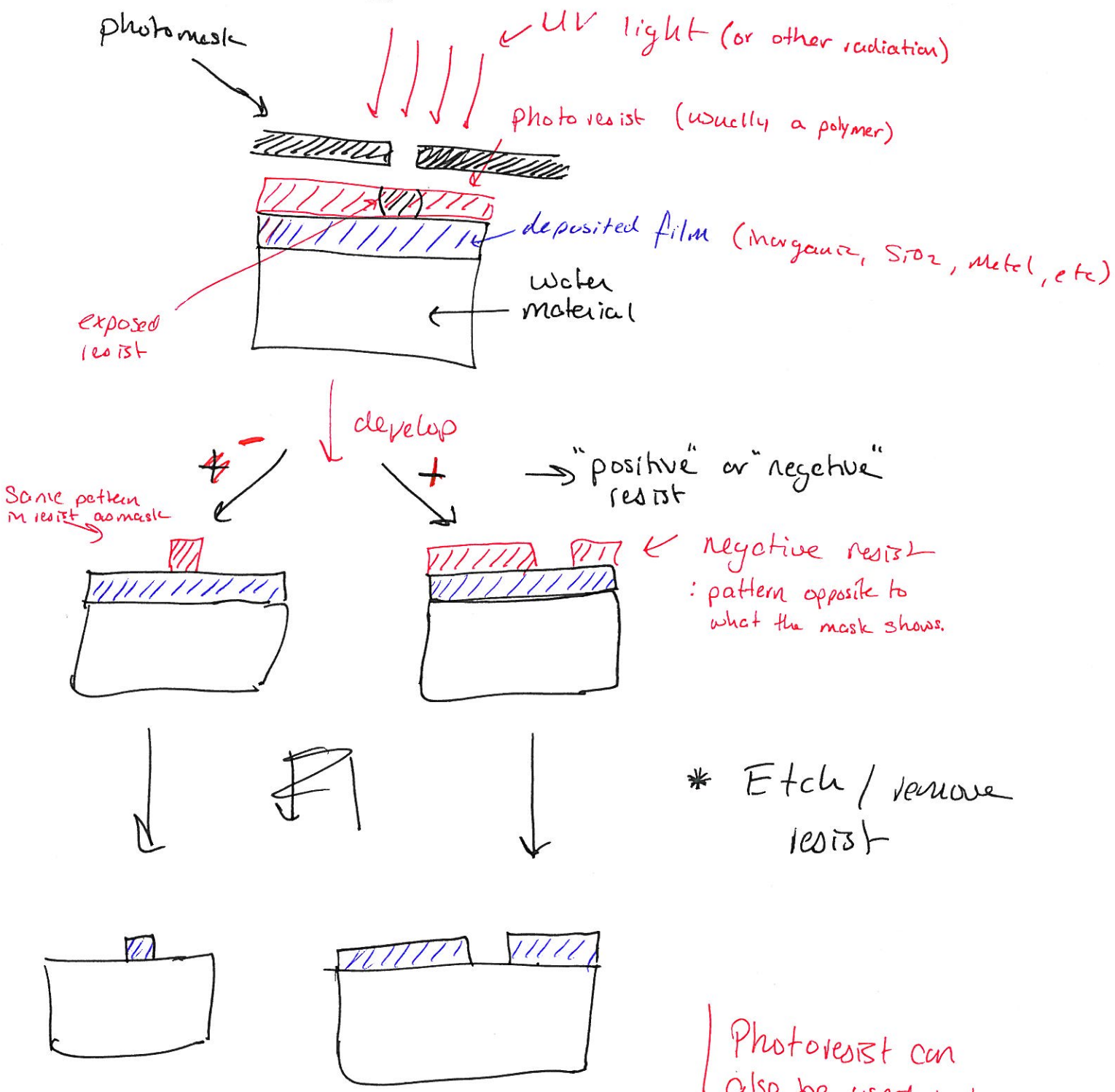
→ Mix of Sze and Wolff

9. Lithography : Writing in Stone

(from 1730- out of engraving precious stones)

Basic process :



Photoresist can also be used before a deposition step, and followed by lift-off

Clean rooms are important for Lithography

→ one dust particle on mask → cause failures in all devices made (if device size < particle size) feature

→ Clean rooms are rated by "Class"

Class 100 clean room is 100 particles / ft^3 that are > $0.5\mu m$

Class 10, 1 → equivalent nomenclature.

$\boxed{\text{Air is class} \sim 10^6}$

EX. Expose 200mm wafer for one minute to air stream under laminar flow at 30m/min how many particles land on the wafer? Class 10 clean room 10 particle / ft^3 = $\boxed{350 \text{ particles}/m^3}$

Air volume over the wafer in 1min is

$$\boxed{\left(30\frac{m}{min}\right) \times \pi\left(\frac{0.2m}{2}\right)^2 \cdot 1min = 0.94\, m^3}$$

$0.5\mu m >$ dust particles $= 0.94\, m^3 \cdot 350/m^3 = \boxed{= 330 \text{ particles}}$

if 400 chips on surface that is almost one particle per chip!

