EE-527: MicroFabrication

Photolithography

Photolithography

- Photo-litho-graphy: *latin*: light-stone-writing
- Photolithography is an optical means for transferring patterns onto a substrate. It is essentially the same process that is used in lithographic printing.
- Patterns are first transferred to an imagable photoresist layer.
- Photoresist is a liquid film that can be spread out onto a substrate, exposed with a desired pattern, and developed into a selectively placed layer for subsequent processing.
- Photolithography is a binary pattern transfer process: there is no gray-scale, no color, and no depth to the image.

Key Historical Events in Photolithography

- 1826- Joseph Nicephore Niepce, in Chalon, France, takes the first photograph using bitumen of Judea on a pewter plate, developed using oil of lavender and mineral spirits.
- 1843- William Henry Fox Talbot, in England, develops dichromated gelatin, patented in Britain in 1852.
- 1935- Louis Minsk of Eastman Kodak developed the first synthetic photopolymer, poly(vinyl cinnamate), the basis of the first negative photoresists.
- 1940- Otto Suess of Kalle Div. of Hoechst AG, developed the first diazoquinone-based positive photoresist.
- 1954- Louis Plambeck, Jr., of Du Pont, develops the Dycryl polymeric letterpress plate.

Overview of the Photolithography Process

- Surface preparation
- Coating (spin casting)
- Pre-bake (soft bake)
- Alignment
- Exposure
- Development
- Post-bake (hard bake)
- Processing using the photoresist as a masking film
- Stripping
- Post processing cleaning (ashing)

Surface Preparation: Wafer Cleaning

- Typical contaminants that must be removed prior to photoresist coating:
  - dust from scribing or cleaving (minimized by laser scribing)
  - atmospheric dust (minimized by good clean room practice)
  - abrasive particles (from lapping or CMP)
  - lint from wipers (minimized by using lint-free wipers)
  - photoresist residue from previous photolithography (minimized by performing oxygen plasma ashing)
  - bacteria, carbon, organics (minimized by good DI water system)
  - water spots (minimized by good SRD practice)
  - water itself! (minimized by a wafer singe step)

Surface Preparation: Wafer Priming

- Adhesion promoters are used to assist resist coating.
- Resist adhesion factors:
    - moisture content on surface – VERY IMPORTANT!
    - wetting characteristics of resist
    - type of primer
    - delay in exposure and prebake
    - resist chemistry
    - surface smoothness
    - stress from coating process
    - surface contamination
- Ideally, the wafer surface should be dehydrated of all H_2O
  - Wafers are given a "singe" step to desorb any water surface film
    - 15 minutes in 80-90°C convection oven, OR
    - 1 minute on 90°C hot plate

