Lecture 17 –
Optical Lithography 2 - Optics

EECS 598-002 Winter 2006

Nanophotonics and Nano-scale Fabrication

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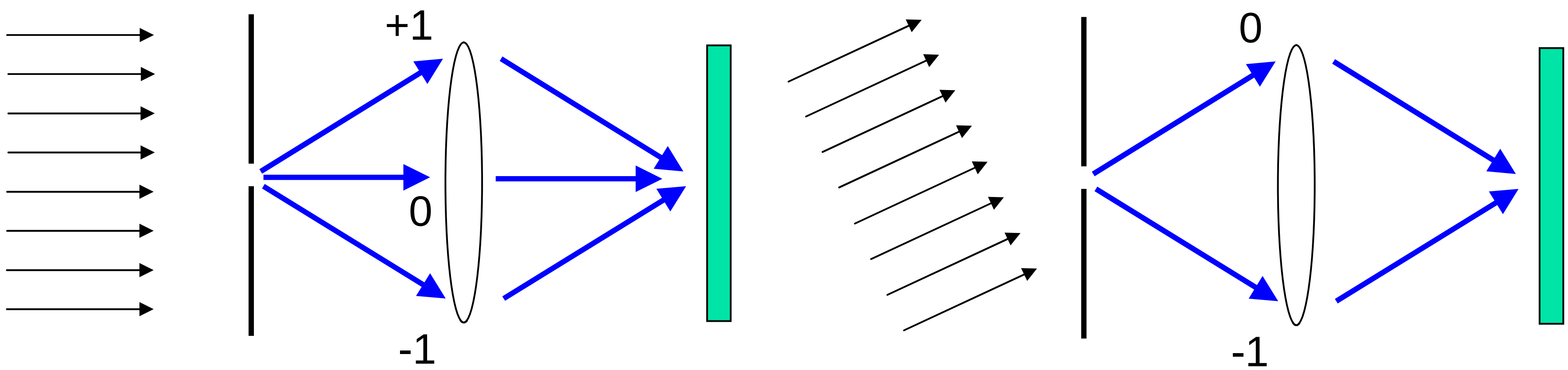
Fundamentals of lithographic optics

- Diffraction
- **Partial coherence**
- **Depth of focus**
- **Reflection and interference**
- **Polarization dependence**

Image formation

- Need to have at least the 0-th and the 1^{st} diffraction orders being collected to recover the pitch information.



Resolution limit (min pitch)

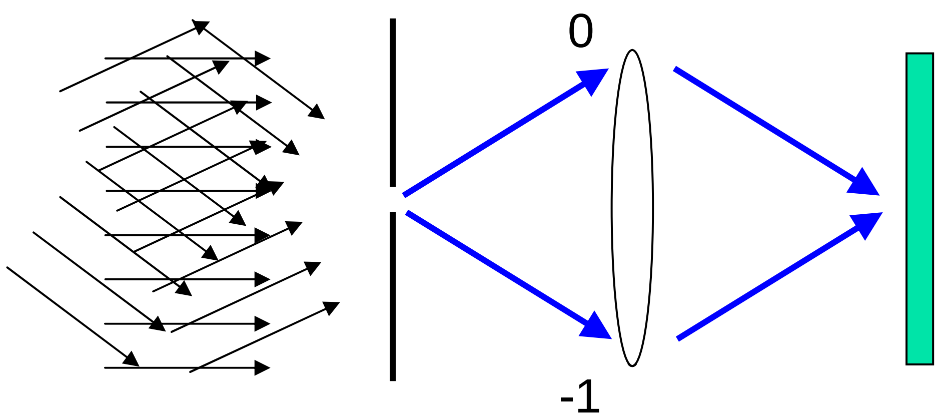
$$= 2\times\frac{\lambda}{2\mathrm{NA}}=\frac{\lambda}{\mathrm{NA}}$$

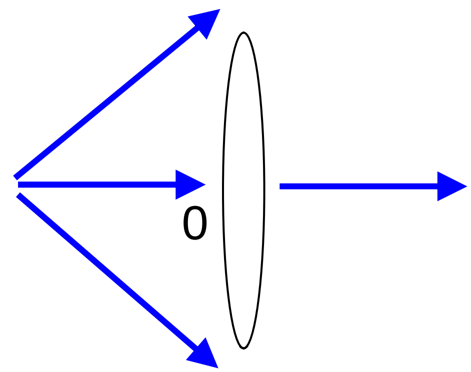
Oblique incidence can improve the minimum pitch but result in a less image contrast.

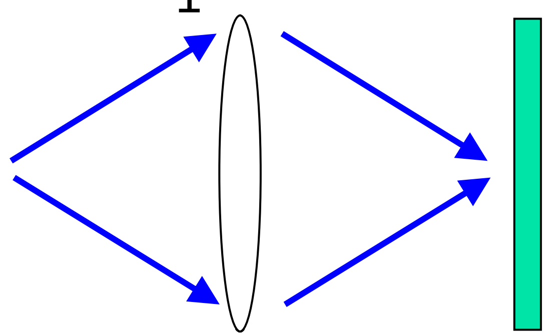
Why not just use oblique incidence?