→ most don't stick! also cleaning steps etc.

Pattern transfer from $\boxed{\text{Mask}}$ to $\boxed{\text{Photoresist}}$

three performance-related parameters

1. Resolution → minimum feature size
2. Registration – measure of how accurately patterns on successive masks can be aligned
3. Throughput → number of wafers / time

Basically Two Optical Exposure Routes:

(1) Shadow printing or (2) projection printing

(1) → { mask + wafer in direct contact

→ v. typical in research setting

↓

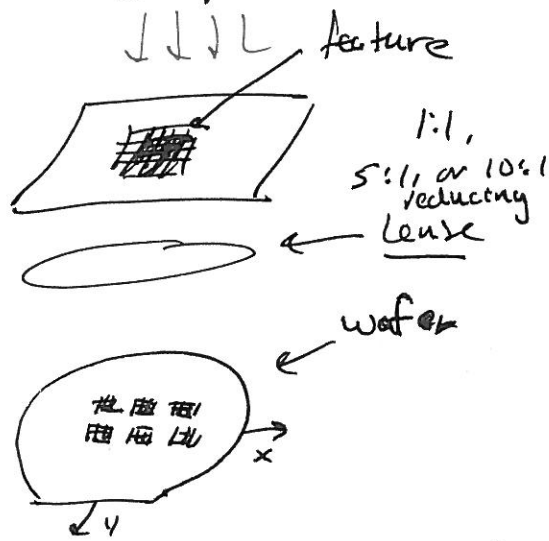
$\text{linewidth} \sim \sqrt{\lambda g} \sim 1\,\mu m$

↑

g = gap between wafer and mask

(2) → often use "stepper" system

{ mask far from sample



can write repeated high fidelity patterns → very high resolution possible

Resolution Limits → "the Diffraction Limit"

light propagates as electromagnetic waves! → obey principle of superposition

$$\mathcal{E}(\bar{r}, \nu) = E_0(\bar{r}) e^{i\phi(\bar{r}, \nu)}$$

position

frequency of the wave

Electric field intensity

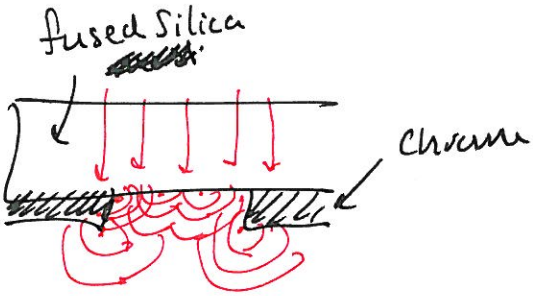
imaginary number

phase

$\bar{E}, \bar{B} \perp$ and stay in same direction as wave travels

plane wave

Huygens principle: ~ local disturbance in the optical system generates large # of spherical wavelets

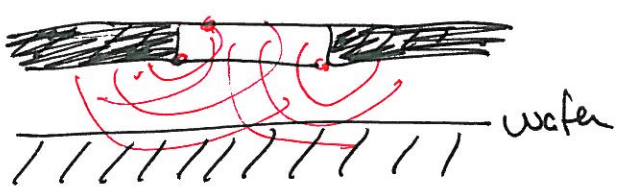


uniform distribution of Huygens Sources

→ must sum these wavelets at the wafer surface to get the electromagnetic field intensity, I. (must account for phase)

→ this gives rise to optical interference.

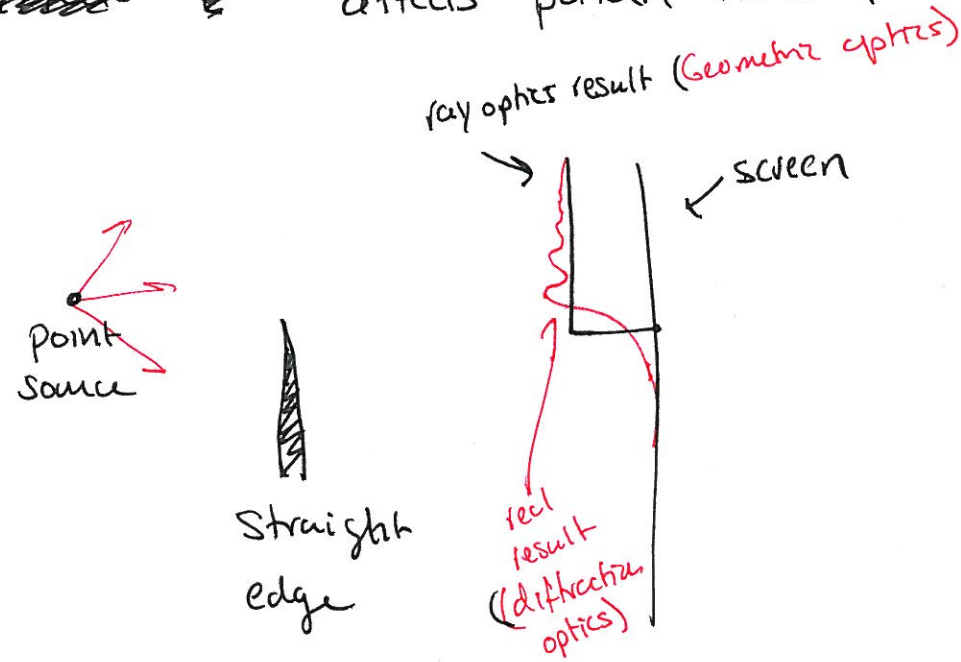
Simplest example — two interfering waves



