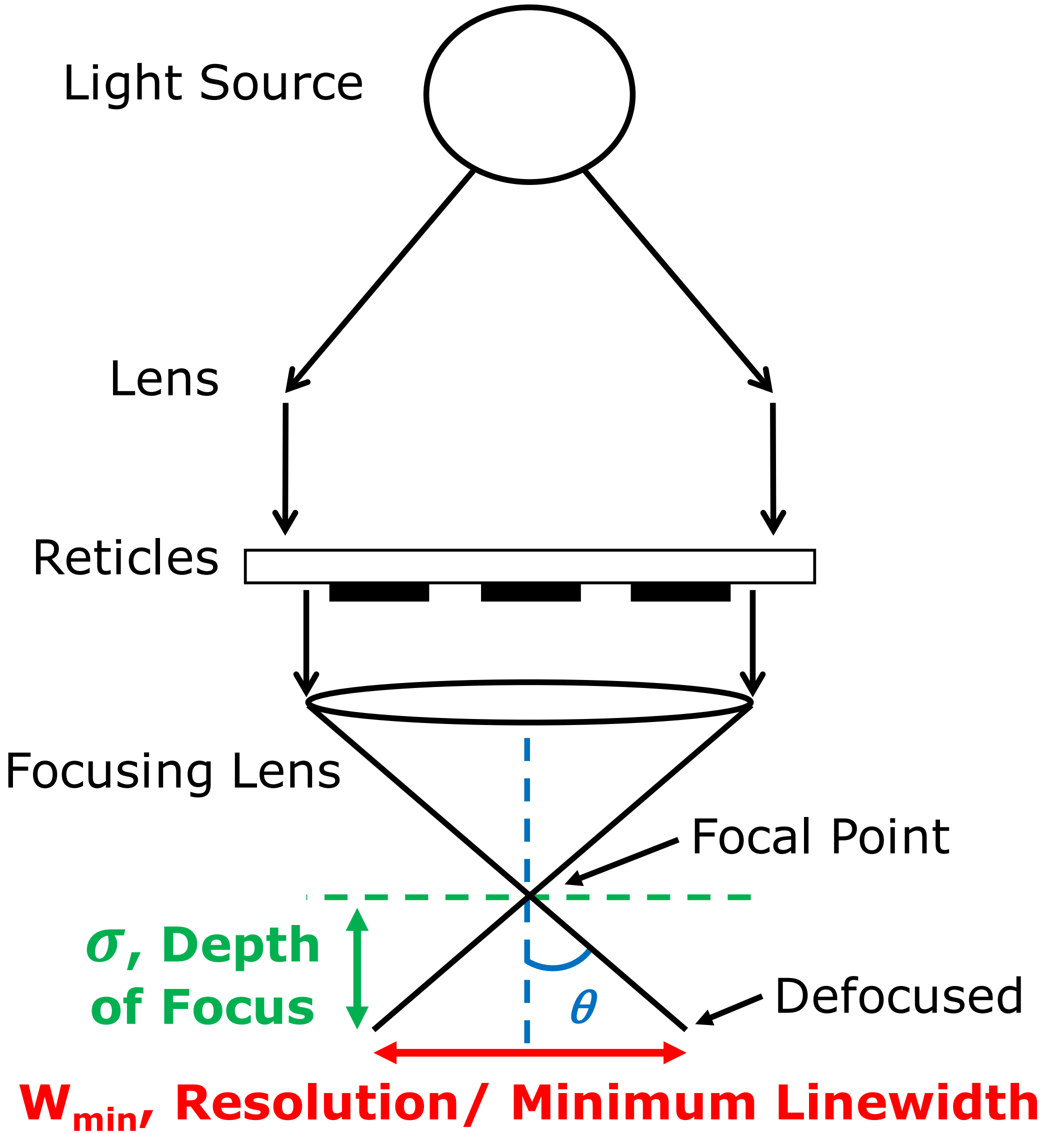


Pause and read carefully

Depth of focus: Range of focus error that a process can tolerate.

high↑ better.

Depth of Focus – How to Deal With It?



Depth of focus:

$$\sigma = \pm \frac{W_{min}/2}{\tan\theta} \cong \pm \frac{k\lambda/2NA}{\sin\theta}$$

$$\sigma = \pm \frac{k\lambda/2NA}{NA/n} \cong \pm \frac{k_2\lambda}{(NA)^2}$$

Pause and read carefully

$\tan\theta \sim \sin\theta$ for θ < 12°

k and k_2 are constant , n = 1 (for air)

Again, like the case of resolution, we used k_2 factor as an experimental parameter. It has no well-defined physical meaning.

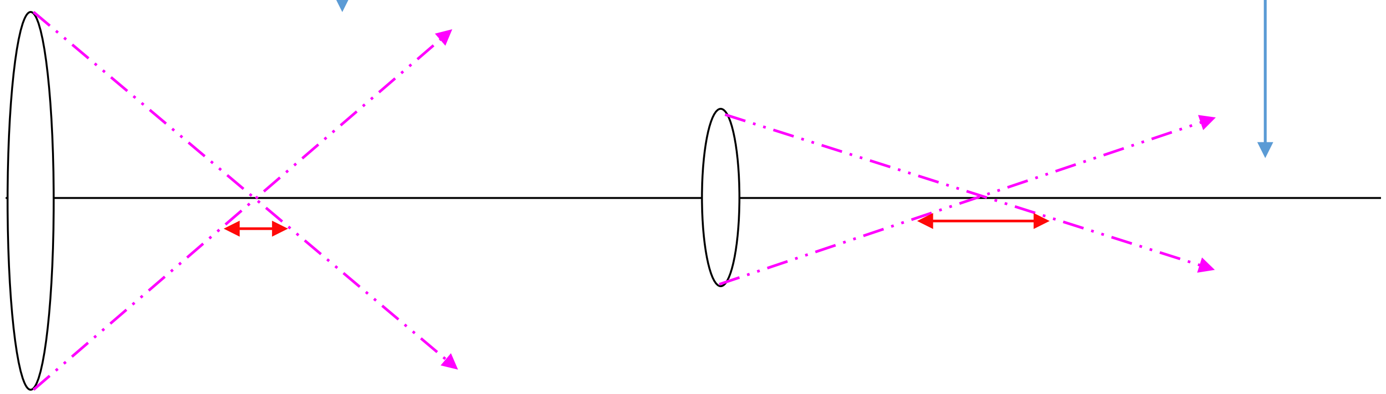
Depth of Focus for Projection Photolithography

$$DOF = \delta = \pm k_2 \frac{\lambda}{(NA)^2}$$

- Large NA gives smaller depth of focus.
- This is also true for the camera. A cheap camera takes photos that are always in focus no matter where the subject is. This is because it has small lenses.