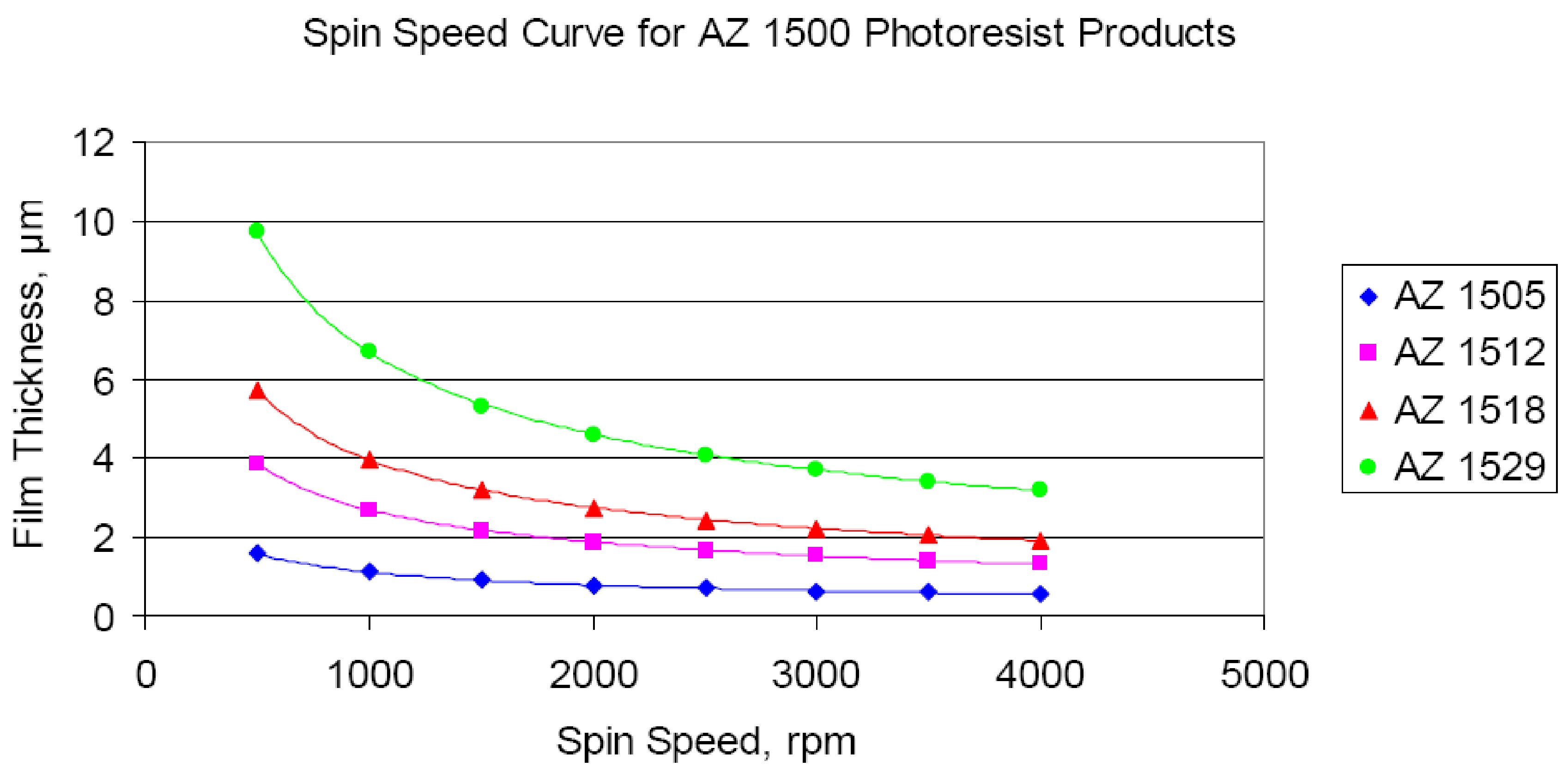
Wafer Primers

- For silicon and sapphire:
  - primers form bonds with surface and produce a polar (electrostatic) surface
  - most are based upon siloxane linkages (Si-O-Si)
    - 1,1,1,3,3,3-hexamethyldisilazane (HMDS), $(CH_3)_3SiNHSi(CH_3)_3$
    - trichlorophenylsilane (TCPS), $C_6H_5SiCl_3$
    - bistrimethylsilylacetamide (BSA), $(CH_3)_3SiNCH_3COSi(CH_3)_3$
- For gallium arsenide and indium phosphide:
  - GaAs already has a polar surface
    - monazoline C
    - trichlorobenzene, $C_6H_3Cl_3$
    - xylene, $C_6H_4(CH_3)_2$
- Note that most of these compounds have high toxicity.
  - Low TLVs, so always use them under a fume hood!

Photoresist Spin Coating

- Wafer is held on a spinner chuck by vacuum and the resist is spread out to a uniform thickness by spin coating.
- Typically 2000-6000 rpm for 15-30 seconds.
- Resist thickness is set by:
  - primarily resist viscosity
  - secondarily spinner rotational speed
- Resist thickness is given by $t = kp^2/\omega^{1/2}$, where
  - k = spinner constant, typically 80-100
  - p = resist solids content in percent
  - ω = spinner rotational speed in rpm/1000
- Most resist thicknesses are 1-2 μm for commercial Si processes.

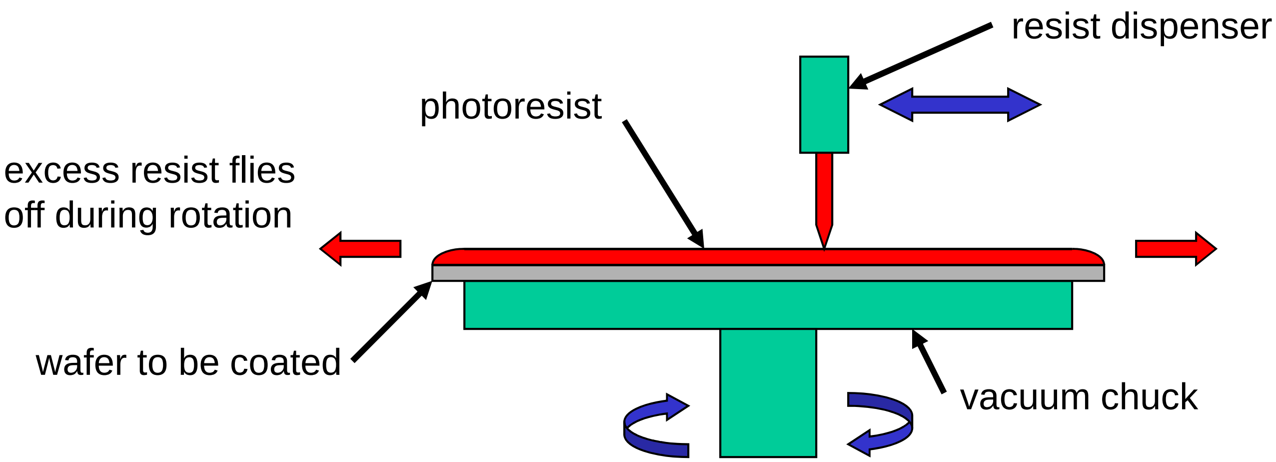
AZ-1500 Series Photoresist Thickness Versus Spin Speed