$$I = \left[E_1 e^{i\phi_1} + E_2 e^{i\phi_2}\right] \times \left[E_1 e^{-i\phi_1} + E_2 e^{-i\phi_2}\right]$$

$$= E_1^2 + E_2^2 + \underbrace{2E_1E_2\cos(\phi_1 - \phi_2)}_{\text{interference term!}}$$

These <u>diffraction</u> and <u>interference</u> affects pattern transfer



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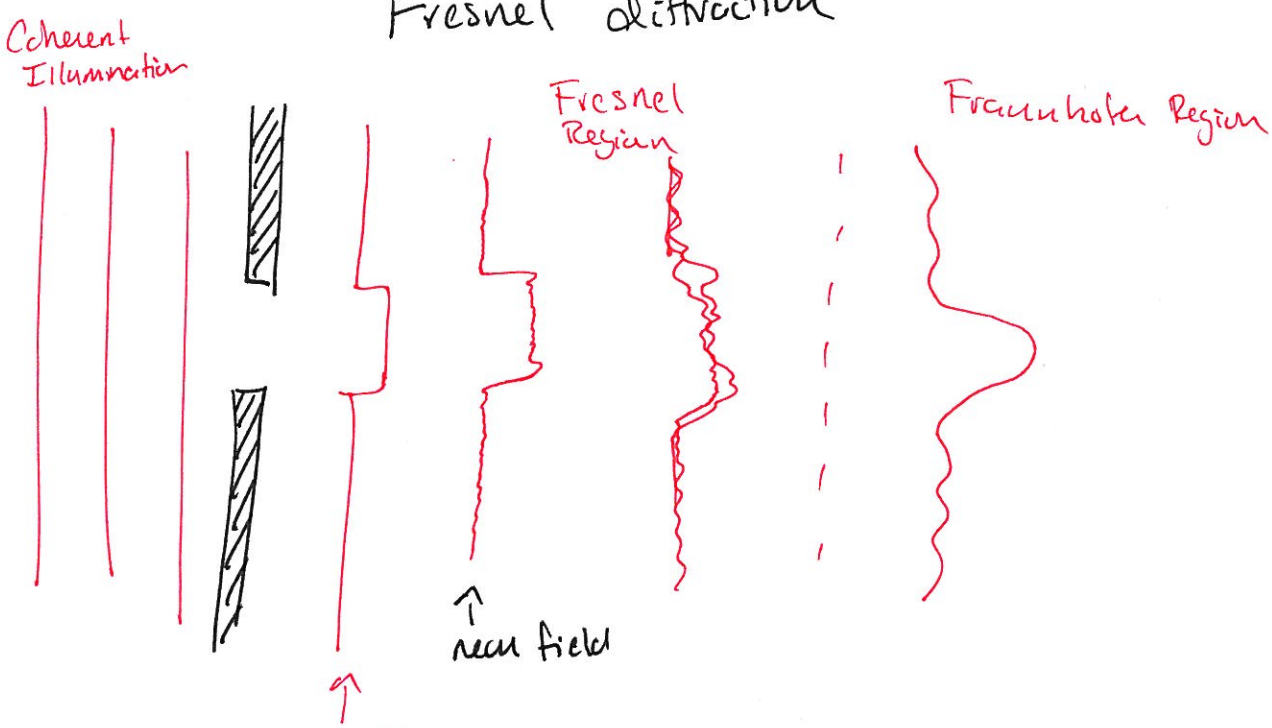
when wafer and mask are close together,