Small DOF
(Background Blurred)
What one need here is a telephoto lens at its widest aperture.

Large DOF
A small aperture was used to ensure the foreground stones were as sharp as the ones in the distance.



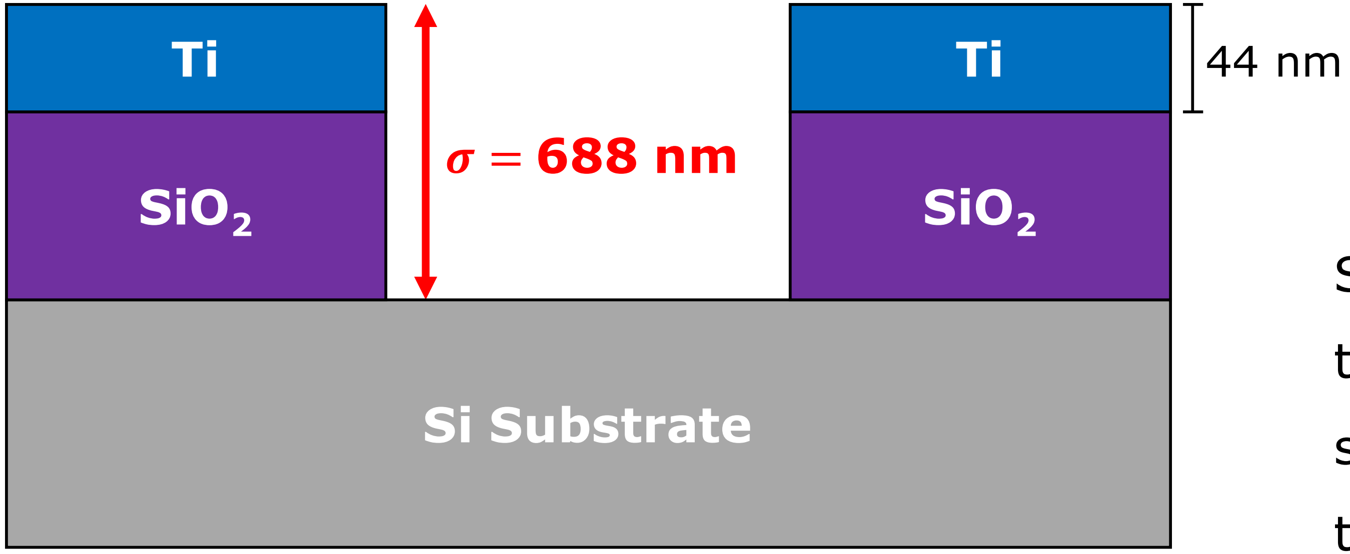
Large Lens (Large NA), Small DOF   Small Lens (Small NA), Large DOF

Practice Question 3

We need to perform lithography patterning on a structure illustrated below using a step-and-repeat aligner ($NA = 0.6$, $k_2 = 1$). The exposure source is excimer laser (248 nm). To obtain a sharp image, what is the maximum thickness of the SiO_2 layer?

Pause and try this

$$\sigma = \frac{k_2 \lambda}{(NA)^2}$$



$$\sigma = 688 \text{ nm}$$

Since titanium has a thickness of 44 nm, the total thickness of titanium and SiO_2 should not exceed 688 nm. Therefore, the SiO_2 layer should be ≤ 600 nm.

Diffraction in Lithography

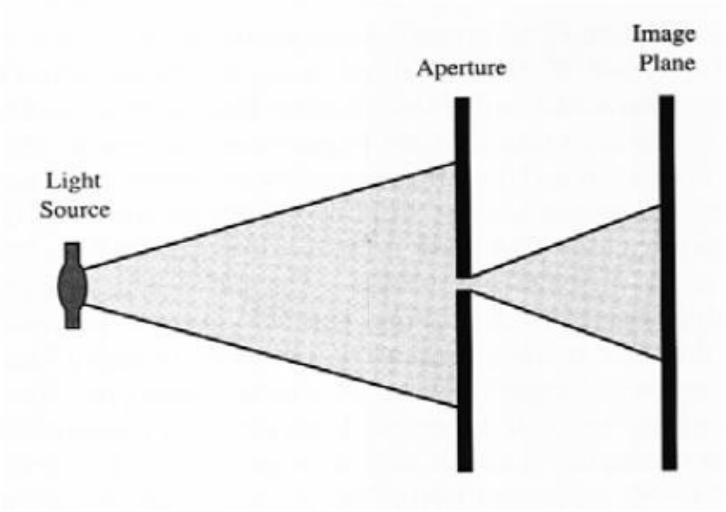
衍射

What is diffraction? Why is it a concern in lithography?

- Diffraction occurs when light passes through a narrow opening or past a sharp edge.
- Interference patterns occur along the edge of the opening, causing a fuzzy image rather than the expected sharp edge that occurs between light and shadow.
- Diffraction patterns rob exposure energy and scatters it, leading to exposure of unwanted areas of the resist.
- Light diffraction is a concern in photolithography because of the extremely small patterns of sharp edges and narrow spaces on reticles. Diffraction patterns rob exposure energy and scatter it, leading to exposure of unwanted areas of the resist.
- We can adopt optical enhancement techniques such as optical proximity correction (OPC), phase-shifting masks (PSM) and off-axis illumination (OAI) – discussed in later lectures.