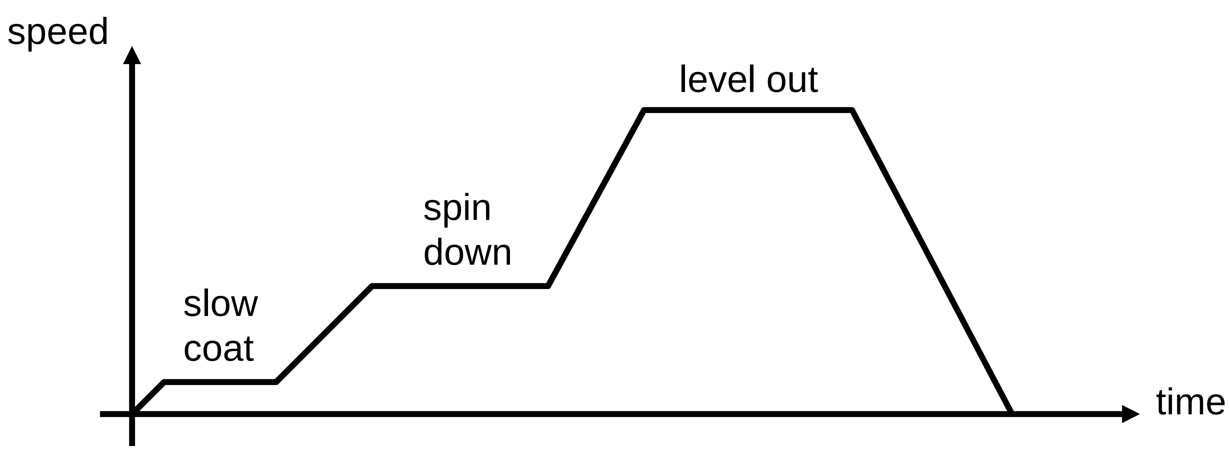


Note that choosing the proper photoresist viscosity is the primary means to control the applied thickness. The spin speed only adds fine adjustment within this range.