- Because patterns on the mask are often random. Oblique illumination at a certain angle is only optimized for a specific structure (e.g. a line/space pattern at a certain pitch.)

Incoherent illumination



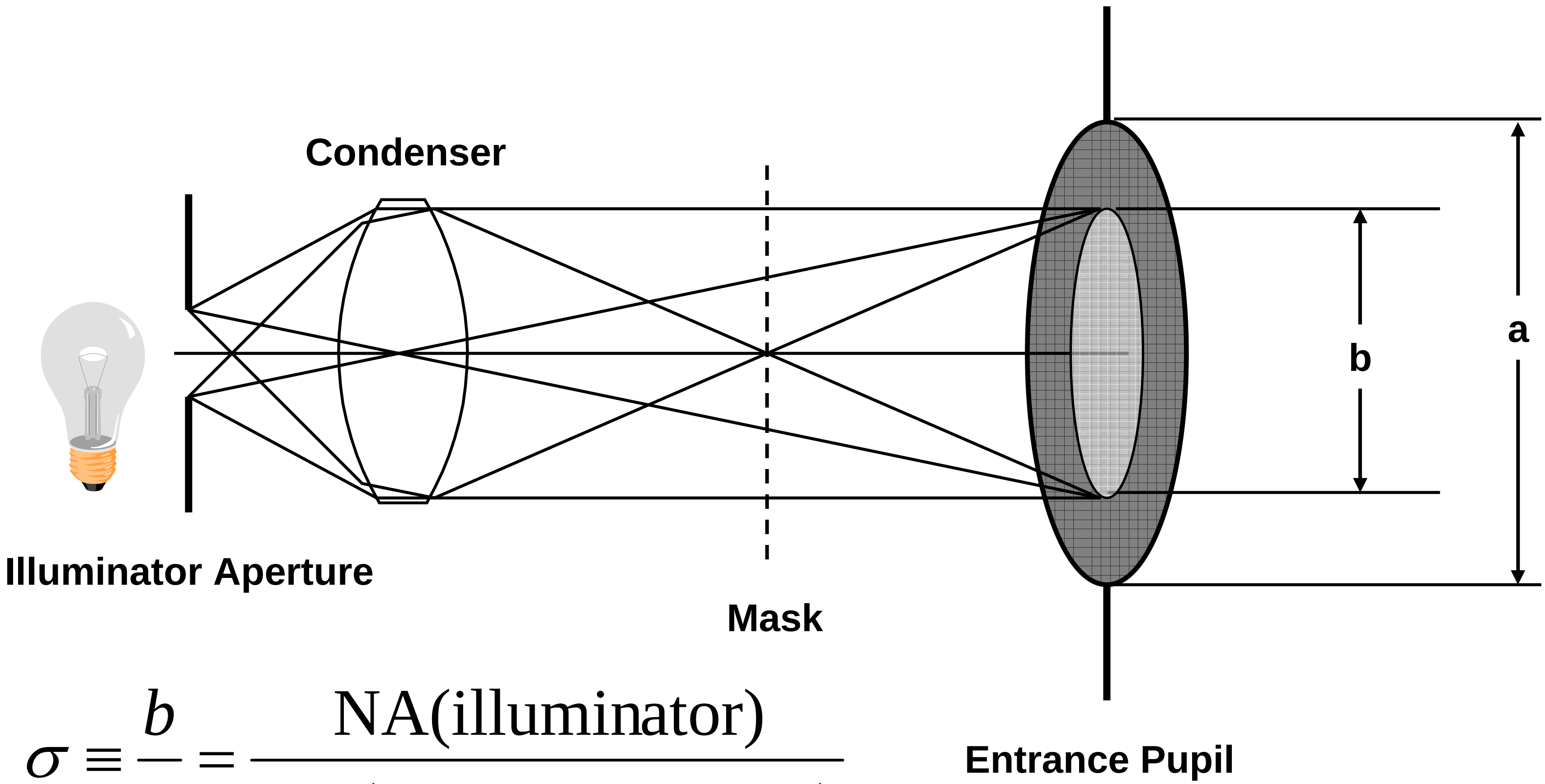




Some images may form.
Some may not.