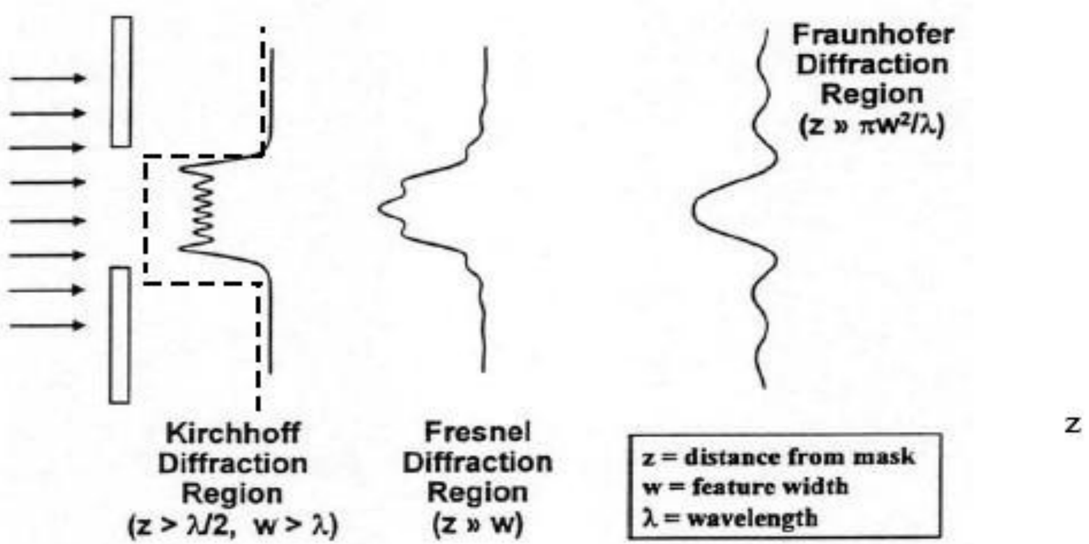
What is Diffraction?

- Diffraction is the spread of radiation into un-wanted(un-exposed) regions
- Modern lithography tools are limited by the spreading of light (and not their optical elements)

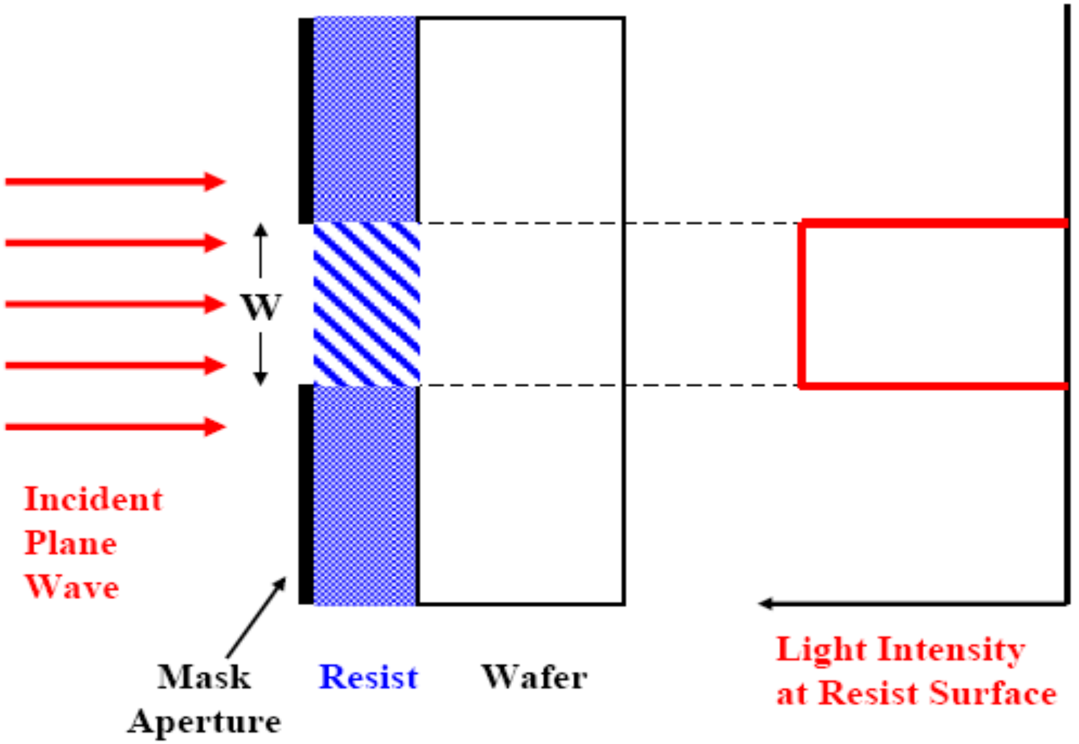


Type of spreading depends on mask - wafer separation :

- Hard contact : (Almost) no diffraction
- Proximity contact: Near field (Fresnel) diffraction
- Projection : Far field (Fraunhofer) diffraction



Contact Printing



It is important to keep the mask as close to the sample as possible by using the high precision vacuum seal on the aligner.

This reduces diffraction of light caused by the gap between the mask and the sample, and hence improves the resolution.