Graph from AZ Electronic Materials data sheet

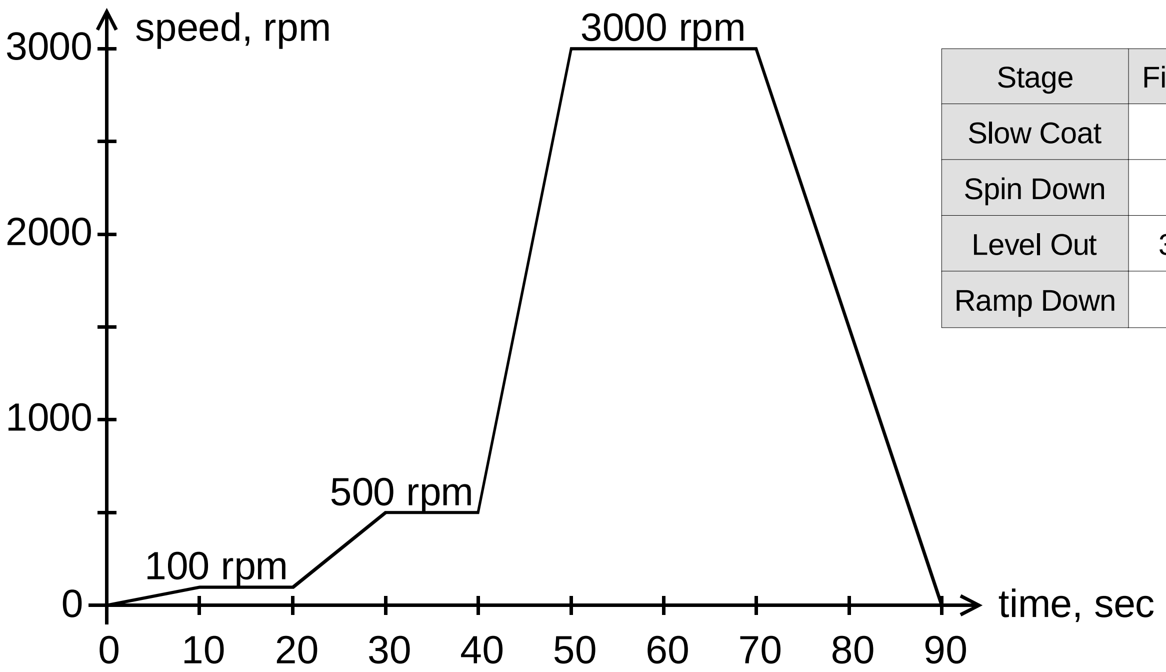
Photoresist Spin Coating





Prototype Spin Coating Recipe

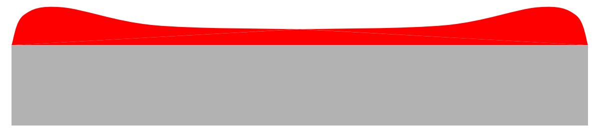
- This is a good starting point for most positive photoresists.
- Automatic systems dispense the resist during the slow coat stage.
- The final spin speed (e.g. 3000 rpm) sets the final resist thickness.



Stage	Final Speed	Ramp Time	Hold Time
Slow Coat	100 rpm	10 sec	10 sec
Spin Down	500 rpm	10 sec	10 sec
Level Out	3000 rpm	10 sec	20 sec
Ramp Down	0 rpm	20 sec	0 sec

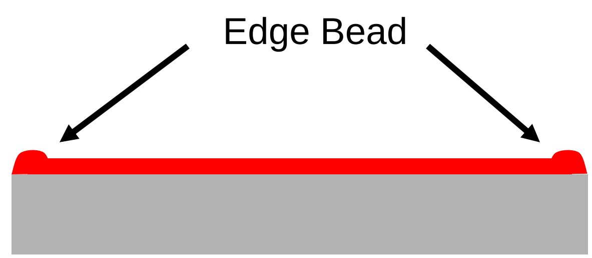
Stages of Resist Coating

1. EQUILIBRIUM STAGE
(stopped)



2. WAVE-FORMATION STAGE
(~ 2 revolutions)

3. CORONA STAGE
(~ 30 revolutions)



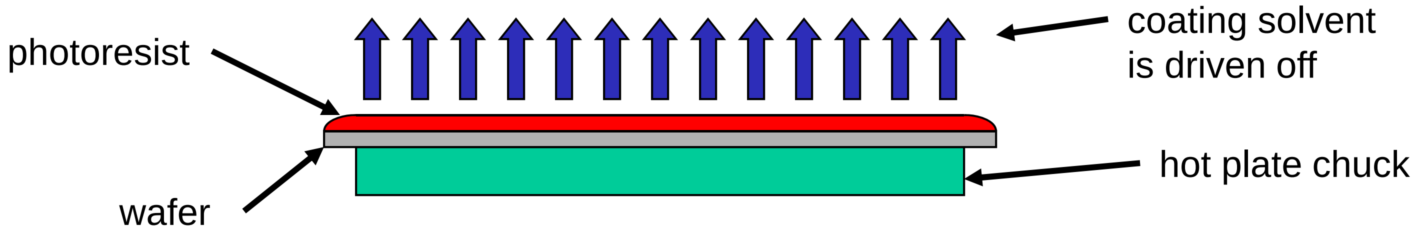
4. SPIRAL STAGE
(~ 1000 revolutions)

Spinning Artifacts

- Striations
  - ~ 30 nm variations in resist thickness due to nonuniform drying of solvent during spin coating
  - ~ 80-100 μm periodicity, radially out from center of wafer
- Edge bead
  - a residual ridge in the resist at edge of wafer
  - can be up to 20-30 times the nominal thickness of the resist
  - radius on wafer edge greatly reduces the edge bead height
  - non-circular wafers greatly increase the edge bead height
  - edge bead removers are solvents that are spun on after resist coating and which partially dissolve away the edge bead
- Streaks
  - radial patterns caused by hard particles whose diameter are greater than the resist thickness