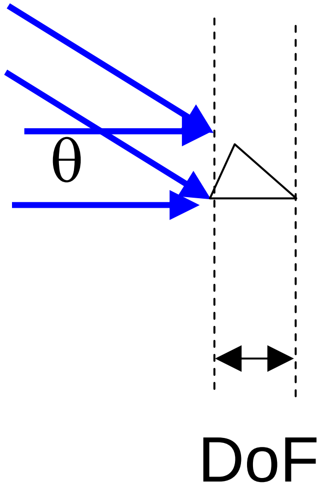
Resolution limit = $\dfrac{\lambda}{2\mathrm{NA}}$

Partial coherence



$$\sigma \equiv \frac{b}{a} = \frac{\text{NA(illuminator)}}{\text{NA(projection optics)}}$$

Depth of focus (DoF) for normal incidence



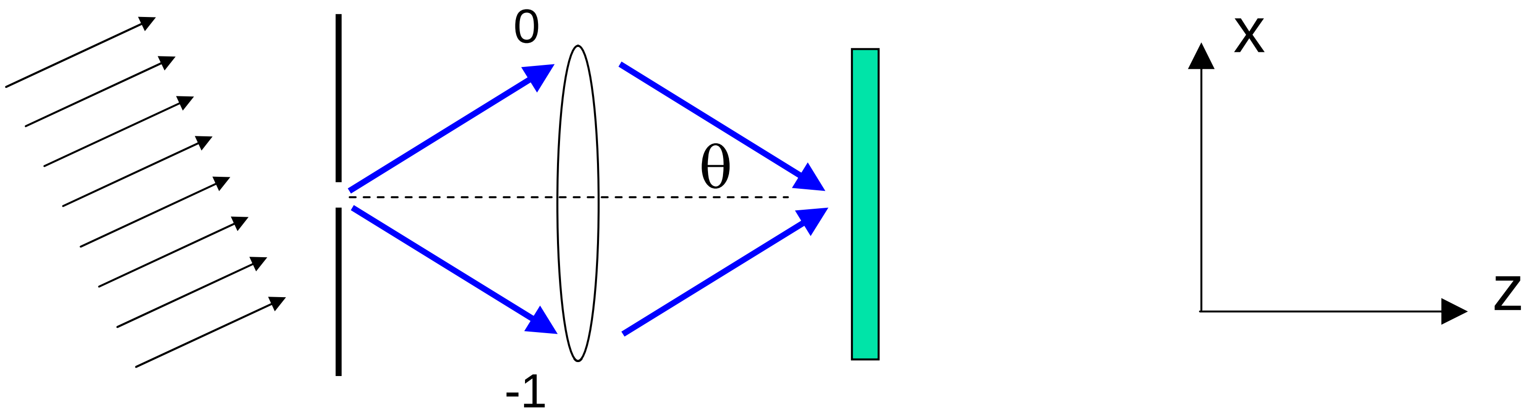
The optical path difference between the 0-th order and the order coming from the edge of the lens needs to be smaller than λ/4.

$$\frac{\lambda}{4} = \mathrm{DoF} - \mathrm{DoF}\cos\theta$$

$$\Rightarrow \frac{\lambda}{4} = \mathrm{DoF}\frac{(\mathrm{NA})^2}{2}$$

$$\Rightarrow \mathrm{DoF} = \frac{\lambda}{2(\mathrm{NA})^2}$$

DoF for oblique incidence



If equal amplitudes:

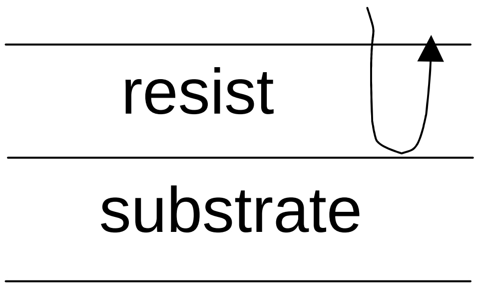
$$E_y = Ae^{i\frac{2\pi}{\lambda}(x\sin\theta + z\cos\theta)} + Ae^{i\frac{2\pi}{\lambda}(-x\sin\theta + z\cos\theta)}$$

$$= Ae^{i\frac{2\pi}{\lambda}z\cos\theta} 2\cos\left(\frac{2\pi}{\lambda}x\sin\theta\right)$$

independent of z!

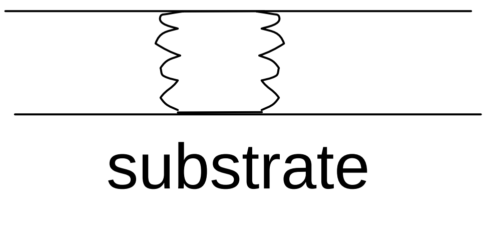
DoF = ∞

Substrate reflection



Reflection from the resist/substrate interface create interference pattern perpendicular to the interface.