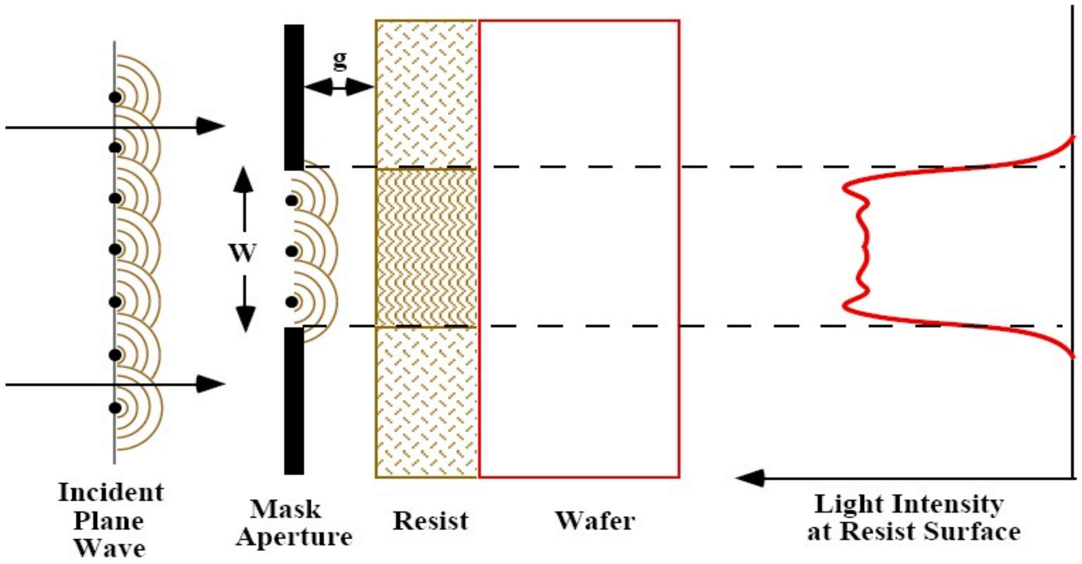
This also makes a steady distribution of UV light across all of the exposure area.

- **Contact Aligner—mask is in hard contact with resist and may cause damage to mask**

- **not diffraction limited**

Proximity Printing

--- limited by Near Field (Fresnel) Diffraction



- Fresnel diffraction applies when

$$\lambda < g < \frac{W^2}{\lambda}$$

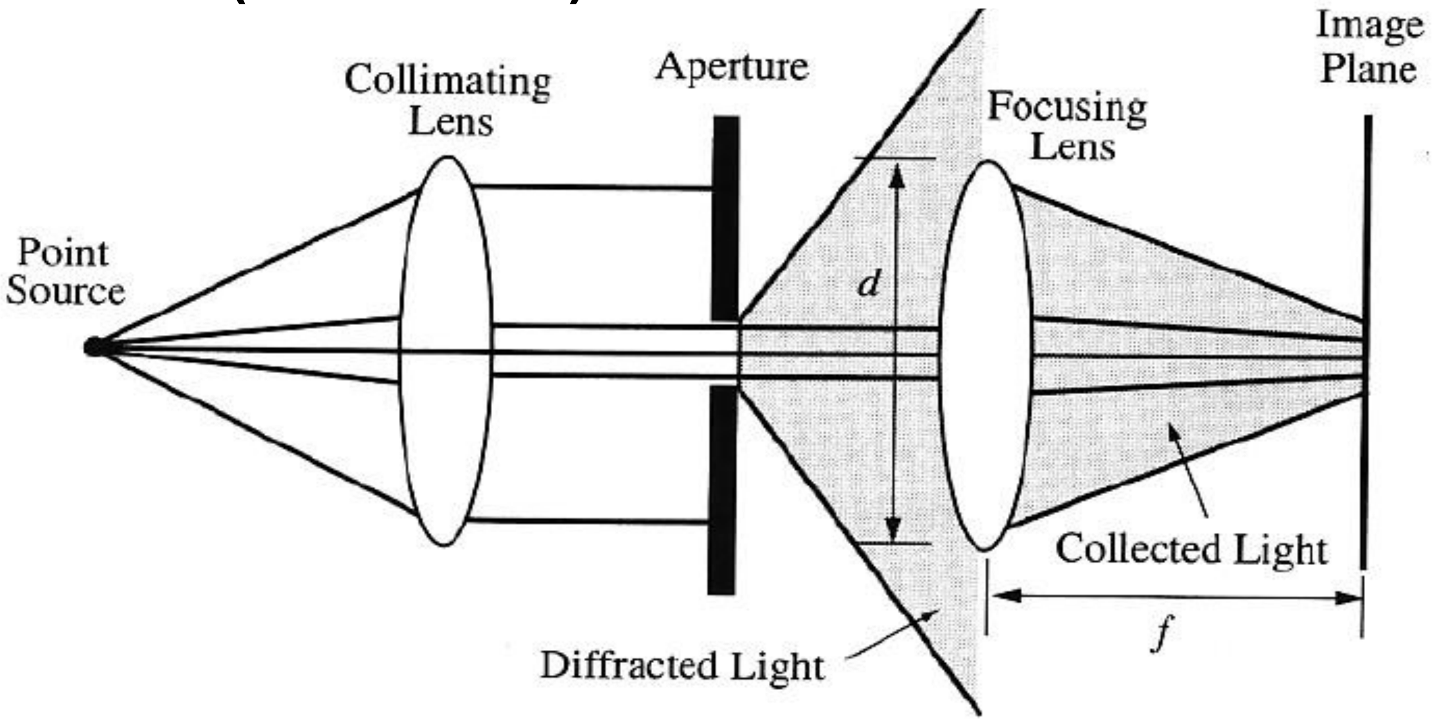
- Within this range, the minimum resolvable feature size is

$$W_{min} \approx \sqrt{k_1 \lambda g}$$

- Mask and wafer are separated by a small gap of 2-20 µm
- The resulting diffraction pattern has several features
  –Intensity rises gradually near the edges producing some resist exposure outside the mask edge
  – Ringing in intensity distribution within the aperture
- As mask separation g increases, quality of image degrades