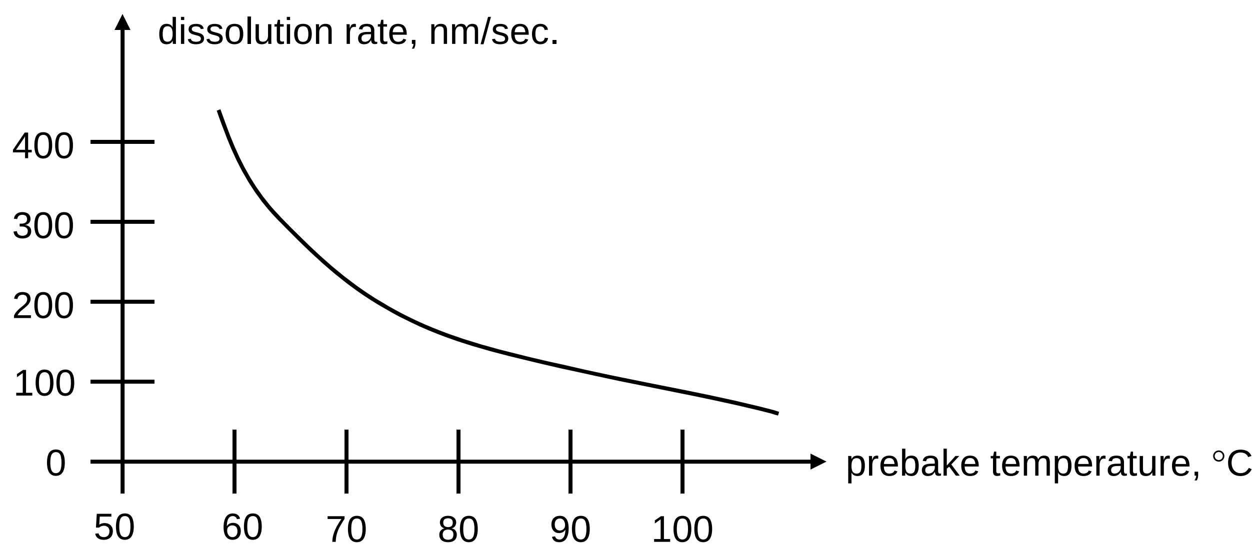
Prebake (Soft Bake) - 1

- Used to evaporate the coating solvent and to densify the resist after spin coating.
- Typical thermal cycles:
  - 90-100°C for 20 min. in a convection oven
  - 75-85°C for 45 sec. on a hot plate
- Commercially, microwave heating or IR lamps are also used in production lines.
- Hot plating the resist is usually faster, more controllable, and does not trap the solvent like convection oven baking.



Prebake (Soft Bake) - 2

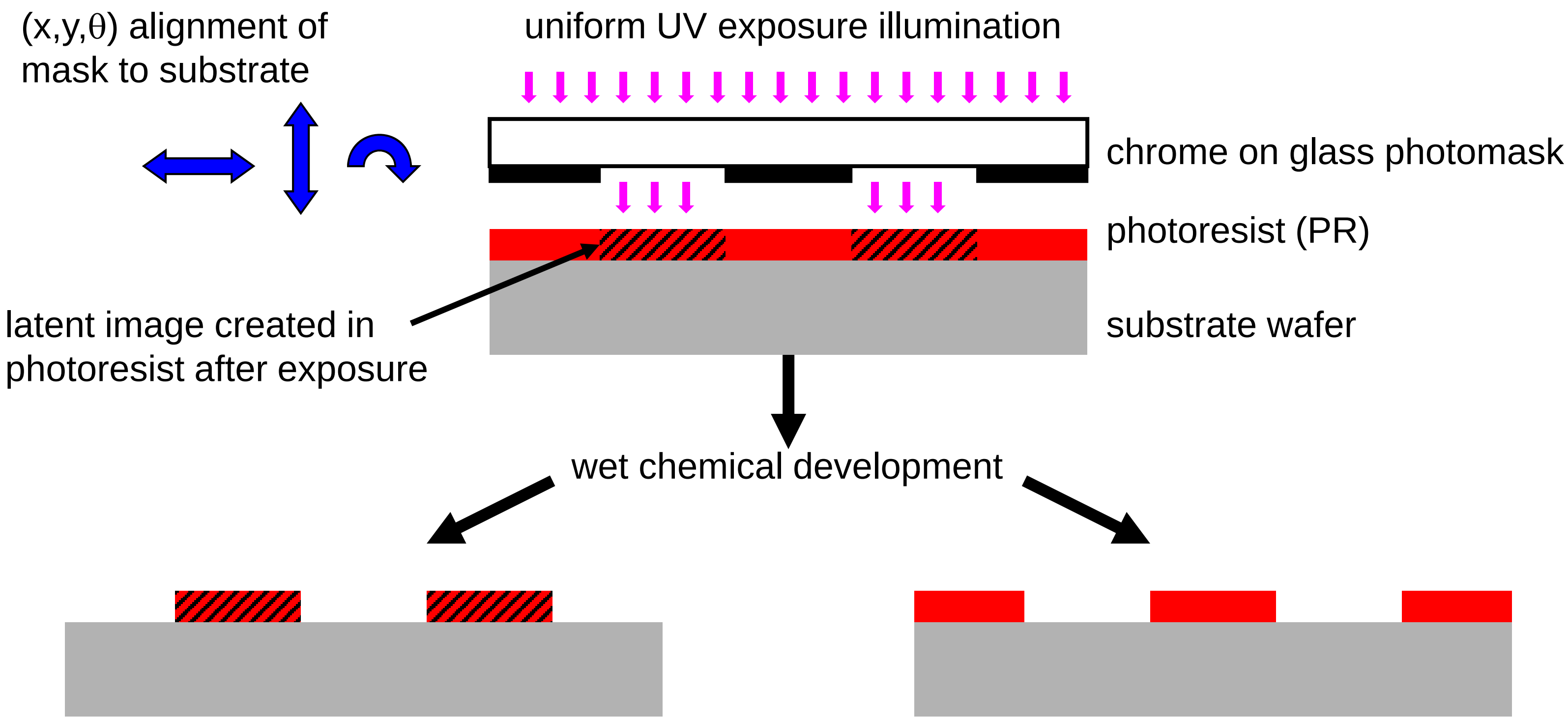
- A narrow time-temperature window is needed to achieve proper linewidth control.
- The thickness of the resist is usually decreased by 25 % during prebake for both positive and negative resists.
- Less prebake increases the development rate:



Prebake (Soft Bake) - 3

- Convection (ovens):
  - Solvent at the surface of the resist is evaporated first, which can cause the resist to develop an impermeable skin, trapping the remaining solvent inside.
  - Heating must go slow to avoid solvent burst effects.
- Conduction (hot plates):
  - Need an extremely smooth surface for good thermal contact and heating uniformity.
  - The temperature rise starts at bottom of wafer and works upward, more thoroughly evaporating the coating solvent.
  - It is generally much faster and more suitable for automation.

Overview of Align/Expose/Develop Steps



NEGATIVE PHOTORESIST

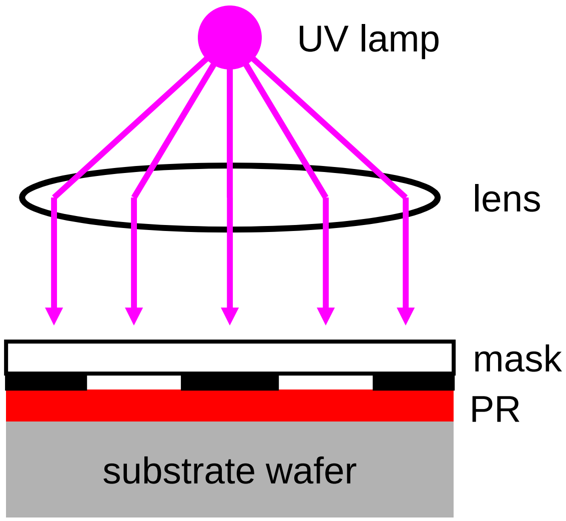
Photoresist is photopolymerized where exposed and rendered insoluble to the developer solution.

POSITIVE PHOTORESIST

Exposure decomposes a development inhibitor and developer solution only dissolves photoresist in the exposed areas.

