Photolithography (PL)

is an optical means for transferring
patterns onto a wafer

History

- From latin: “photos” =light; “lithos” =stone; “graphein” =writing
- Joseph Nicephore Niepce, 1826, first photolithography; engraving of Cardinal d’Amboise. Resolution ~1 mm.
- More than 100 years later – another try: Louis Minsk developed the synthetic photosensitive polymer, polyvinylcinnamate, the first negative photoresist.
- In 1960’s – large amounts of transistors

Engraving, 1650

Copy of the Engraving
Heliograph, 1826

chemical treatment of a light sensitive form of asphalt, called bitumen of Judea

http://www.hccs.cc.tx.us/JWoest/Research/photography.html

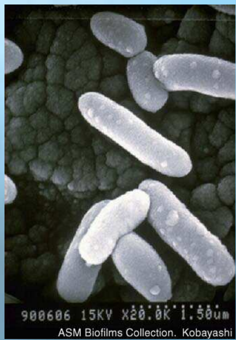
Overview of the PL Process

- Surface Preparation
- Spin Coating
- Pre-Bake (Soft Bake)
- Alignment
- Exposure
- Development
- Post-Bake (Hard Bake)
- Processing (thin-film deposition or etching, etc.)
- Photoresist Stripping
- Post Processing Cleaning (Ashing)

Surface Cleaning

- *Typical "dirt" that must be removed before applying photoresist:*

- dust, dandruff etc.
- abrasive particles from lapping 1-100 micron
- fibers from wipers
- residues from previous photolithography
- bacteria 1-20 micron (wash hands)
- also:
  - solvent residue
  - water residue (moisture)
  - photoresist or developer residue
  - oil (vacuum pumps)
  - silicone (vacuum grease)



ASM Biofilms Collection. Kobayashi

Surface Cleaning

- **Standard degrease:**
  - 2-5 min. soak in acetone with ultrasonic agitation
  - 2-5 min. soak in methanol with ultrasonic agitation
  - 2-5 min. soak in DI water with ultrasonic agitation
  - 30 sec. rinse in DI water
  - spin-rinse dry for wafers;
  - nitrogen blow-off dry for small substrates
- **Organic residues:** oxygen plasma (strip 2-3 min 200-300 W)
- **Hazards:**
  - acetone is flammable
  - methanol is toxic by skin adsorption

Photoresist Adhesion

Resist adhesion factors:

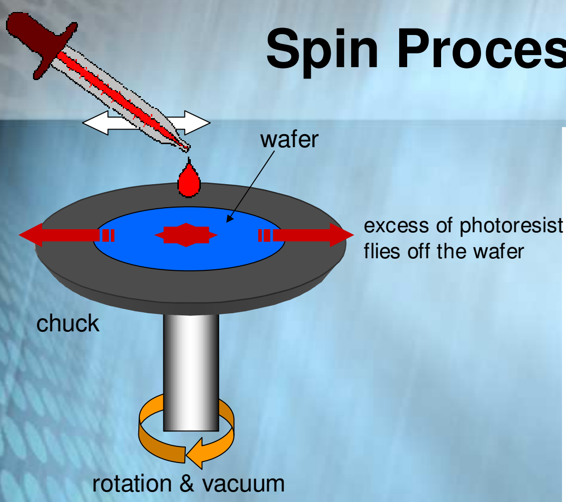
- moisture content on surface
- wetting characteristics of resist
- delay in exposure after the pre-bake
- resist chemistry
- surface smoothness
- stress from coating process
- surface contamination

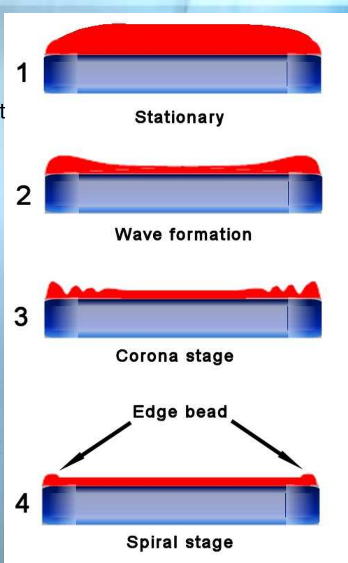
To improve adhesion photoresist *primers* are used.