Projection Printing

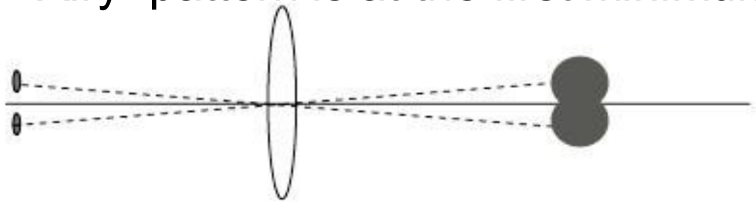
--- limited by Far Field (Frauhoffer) Diffraction

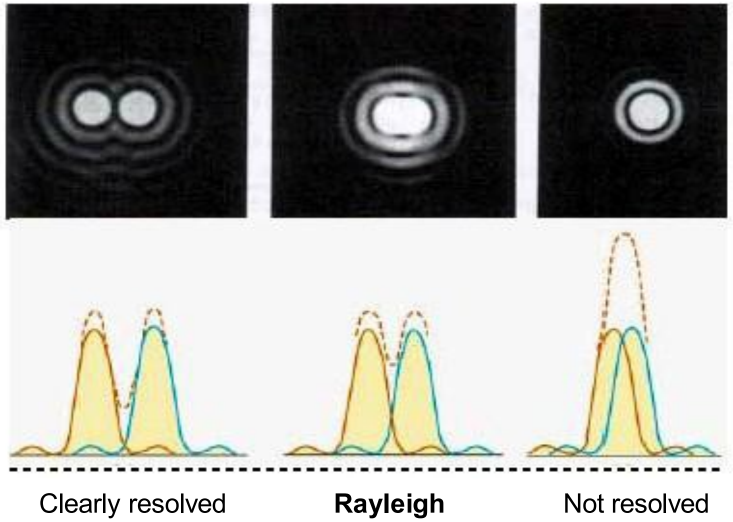


Diffraction light from the Aperture on the mask is collected by the Focusing Lens to project an image of the mask at the image plane on the photoresist on the wafer. The finite size of the condenser lens means that some of the diffracted light is lost.

Rayleigh Criterion for Resolution

The Rayleigh's criterion for resolution of the images occurs when the center of one "Airy" pattern is at the first minimum of the other "Airy" pattern





R = f = focal length of lens
d=2a=aperture diameter

- Resolution (minimum distance between the two sources) is given by

$$W_{min} \approx k_1 \frac{\lambda}{NA}$$

where λ is the wavelength of the light, **nsinα** is called numerical aperture (NA) of the Lens, n is the index of refraction of the medium surrounding the lens,
The quantity n=1 when the lens is used air for standard stepper.

Modulation transfer function (MTF)

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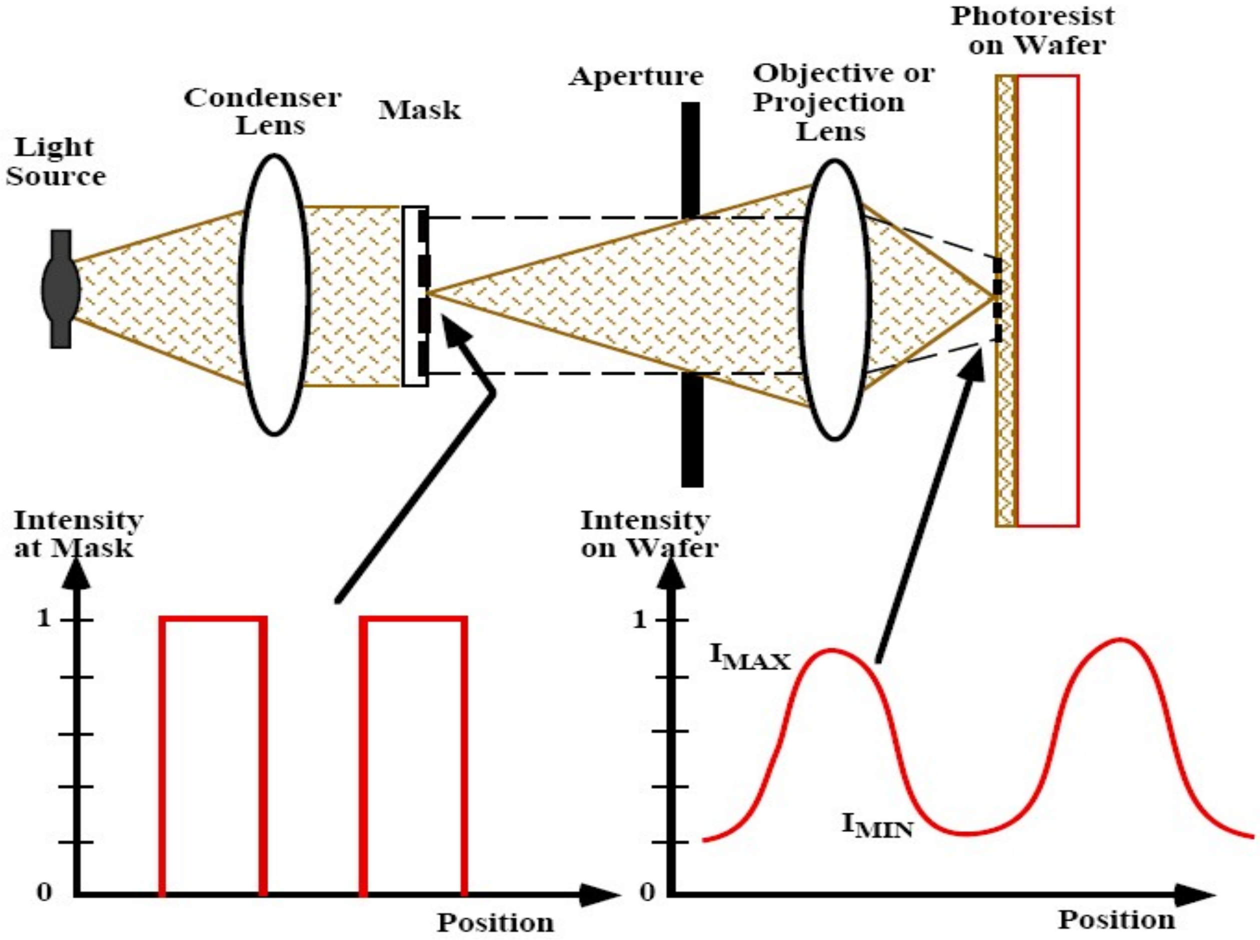
For line and spaces pattern (diffraction grating) on lithography masks, rather than a single aperture, the Fraunhofer diffraction image has minimum and maximum.