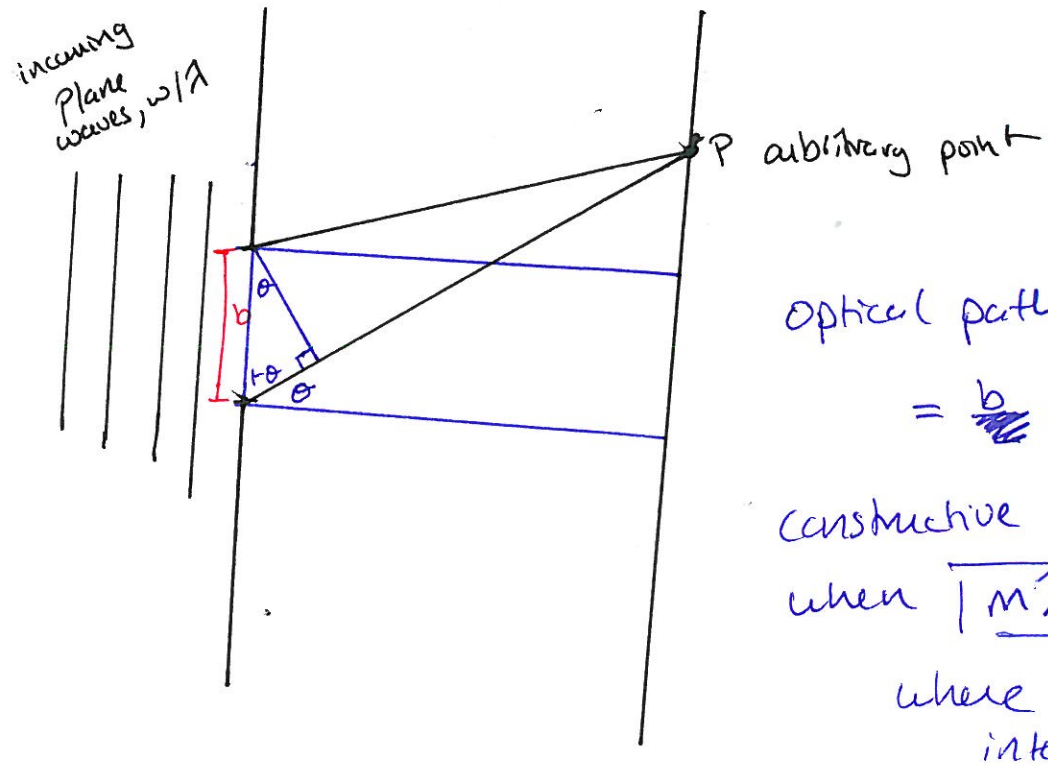
"near-field" diffraction

or

Fresnel diffraction



→ cannot ever get mask intimate contact everywhere → also P.R. is of finite thickness



optical path difference

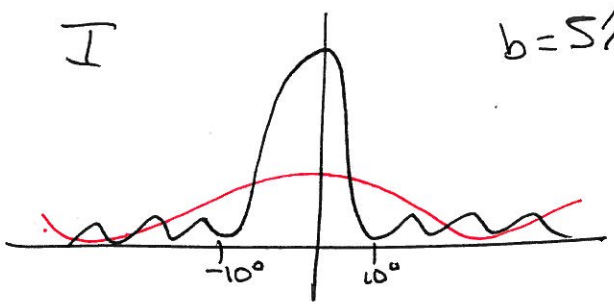
$= b \sin\theta$

constructive interference

when $\boxed{m\lambda = b\sin\theta}$

where m is an integer.

→ must add conditions for interference for all exciting wavefronts.



$b = 2\lambda$ → broad diffraction of light wave

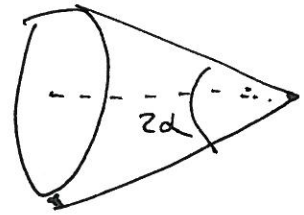
$b \to \lambda$

Define this on next page

Numerical Aperature → ability of lense to collect diffracted light to refocus it (onto water) or into image

key for re-imagine features in a projection system.