Spin Coating

- Substrate or wafer is kept on a rotated chuck by vacuum and resist is applied by spin coating.
- Typically 3000-6000 rpm for 15-60 seconds.
- Resist thickness depends on:
  - resist viscosity
  - spinning velocity ($\sim 1/\sqrt{\omega}$)
- Most resists are 1-2 micron thick (SU-8 up to 200 micron)

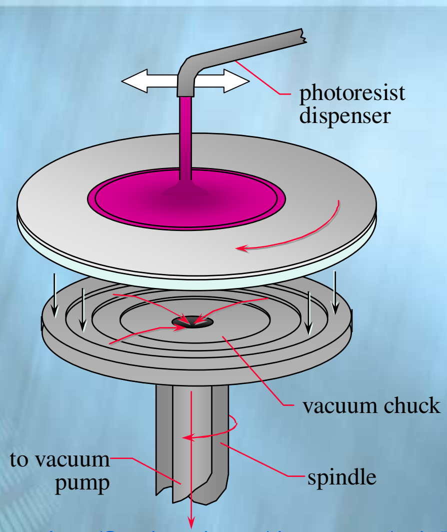
Spin Process





- **Edge Bead Height**
  - up to 20-30 times the thickness of the resist
  - non-sharp edge reduces it
  - non-circular wafers increase it

Spin Process: Large Wafers

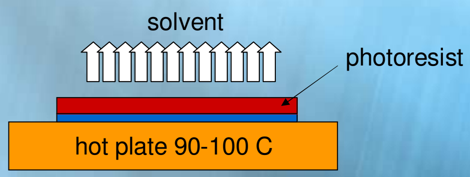


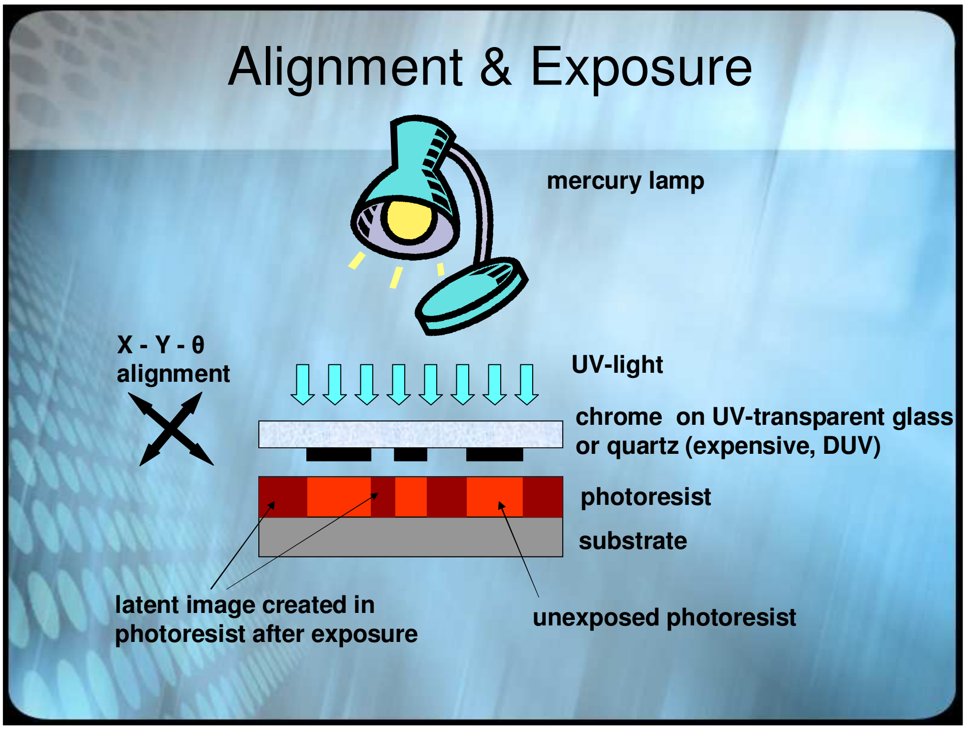
http://engineering-ed.org/Semiconductor/documents/unit 5 Intro to Litho.ppt