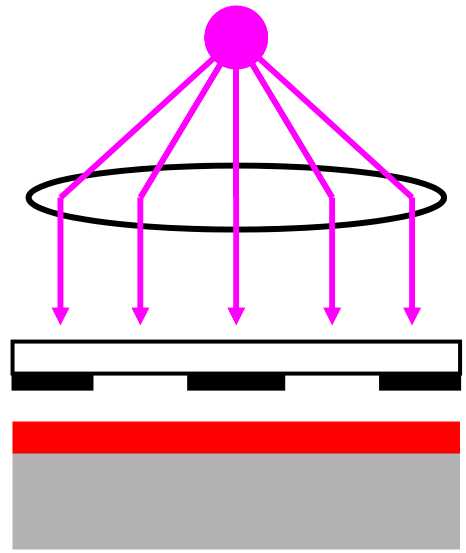
Alignment and Exposure Hardware - 1

CONTACT ALIGNER



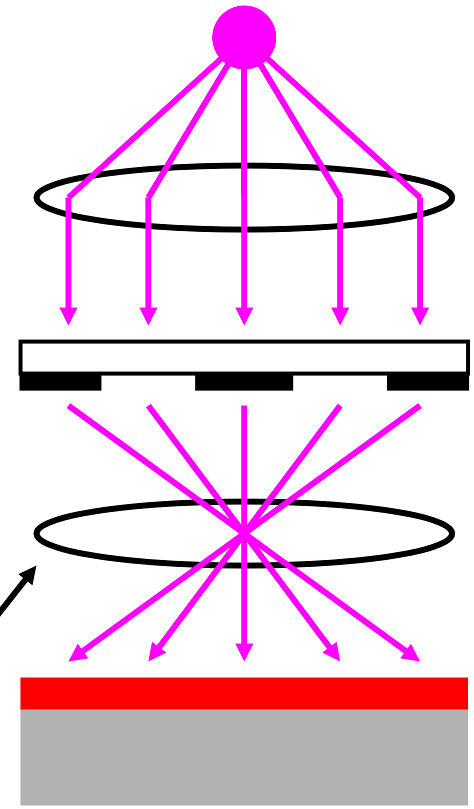
2 operating modes:
contact for expose;
separate for align.
Examples:
Kaspar 17A
Oriel
Karl Suss MJB3

PROXIMITY ALIGNER



less wear on mask, but poorer image than from a contact aligner.
Examples:
Kaspar-Cobilt

PROJECTION ALIGNER



Examples:
Perkin-Elmer Micralign

Projection systems use imaging optics in between the mask and the wafer

Alignment and Exposure Hardware - 2

- For simple contact, proximity, and projection systems, the mask is the same size and scale as the printed wafer pattern. I.e. the reproduction ratio is 1:1.
- Projection systems give the ability to change the reproduction ratio. Going to 10:1 reduction allows larger size patterns on the mask, which is more robust to mask defects.
- The mask size can get unwieldy for large wafers.
- Most wafers contain an array of the same pattern, so only one cell of the array is needed on the mask. This system is called Direct Step on Wafer (DSW). These machines are also called "Steppers"
- Example: GCA-4800 (the original machine)
- The advantage of steppers: only 1 cell of wafer is needed.
- The disadvantage of steppers: the 1 cell of the wafer on the mask must be perfect – absolutely no defects, since it gets used for all die.

Alignment and Exposure Hardware - 3

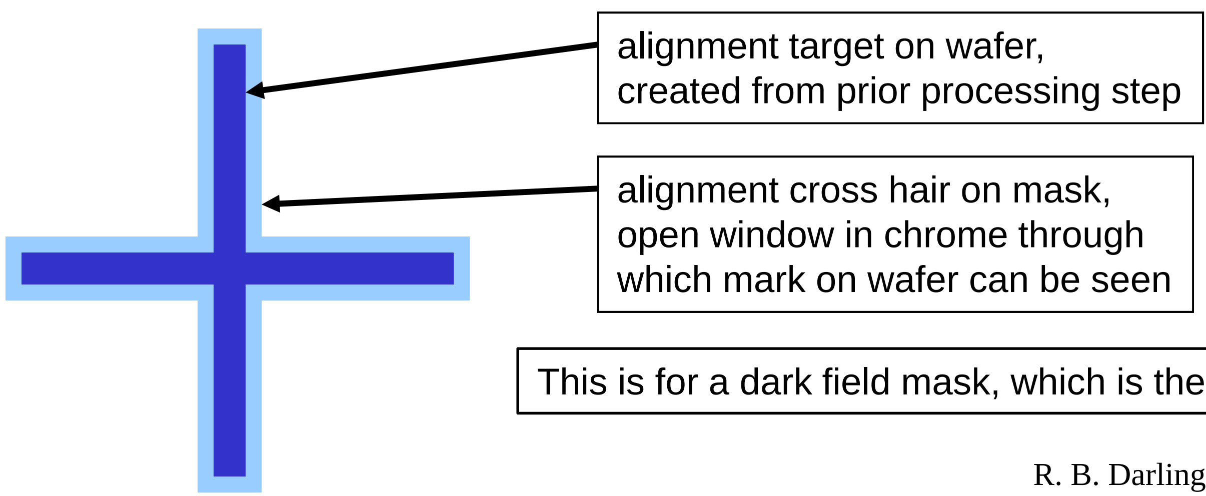
- Higher end research systems go one step further and use Direct Write on Wafer (DWW) exposure systems.
- This can be accomplished using:
  - Excimer lasers for geometries down to 1-2 μm,
  - Focused ion beams for geometries down to 100-200 nm, or
  - Electron beams for geometries down to 30-50 nm.
- No mask is needed for these technologies.
- These are serial processes, and the wafer cycle time is proportional to the beam writing time – the smaller the spot, the longer it takes!