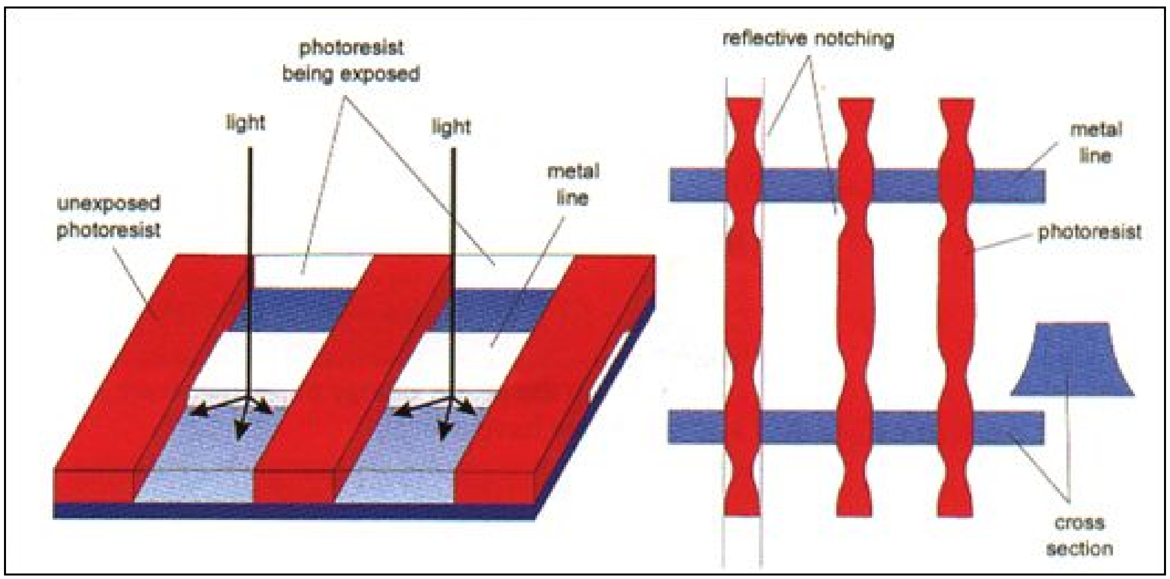
After exposure



1. Dose varies with depth.
2. Dose varies with resist thickness.
3. Focus must be maintained for at least twice the thickness of the resist thickness.

Nonplanar substrates

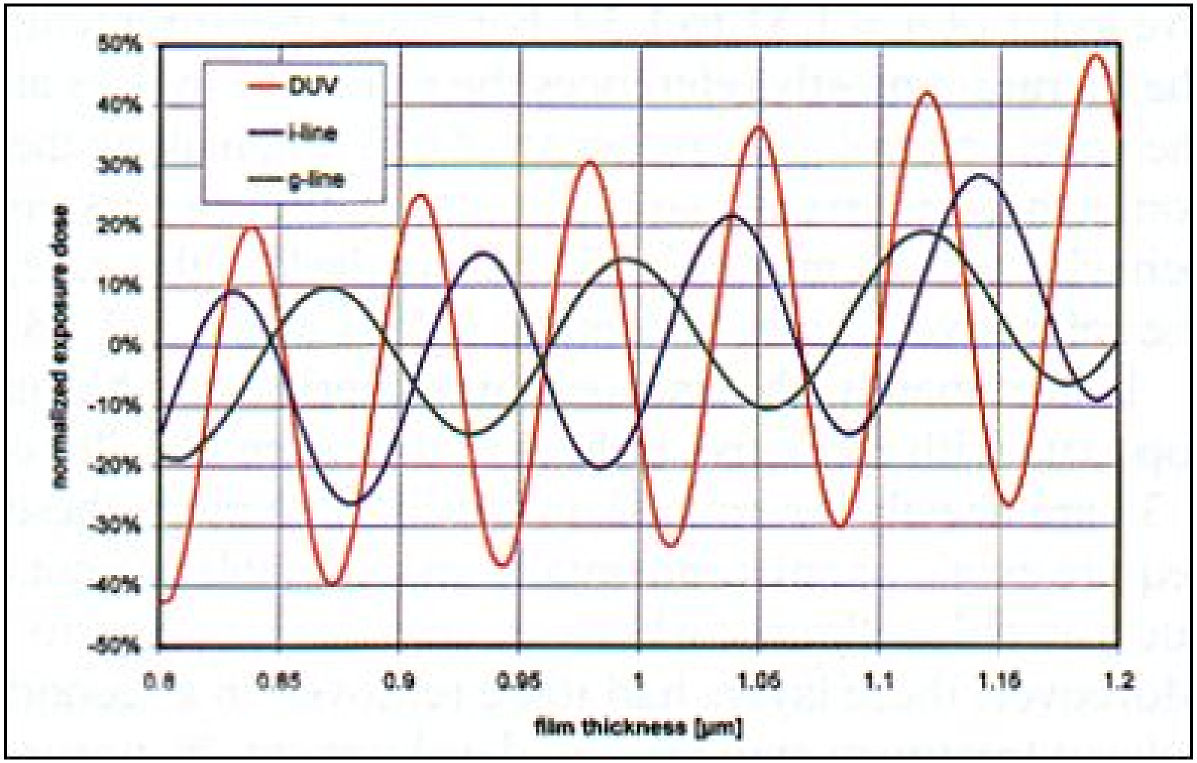
The resist is spun on a non-flat substrate.