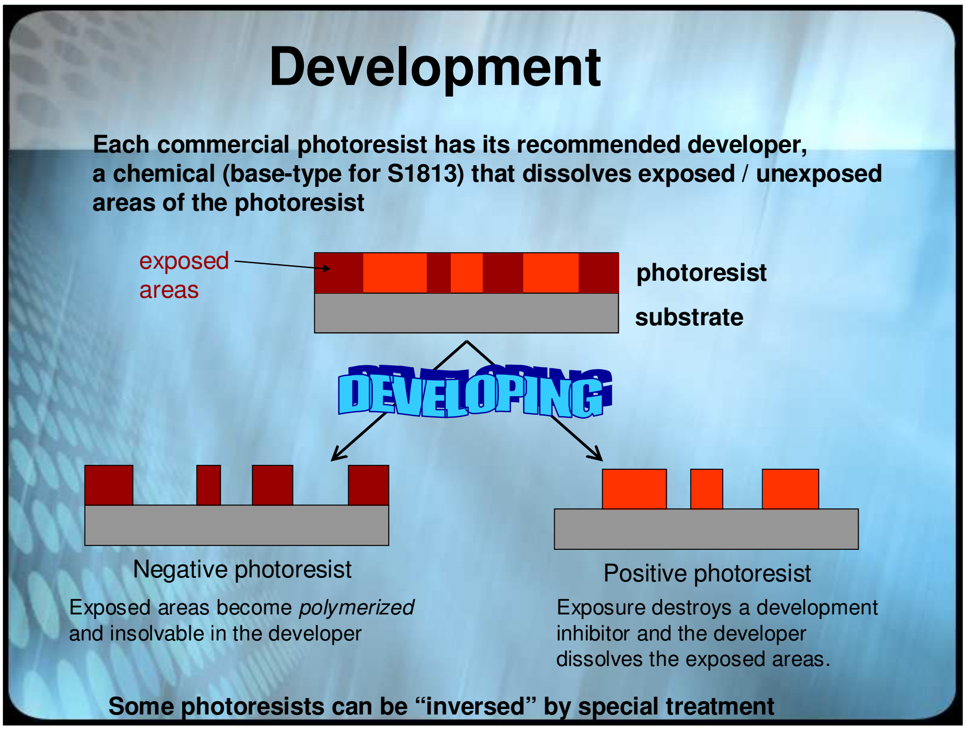
Prebake

- Used to evaporate the solvent from the resist after spin coating.
- Typically:
  - 90-100°C for 20 min. in a convection oven
  - 90-100°C for 1-2 min on a hot plate
- Hot plate is usually faster, more controllable, does not trap solvent like in oven.

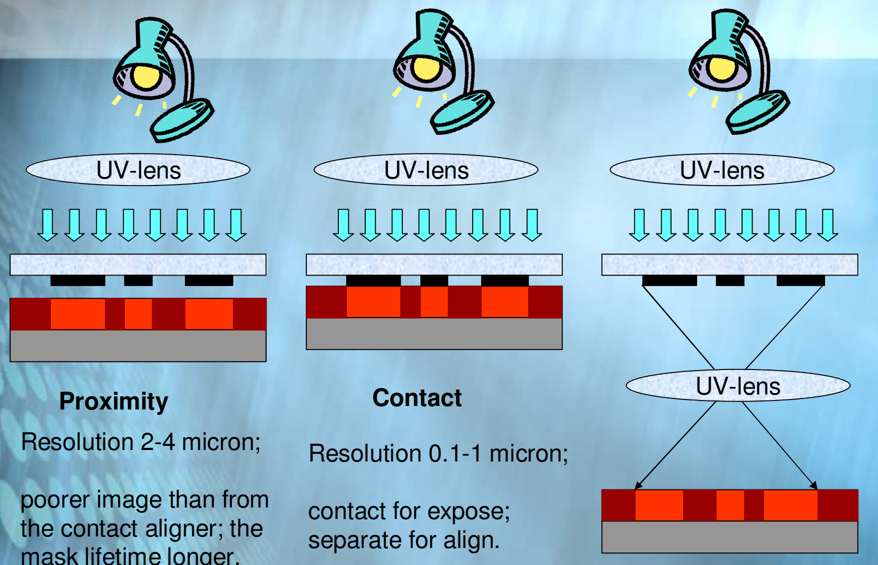
•Improves adhesion
•Improves uniformity
•Improves etch resistance
•Improves line-width control
•Optimizes light absorbance characteristics of photoresist