$$NA = n \sin\alpha$$

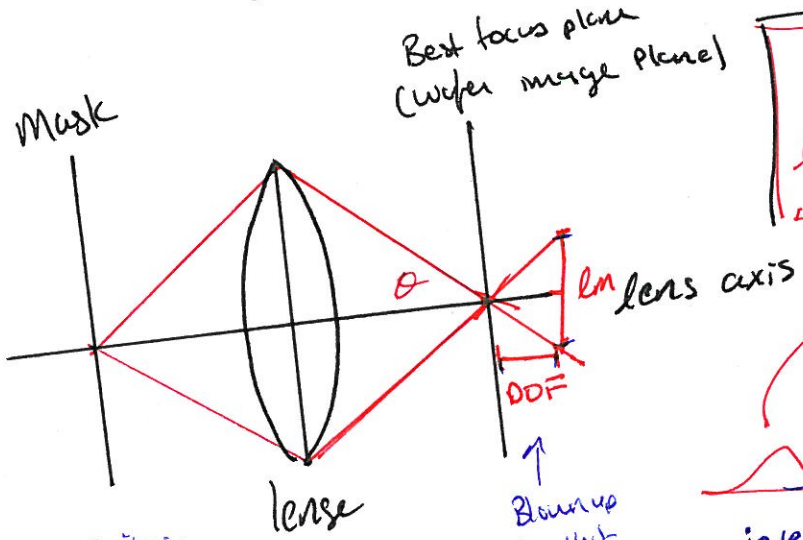


(related to f number of camera lense by $Na \approx n\,D/2f$

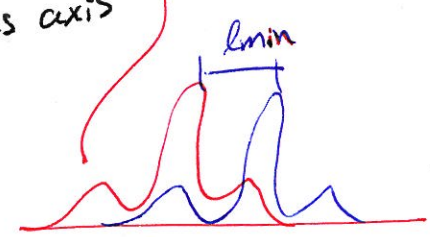
D is lense diameter

Rayleigh Criterion

→ Lense <u>must</u> at a minimum <u>collect</u> and re-image diffracted light from mask.



$$\boxed{\begin{aligned} NA &= n\sin\theta \\ l_{min} &= k_1 \frac{\lambda}{NA} \end{aligned}}$$



interference of Airy patterns

Rayleigh's Resolution Criterion:

$$l_{min} = k_1 \lambda / NA \Rightarrow$$

k_1 is a process dependent parameter that depends on P.R. etc. ($0.5 \Rightarrow 0.75$)

Depth of focus also important:

$$DOF = \frac{\pm l_m/2}{\tan\theta} \cong \frac{l_m/2}{\sin\theta}$$

write in rayleigh limit form

write in terms of NA

(true when theta is small!)

theta not small here, necessarily

wafer must be uniform to within DOF!

$$\boxed{DOF \cong k_2 \lambda / (NA)^2}$$

DOF goes as 1/square of NA!

better to increase Resolution via decreasing λ.

Increase Resolution by

note:
Excimer KrF^* excited state molecule w/ long lifetime
$\Rightarrow$ can get population inversion needed for lasing in cavity

(1) decrease λ

Mercury lamp $\Rightarrow$ 436nm g line $\rightarrow$ 365nm i-line $\rightarrow$ 248 nm (KrF excimer laser) $\rightarrow$ 193nm (ArF laser) $\rightarrow$ 157nm F_2 laser!

(7.9eV!)

x-rays?
electron beams?

E_g pure SiO_2 ~8.9eV!

(2) Increase NA $\rightarrow$ hard to make perfect UV-transparent large lenses $\rightarrow$ v. large already

$\rightarrow$ downside
$\rightarrow$ reduces D.O.F. very fast
$\rightarrow$ need ultra-smooth wafers!

(3) reduce $\underline{k}$ $\rightarrow$ Photo Resist (P.R.) properties.
optical tricks, etc (more later).

Some Estimates of Rayleigh resolution limits:

$$l_m = k\,\lambda / NA$$

$k = 0.5$

$\lambda = 193\,nm$ ArF

$NA = 0.8$

$$\boxed{= 120\,nm}$$

↳ hitting well w/o more tricks

$$DOF \cong k_2\,\lambda / (NA)^2 \cong$$ ~~[illegible]~~ 150 nm

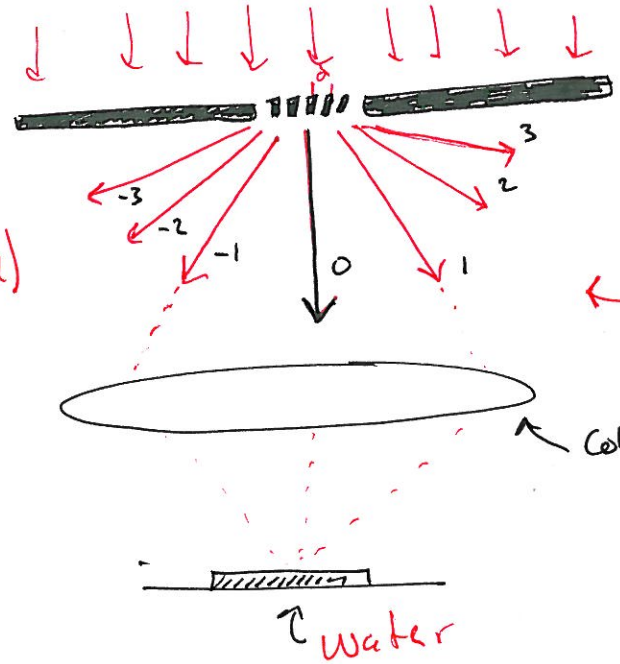
↓ need smooth wafers!