By R. R. Dammel et al., “Antireflection coating”

Swing curve vs wavelength

- Typical substrates exhibit a larger reflectivity at a shorter wavelength.



By R. R. Dammel et al., “Antireflection coating”

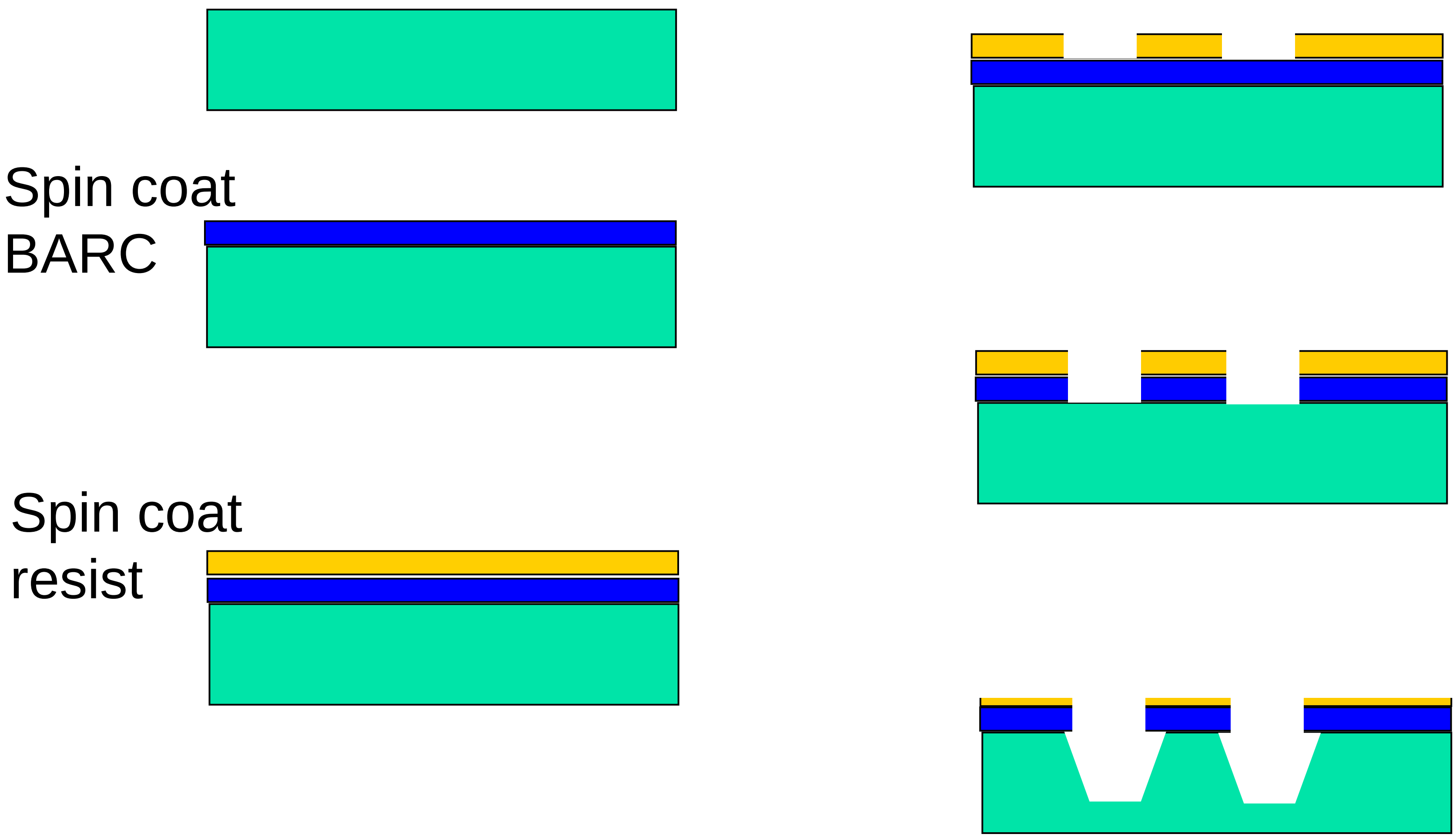
Minimize the reflectivity problems

- Very minimum we can do:
  - Post exposure bake (PEB) to induce the diffusion of the photo generated compound to smooth out the interference profile.