Modulation M of an image is defined as:

$$Modulation = M = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

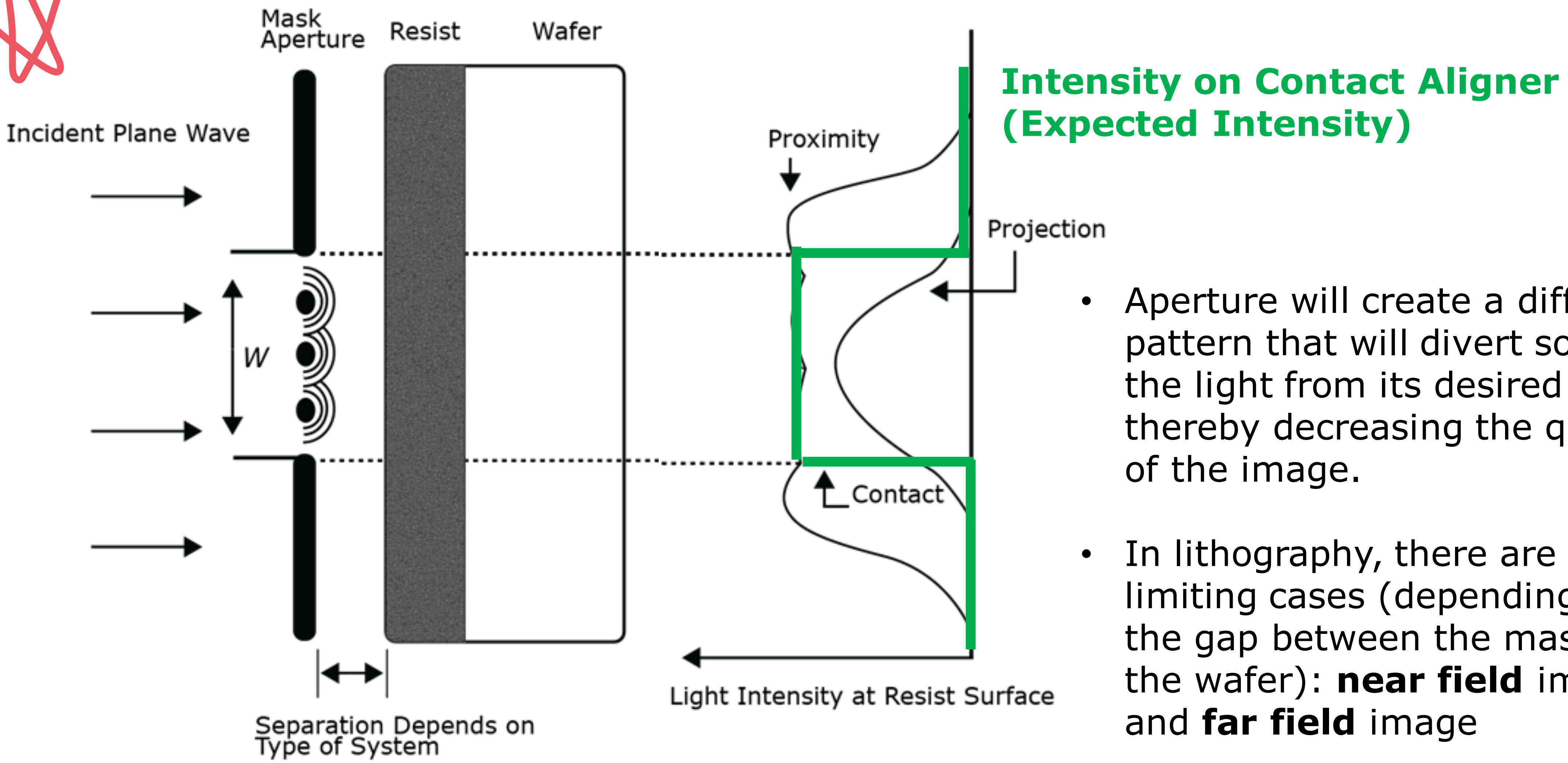
$$M_{mask} = 1 \qquad M_{image} = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

The modulation transfer function (MTF) of an image is defined as:

$$MTF = \frac{M_{image}}{M_{mask}} = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