B.* Other measurements of Resolution beyond the Rayleigh Limit

Rayleigh limit → ~~[illegible]~~ for ~~[illegible]~~ telescopes / microscopes

→ no information about image quality

→ Optical Grating Resolution (Wolff 13.2.2.3)



← diffraction grating period = d

(open spaces = d/2 = b
blocked spaces = b)

← Huygens Principle leads to discrete orders of diffraction.

← Collection lense

↑ must be able to collect diffracted beams from grating

$\theta_N = \pm \sin^{-1}(N\lambda/d)$

($N = 0, \pm 1, \pm 2 \ldots$)

or

$\sin\theta_N = N\lambda/d$

$d = b/2$

→ Here lense NA is not large ~~[illegible]~~ enough to collect all diffracted beams so "information" about mask is lost!

→ to get a pattern: ~~[illegible]~~ must collect at least 0 and 1st order diffraction (to get interference) (0th order beam contains no information regarding the pattern)

Therefore minimum feature ($b = d/2$) that can be resolved

→ is $b = 0.5\lambda/\sin\theta = 0.5\lambda/NA$ $NA = \sin\theta$ (when $n=1$)

Resolution : Fourier Optics : diffraction described by the Fourier Transform

→ for mask function $\boxed{m(x)}$

out going diffracted light is:

$$\boxed{FT(m(x))}$$

(same process that describes diffraction from a crystal)

for diffraction grating

$$m(x) = \frac{A}{2} - \left(\frac{A}{\pi}\sum_{n=-\infty}^{\infty}\frac{(-1)^n}{2n-1}\cos\frac{(2n-1)\pi x}{d}\right)$$

amplitude of incoming light

constant term (0th order)

+ series of cos oscillations functions ~~of~~ increasingly higher order - w/ higher frequency oscillations.

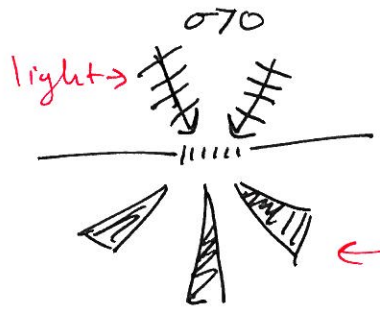
lense performs inverse Fourier Transform → i.e. takes all diffracted beams and "re-~~[illegible]~~ images" them.

but, no lense can collect all the diffracted light!

→ **Coherence in Optical systems**

→ assumed : light = plane wave, ie, arrives in phase to all portions of the mask

→ real $\boxed{\sigma = \text{partial coherence factor} > 0}$

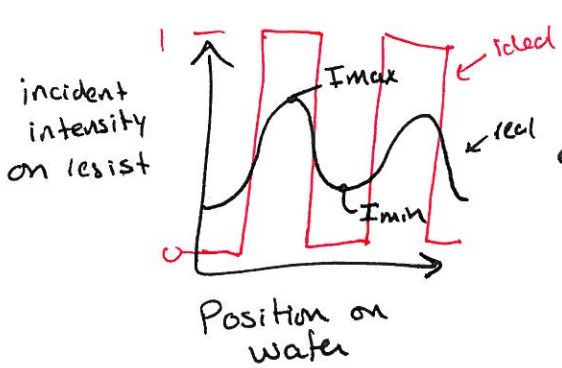


← diffracted beams have now a spread.
→ lowers resolution

Modulation Transfer Function and Image Contrast

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

($M = 1$, best



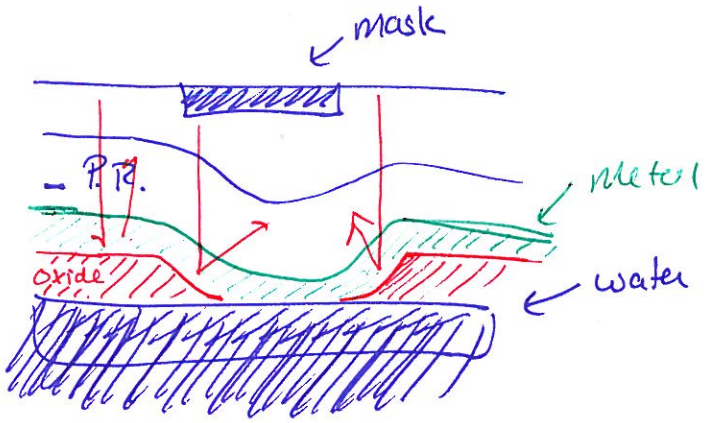
$\boxed{M \sim 0.3 \text{ here.}}$

Focus - Exposure plots → data = profile of resist (linewidth etc)

→ key experimental parameters for P.L. System · need to optimize.

Secondary Effects

Surface Reflections and standing waves:



Skip picture

→ Metal features and edges can scatter light where you don't want it.