- Antireflection layer (AR):
  - Can be inorganic or organic materials.
  - Can be on top of or underneath the resist.
  - Typically good to absorb the light before it reaches the substrate

  - Examples:
    - Si(ON) (hardmask) – a good mask for metal etch
    - BARC (bottom AR coating) } Can be spun on just like resist itself
    - TARC (top AR coating)

BARC process (for non-developable organic BARC)



Advantages of organic BARC vs hardmask

- Can be spin-coated.
- Can planarize the surface topology
- Some BARC's can be developed at the same time as the resist. Save one etching step.
- BARC can be stripped at the same time with the resist while the hardmask can not be removed after it's been deposited. This will improve the line yield.

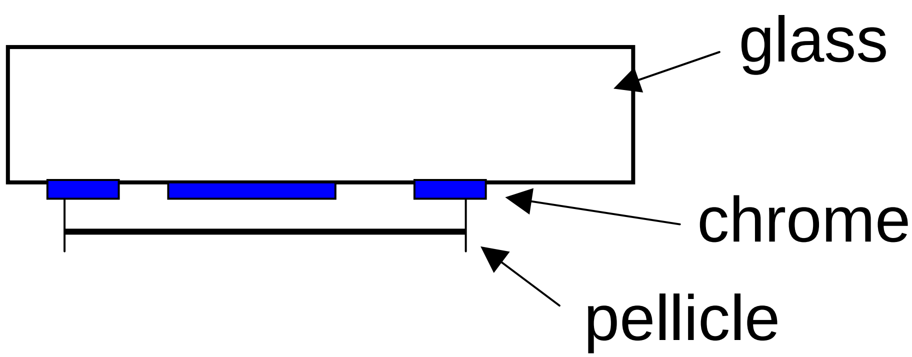
Polarization dependence

- In general, the reflectivity of TE and TM components are different from each other.

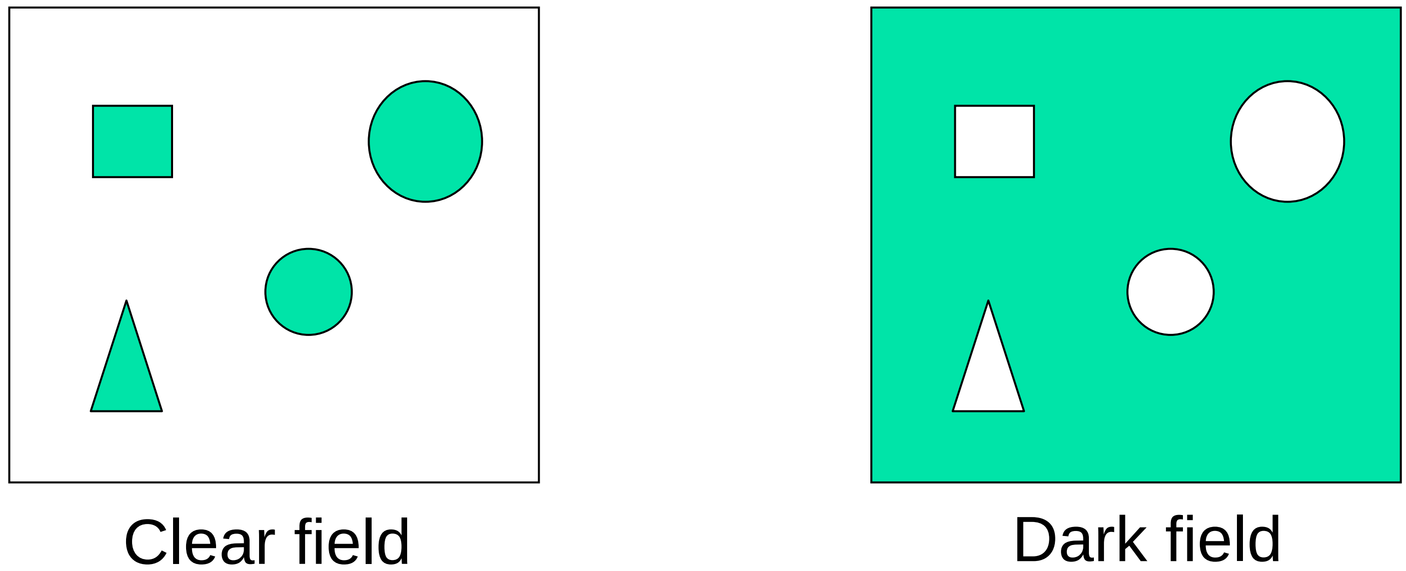
- As the feature size on the mask becomes comparable to the wavelength, a fully vectorial diffraction theory needs to be taken into account to accurately simulate the aerial image.