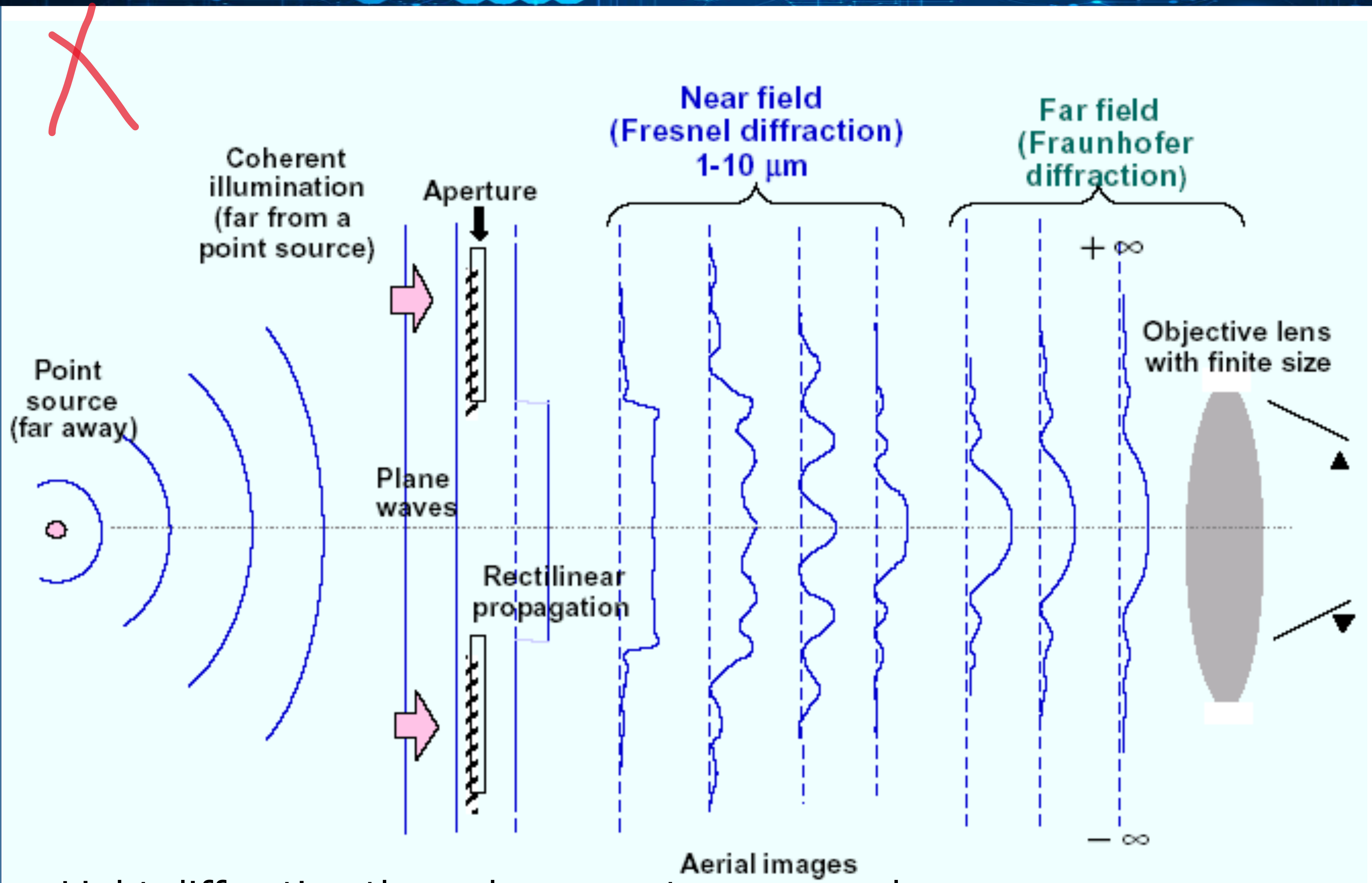
Generally, MTF needs to be > 0.5 for the resist to resolve features

Diffraction in Lithography – In Summary



- Aperture will create a diffraction pattern that will divert some of the light from its desired path, thereby decreasing the quality of the image.
- In lithography, there are two limiting cases (depending on the gap between the mask and the wafer): **near field** image and **far field** image

Diffraction in Lithography – In Summary



Light diffraction through an aperture on mask

- Aperture will create a diffraction pattern that will divert some of the light from its desired path, thereby decreasing the quality of the image
- In photolithography, there are two limiting cases (depending of the gap between the mask and the wafer): **near field** image and **far field** image