→ Standing waves can change intensity profiles in resist

→ your process might be different if you do Lithography on Si or on SiO_2 Layer.

Masks

→ Computer Aided Design → Design in CAD

→ drives optical or electron-beam pattern generator which makes patterns in photoresist

→ pattern in P.R. transferred into fused silica / Chromium layer

— Patterns in mask represent one level of IC design.

(deposition, etching, diffusion, metallization etc.)

15-20 different mask levels are used to complete a typical IC process

→ standard size is 15×15 cm, 0.6 cm thick

↑ accomodate NA of 5:1 reduction lens system

↓ minimize errors due to bending

→ Mask Defects very critical! → cleaning and inspection critical

$$Y = \frac{\text{good chips}}{\text{total \# of chips}} \cong e^{-DA}$$

A ← area of chip

D ← avg. # of fatal defects per unit area

for N layers

$$Y = e^{-NDA}$$

→ harder to make big chips as A goes up

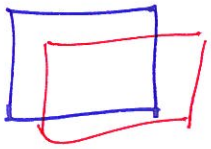
→ w/ more layers!

Registration

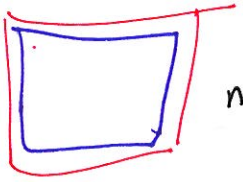
→ I.C. Design involves multiple (15-20) masking and process steps.

→ must have precise spatial relationship between the layers on the semiconductor. (e.g. doped region and metal contacts, or gate electrode and gate oxide. etc!)

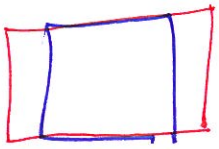
Overlay Errors



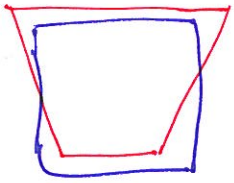
translation



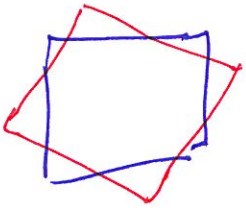
magnification



x-magnification

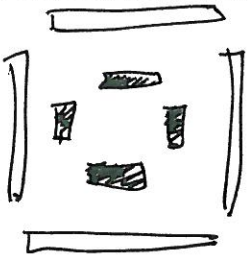


trapezoid

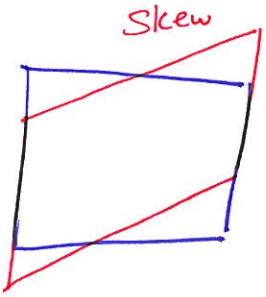


reticle rotation

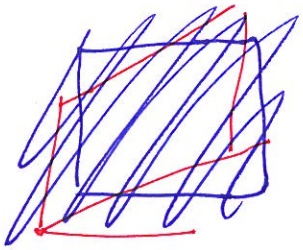
Overlay Metrology



printed in same spot on different mask levels so that misorientations can be seen.

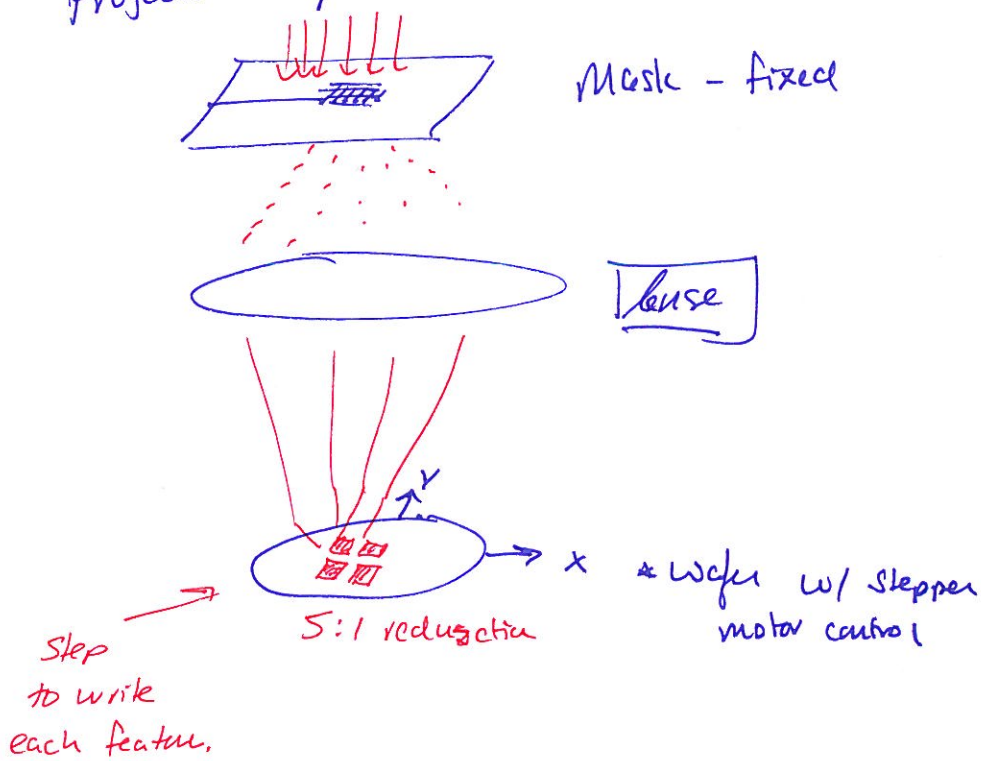


Skew



Steppers

Projection Systems → "Steppers"