Alignment & Exposure
mercury lamp
X - Y - θ
alignment
UV-light
chrome on UV-transparent glass
or quartz (expensive, DUV)
photoresist
substrate
latent image created in
photoresist after exposure
unexposed photoresist


Development
Each commercial photoresist has its recommended developer,
a chemical (base-type for S1813) that dissolves exposed / unexposed
areas of the photoresist
exposed
areas
photoresist
substrate
DEVELOPING
Negative photoresist
Exposed areas become polymerized
and insolvable in the developer
Positive photoresist
Exposure destroys a development
inhibitor and the developer
dissolves the exposed areas.
Some photoresists can be "inversed" by special treatment

Alignment and Exposure Hardware



Proximity

Resolution 2-4 micron;

poorer image than from the contact aligner; the mask lifetime longer.

Low-cost processes

Contact

Resolution 0.1-1 micron;

contact for expose; separate for align.

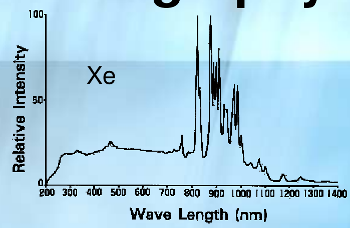
Research

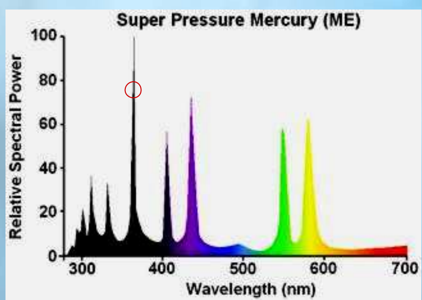
Projection

0.1-1 micron, mainstream

UV-Light in Photolithography

- High pressure Hg-vapor lamps
- Xenon lamps
- UV diodes (?!)