Mask

Mask (reticle) design

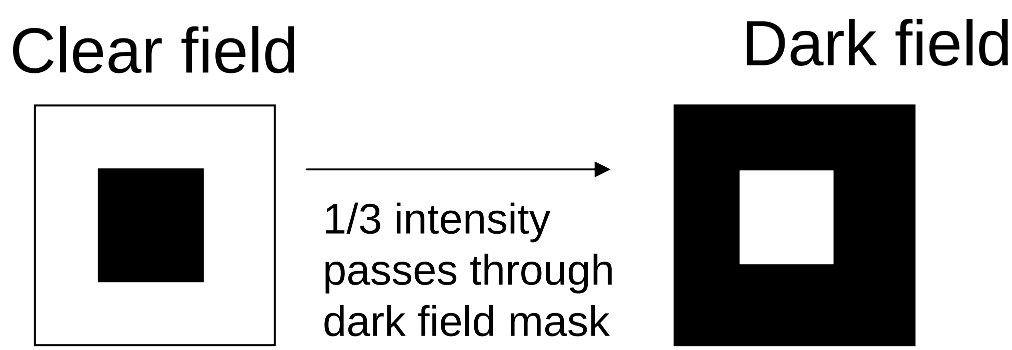


E-beam litho is typically used for mask making.



Dose sensitivity

- Comparison of clear and dark fields



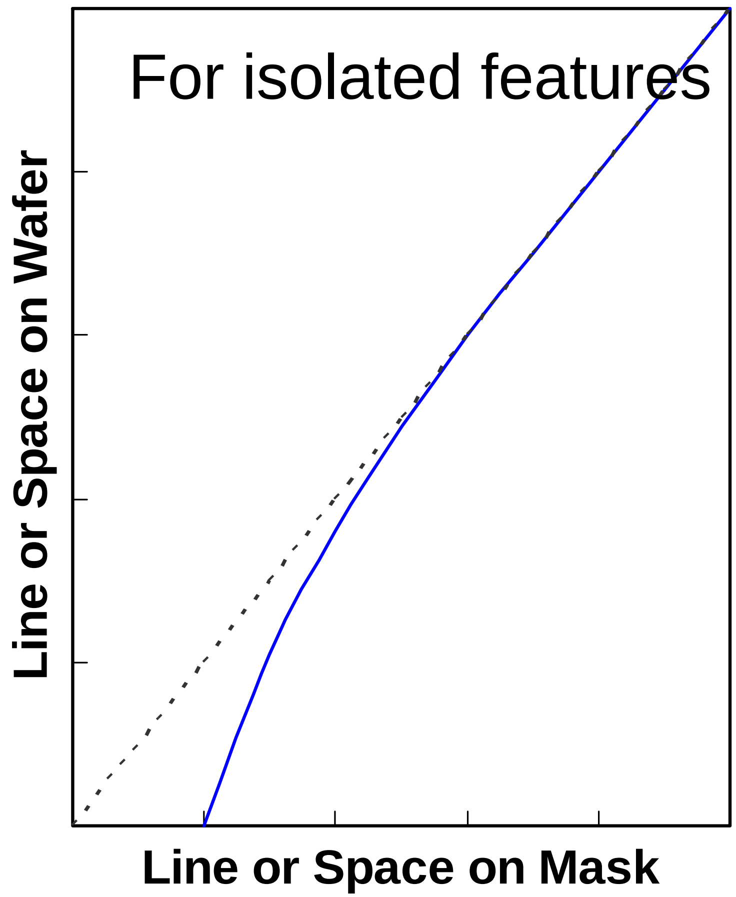
Reaching reticle 20 mJ → 24 mJ reach mask   60 mJ → 64 mJ reach mask

↓   ↓

Reaching wafer 15 mJ → 18 mJ reach wfr   15 mJ → 16 mJ reach wfr

same variation of laser intensity → { 20% dose error for clear field; 6.7% dose error for dark field }