→ advantages: (1) use smaller lenses / masks to get same small features

(2) can auto focus each exposure

→ D.O.F. limitations due to wafer warpage reduced.

(3) → scalable to any wafer size

Disadvantage: Slower process

* Methods for Resolution Enhancement

→ immersion lithography → NA depends on index of medium n. $n_{air} = 1$, $n_{H_2O} = 1.3$

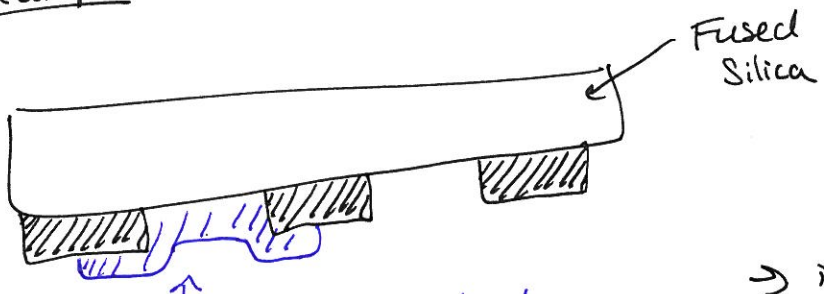
→ significant resolution gain.

Advanced Mask Concepts

→ also called reticle or photo reticle

> 150 nm features require phase-shifting mask

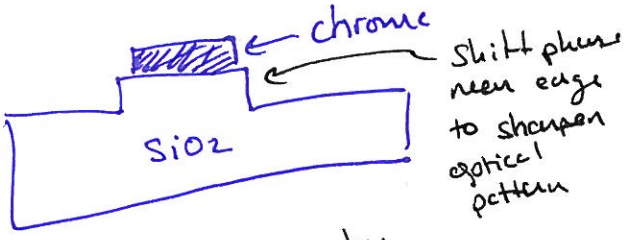
example



↑ phase shift material (thickness and n tuned to shift phase 180°)

→ in this simple example, phase shifting at one half of the period leads to destructive interference of the tails of interference and hence sharper patterns.

Self-aligned Phase Shifting



(easily made by P.L. and etching)

Optical Proximity Correction

→ compensates for image errors due to diffraction or due to process effects

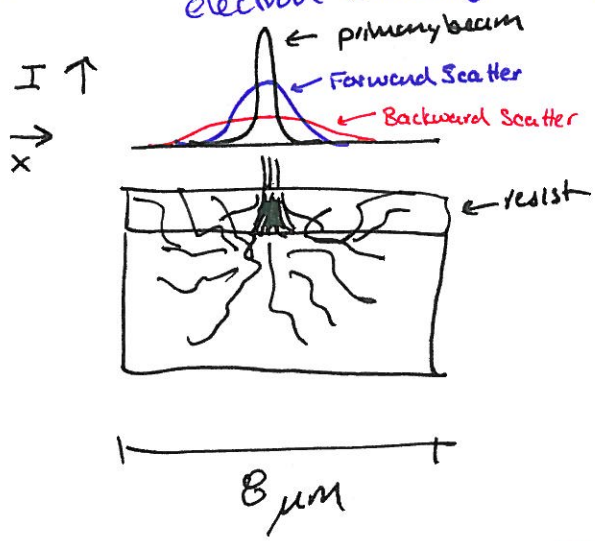
→ takes diffraction effects into account in mask design.

- uses optical materials
- distorted lines, etc.

Next-generation Lithographic Techniques

a) Electron beam lithography

- can be focused to small diameters (< 1nm)
- readily scanned w/ high resolution (wavelength of 10kV = 12.3pm)
- feature size limited by electron scattering and proximity effect



Slow, serial writing, used mainly for mask writing and academic research

b) Extreme UV lithograph (Soft xrays)

$\lambda = 10-15\,nm$ $E \sim 100\,eV$

→ Nothing is transparent to make a lense from.

→ mirror based reflective optics are used

↳ reflective reticle
↳ reflective lensesse > Si-Mo interference coatings

⇒ Starting to infiltrate industry NOW!

→ highlight CGMC research! (inorganic resists)