http://www.lamptech.co.uk/Spec%20Sheets/Osram%20HBO3500.htm

MC2's Mask Aligners

Karl-Süss contact DUV aligner

- wavelength: 248nm
- mask size: 3 inch
- intensity: 1.5mW/sqcm

Canon projection aligner

- wavelength: 365nm
- mask size: 2 inch
- intensity: 5mW/sqcm

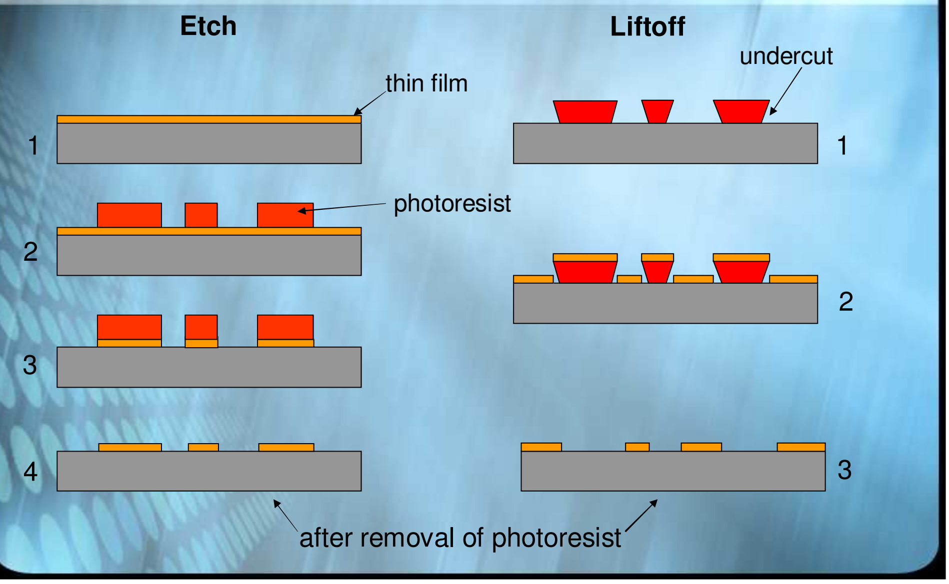
Postbake

Used to stabilize and harden the developed photoresist prior to processing steps

- Postbake is needed for acid- and Ar-ion etching
- Postbake is *not* needed for processes for liftoff processes.
- Photoresist will undergo plastic flow with sufficient time and temperature:
- Glass transition temperature is important parameter.
- Postbake removes any residuals of the coating solvent and developer.
- Postbake introduces stress into the photoresist.
- Some shrinkage of the photoresist may occur.
- Longer and hotter postbake makes subsequent resist removal more difficult.

Typically 120-140C for 10-20 min (all depend on photoresist)

Processing



Processing

Pros and cons

Etch

•The final thin-film pattern is the same as photoresist pattern

•Photoresist is not in contact with substrate

Liftoff

•The final thin-film pattern is negative with respect to photoresist pattern

•Photoresist is in contact with substrate (chemical reaction can occur)

Photoresist Removal

- Simple solvents are generally sufficient for non-postbaked photoresists:
  - Positive photoresists:
    - acetone
    - trichloroethylene (TCE)
    - phenol-based strippers
    - Shipley 1165 stripper (good for hard baked resins)
  - Negative photoresists:
    - methyl ethyl ketone (MEK), $CH_3COC_2H_5$
    - methyl isobutyl ketone (MIBK), $CH_3COC_4H_9$
- Oxygen-plasma stripping is very effective in general for removing organic polymer residues
- Some photoresists (SU-8) are *very* hard to remove: can be as parts of a final device

Process Recipes

A collective wisdom

S-1813 example process (B. Nilsson, MC2)

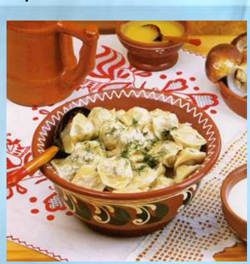
- **Clean substrate**
- **Spin spacer layer LOL-2000 @ 3000 rpm for 200nm thickness**
- **Bake 140 C on hot plate for 5 minutes**
- **Spin resist layer S-1813 @ 4000 rpm for 1.3 um thickness**
- **Bake 110 C on hot plate for 2 minutes**
- **Expose through pattern mask,**
  - **45s @ 2.45 mW/cm2 (110 mJ/cm^2 nominally)**
  - **15 s @ 10 mW/cm2 (150 mJ/cm^2 nominally)**
- **Develop in MF319 for 30 sec, CAREFUL agitation**
- **Rinse in DI water**
- **Blow dry CAREFULLY.**
- **Ash at 50W 250mTorr Oxygen for 30 s**
- **Deposit thin film**
- **Lift off in acetone or NMP (Remover 1165)**
  - **If you do liftoff in acetone, do a final clean step in photoresist developer , NMP stripper, or oxygen plasma afterwards. LOL-2000 does not dissolve well in acetone.**
- **Rinse in IPA and blow dry.**

very similar to

Cooking Recipes

see, for instance, http://www.RusCuisine.com/

Pelmeni recipe -



- **Ingredients**
  1 1/2 cups flour
  2 eggs
  1/2 cup water
  1/2 tsp. salt
  1/2 lb. ground beef
  1/2 lb. ground pork
  2 medium onions, finely chopped
  1 tsp. salt
  1/2 tsp. black pepper
  garlic to taste

  Method
  To make the dough, combine the flour, eggs, water and 1/2 tsp. salt. Knead mixture. Let rest for 30 minutes. Mix the ground beef, ground pork, onions, 1 tsp. salt, pepper and garlic together. Cut the dough into three equally sized pieces and roll each one into a cylinder the diameter of a finger. Cut each cylinder into pieces the size of a walnut, then roll each piece into a very thin flat cake with a diameter of about 2 inches. Put some of the ground meat mixture in the center of each flat cake (quite a lot, but not so much that you can't then seal up the dough). Then fold the dough in half and join up the edges to seal them. Pinch the corners together: you should now have a ravioli-shaped "flying saucer."