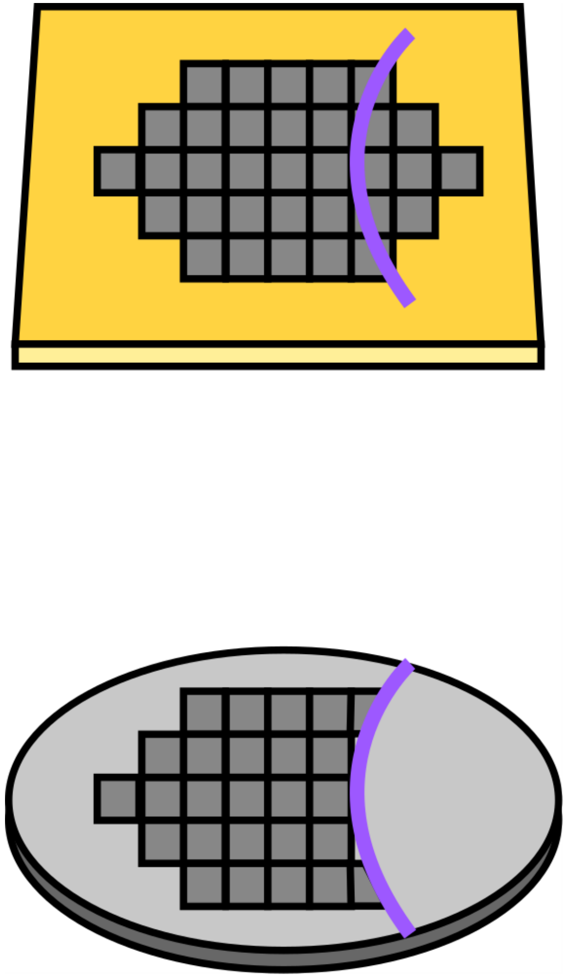
Mask and Reticle

Mask and Reticle for Lithography

Mask
Single Exposure:
1:1 Mask

Pattern for a Complete Wafer

Same Size Pattern



Wafer

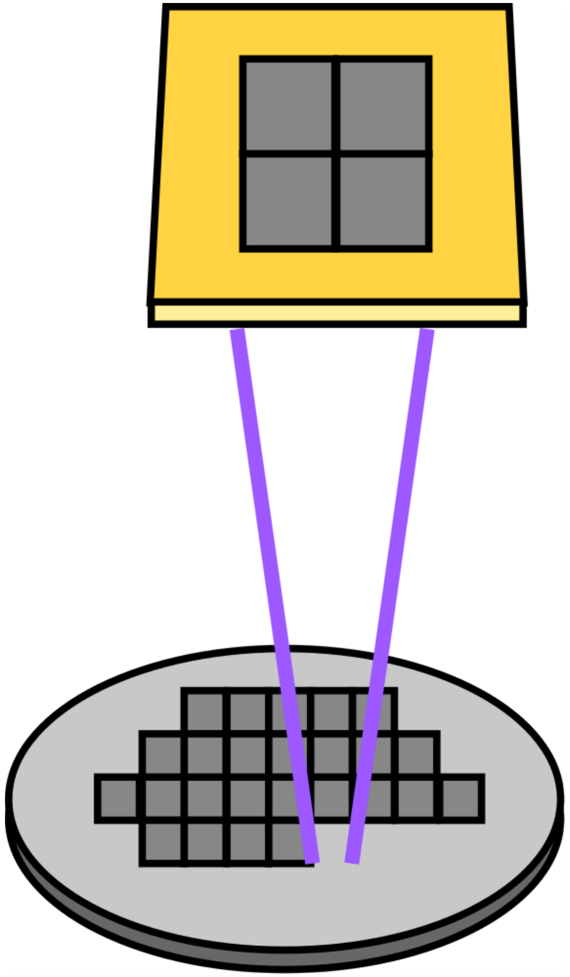
Scanner

Reticle
Multiple Exposure:
Reticle (Typically 4:1)

Pattern for Only Part of the Wafer

Reduced Size Pattern

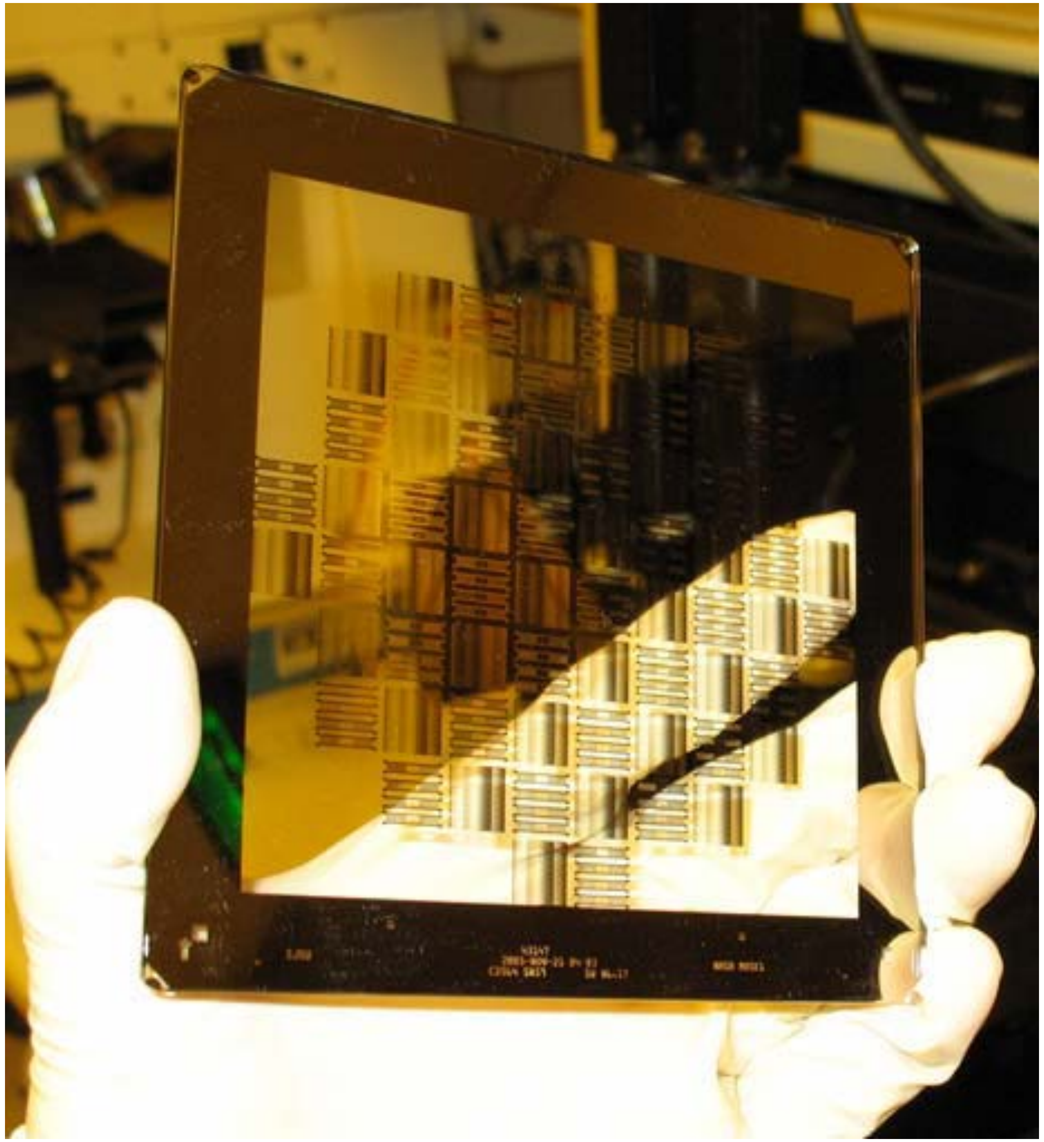
Achieve Higher resolution



Reduction Stepper

Mask and Reticle – Required Properties

- Flat and highly polished
- One surface of glass is patterned with opaque chromium
- High degree of transparency for optimal usage, better exposure, higher transmitted power to PR



Lithography Technology – Summary

Lithography technology:

- Lithography aligners can be single exposure or multiple exposures.
- The resolution of lithography determines the smallest feature size it can print, whereas the depth of focus determines the range of tolerable focus error.
- Masks are used in single exposure aligners, whereas reticles are used in multiple exposure aligners.