Mask Error Enhancement Factor

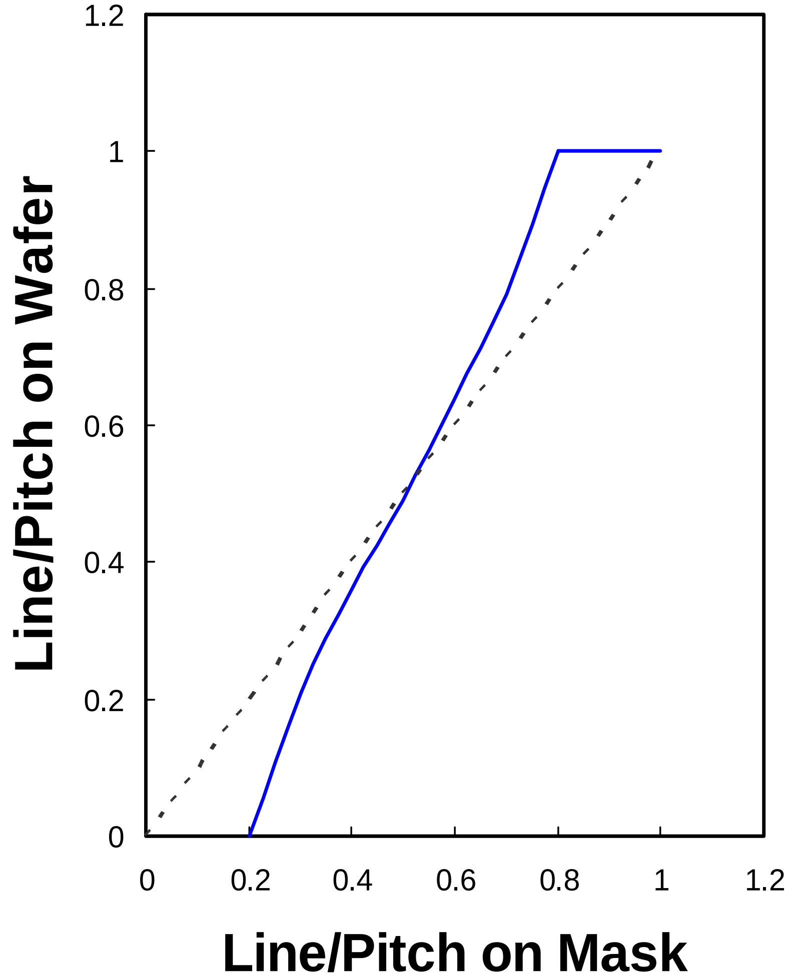


- CD error on the mask translates to the CD error on the wafer.

$$\frac{\Delta CD_{wafer}}{\Delta CD_{mask}} = \text{Reduction} \times \text{MEEF}$$

- MEEF = 1 when isolated features on the mask >> wavelength
- When isolated features on the mask ~ wavelength → Mask width determines the image intensity → determines the CD of the resist

MEEF for lines/spaces



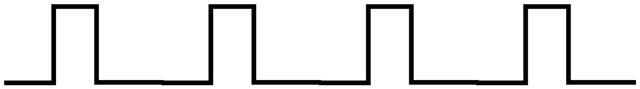
- Non-linearity is generally worse than for isolated lines or spaces.

Light source

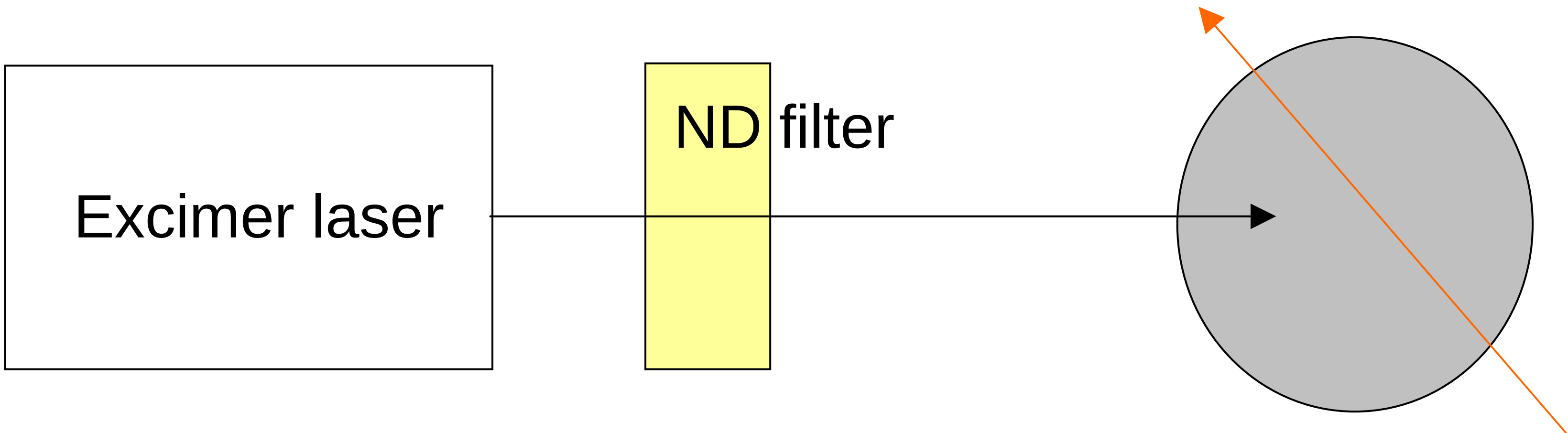
Overview

- Exposure wavelength
  - G-line (436 nm)
  - I-line (365 nm)
  - KrF (248 nm) } DUV
  - ArF (193 nm) } DUV
  - ~~F_2 (157 nm)~~
  - EUV (13.4 nm)
  - ~~X-ray (~ 1 nm)~~
- Minimum feature size:
  - ~ 500 nm
  - ~ 350 nm
  - ~ 120 nm
  - ~ 70 nm ?
  - ?
  - ?
  - ?

Excimer lasers and dose control



Excimer laser is a pulsed laser
Repetition rate ~ 1 kHz



Moving wafer
Scanning speed
< 100 mm/sec

Adjust ND filter OD setting and the scanning speed to control the exposure dose (mJ/cm^2)