  Boil the pelmeni in salted water for seven minutes, or until they float to the surface. Serve them in soup plates with sour cream or in broth.

Photolithography Resolution

- Resolution is limited by the diffraction of the light used for exposure

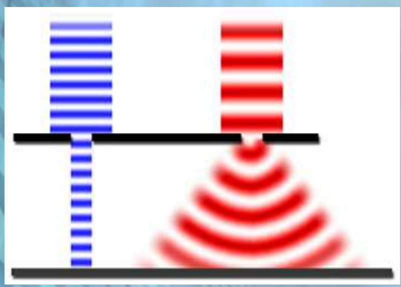
- To reduce diffraction and achieve the highest resolution, the exposure system can use:
  - shorter wavelengths of light (ArF excimer laser at 193 nm, Hg-vapors lamp, Xe-lamp)
  - high numerical aperture lenses to project the light

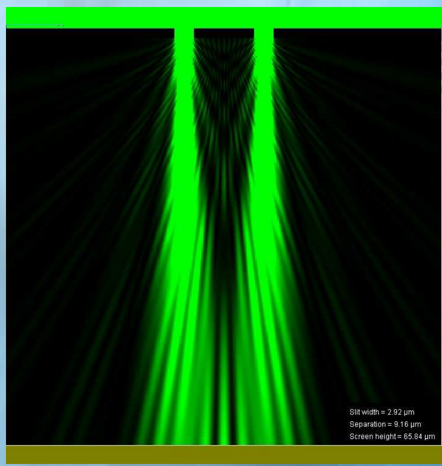
Photolithography Resolution

http://www.falstad.com/mathphysics.html

Diffraction limits the resolution

one wants one gets





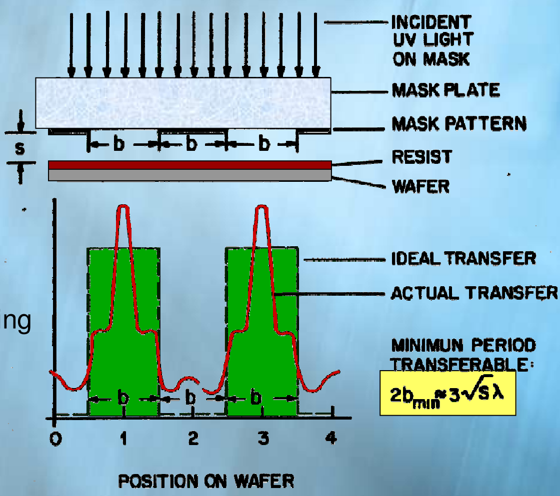
http://www.barrettresearch.ca/teaching/nanotechnology/nano04.htm

proximity- and contact-

Photolithography Resolution

$$2b_{\min} = 3\sqrt{\lambda\left(s+\frac{t}{2}\right)}$$

b: minimum feature size
λ: wavelength
s: mask-photoresist spacing
t: photoresist thickness



adopted from C.G. Willson, Introduction to Microlithography projection

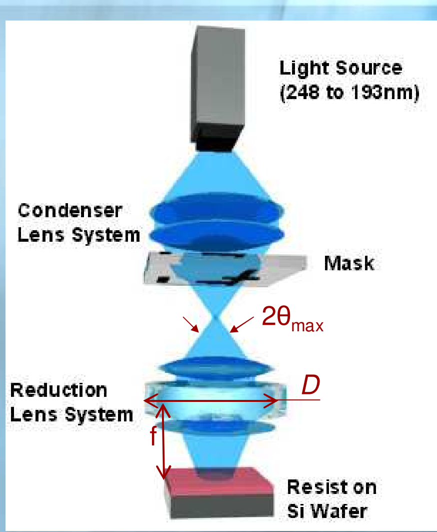
Photolithography Resolution

b: minimum feature size
λ: wavelength
M: magnification
NA: numerical aperture
k_1: parameter 0.5-1

$$2b_{\min} = \frac{k_1 \lambda}{NA}$$

$$NA = \frac{D}{(1+M)f}$$

Also, the resolution for coherent light is two times better than for incoherent one.



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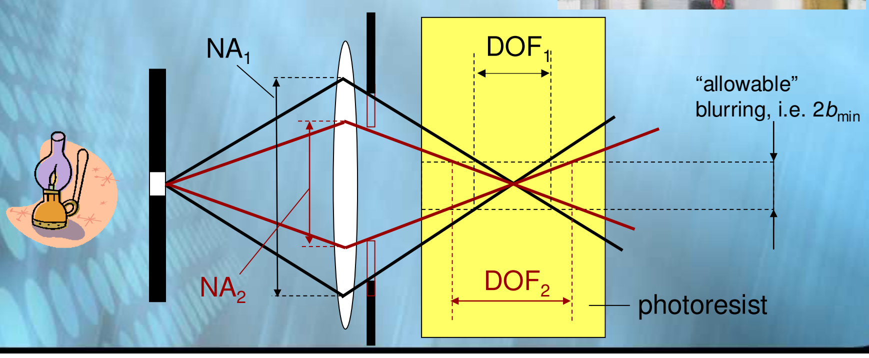
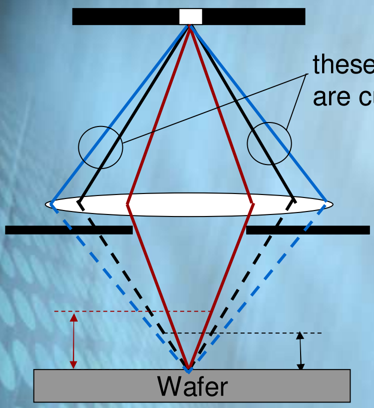
Depth of Focus (DOF)

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

$$DOF = \pm \frac{k_2 (2b_{\min})^2}{k_1^2 \lambda}$$



Balance Between DOF and $2b_{min}$



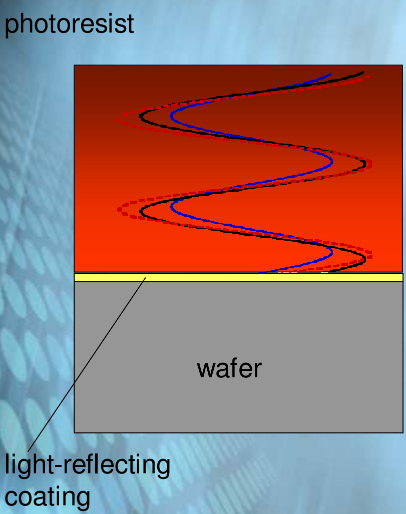
these diffraction rays
are cut out by the aperture

The image is constructed
from all the diffracted light

less “information” is delivered
through smaller apertures →
→ less resolution

A balance between DOF and $2b_{min}$ should be sought

Standing Waves



When a resist is exposed to a monochromatic light, *standing waves* are formed in the resist as a consequence of coherent interference between incoming and reflected from the substrate waves.

It results in a periodic intensity distribution across the resist thickness. Is function of the resist thickness.

- Thinner photoresist
- Broadband illumination

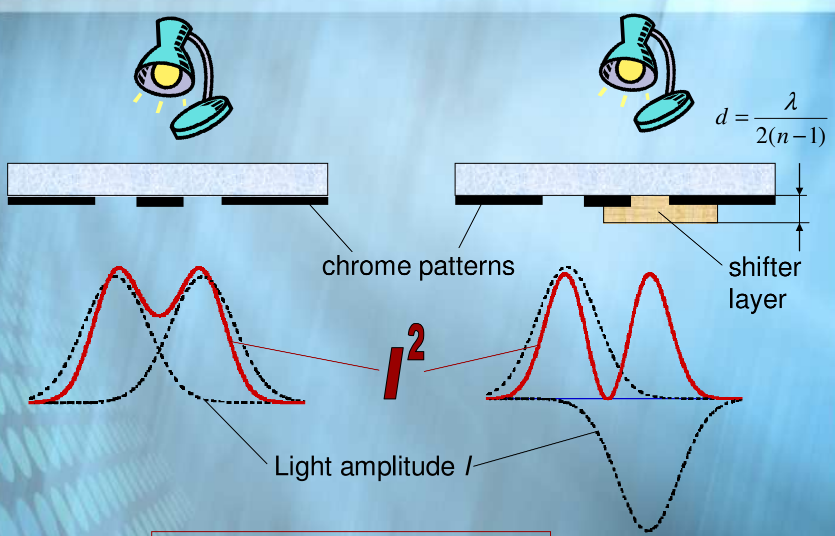
How to Make It Better

Obvious ways:
- Thinner photoresist & larger NA
- Shorter wavelength (DUV, and even X-rays)

Smart ways:
- Phase-shifting masks
- Diffraction-compensating pattern design
- Immersion photolithography

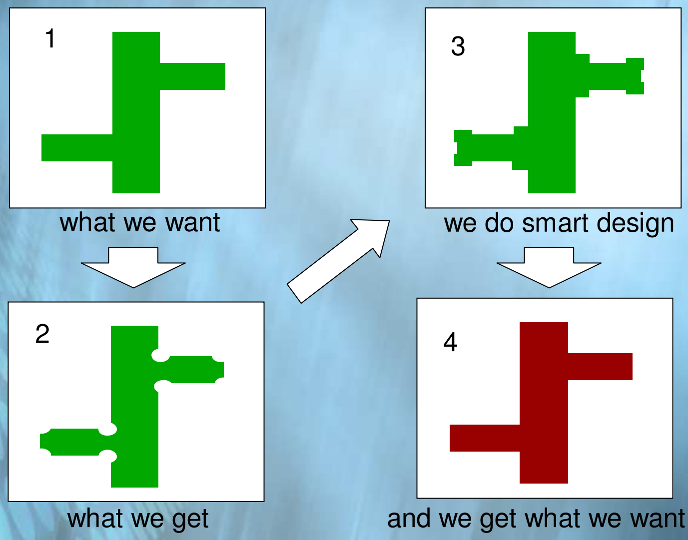
Phase-Shifting masks

from 1980 by Nikon and IBM



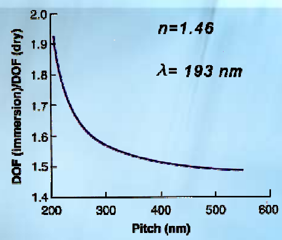
Resist is sensitive to intensity, I^2

Diffraction-Compensating Pattern Design (Proximity Correction)



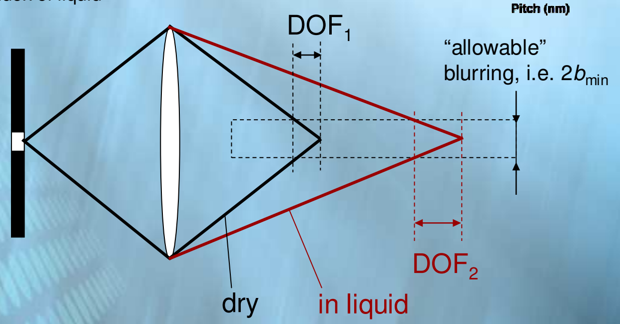
Immersion Photolithography

C.A. Mack, Microlith. World, 13(1), 14 (2004)



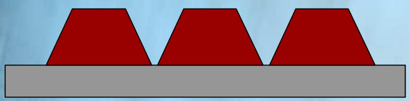
$$\frac{DOF(immersion)}{DOF(dry)} = \frac{1-\sqrt{1-\left(\frac{\lambda}{p}\right)^2}}{n-\sqrt{n^2-\left(\frac{\lambda}{p}\right)^2}}$$

p: pitch
n: refractive index of liquid

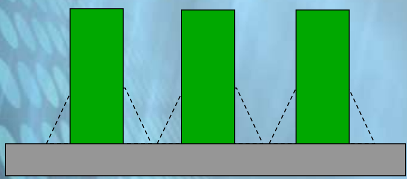


Contrast of Resist

low-contrast resist



high-contrast resist



(diffraction ignored)

SU-8