Photomasks

- Master patterns which are transferred to wafers
- Types:
  - photographic emulsion on soda lime glass (cheapest)
  - Iron oxide (Fe_2O_3) on soda lime glass
  - Chrome (Cr) on soda lime glass
  - Cr on quartz glass (most expensive, needed for deep UV litho)
- Dimensions:
  - 4.000 in. square x 0.062 in. thick for 3-inch wafers
  - 5.000 in. square x 0.093 in. thick for 4-inch wafers
- Polarity:
  - “light-field” masks are mostly clear; the drawn features are opaque.
  - “dark-field” masks are mostly opaque; the drawn features are clear.

Mask to Wafer Alignment - 1

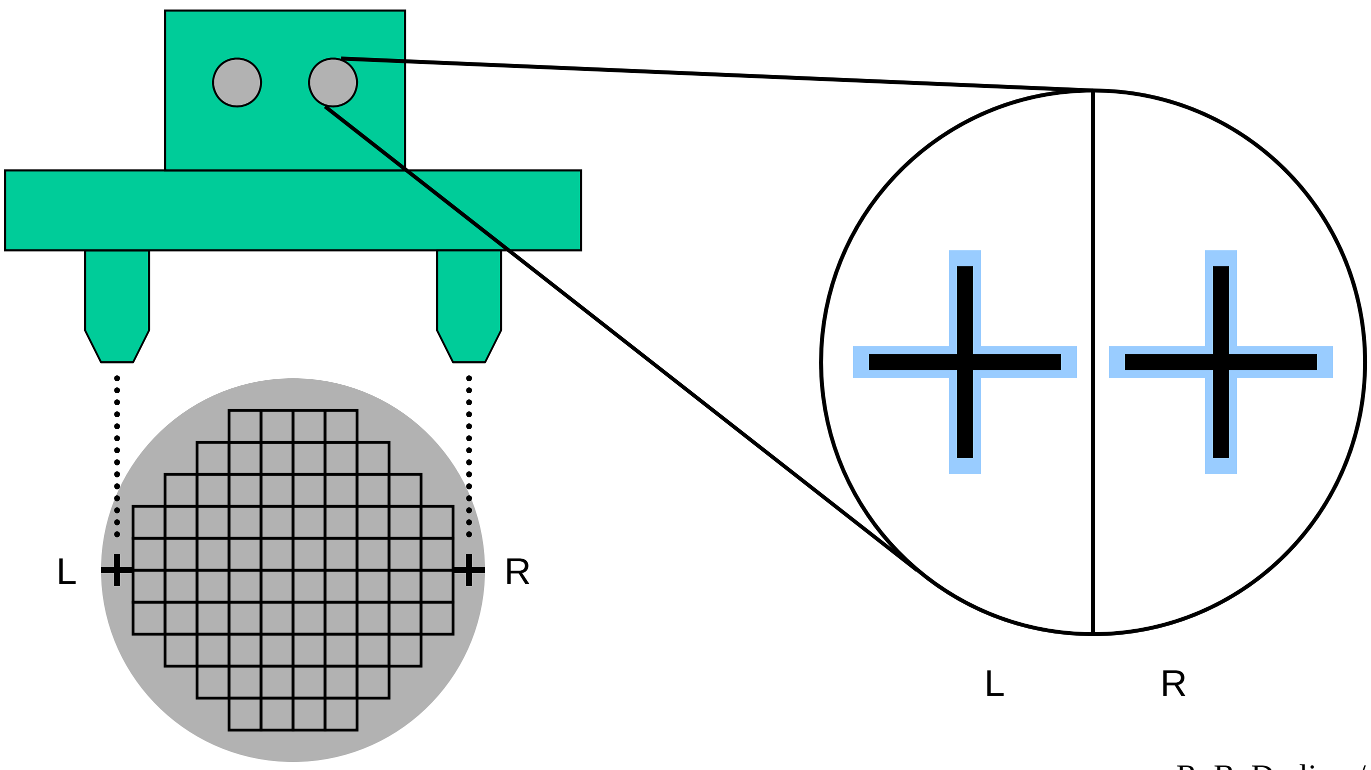
- There are 3 degrees of freedom between mask and wafer: (x, y, θ)
- Use alignment marks on the wafer (the target) and on the mask (the cross hair) to register patterns prior to exposure.
- Modern process lines (steppers) use automatic pattern recognition and alignment systems.
  - Usually takes 1-5 seconds to align and expose on a modern stepper.
  - Experienced human operators usually take 30-45 seconds with well-designed alignment marks.



This is for a dark field mask, which is the most common.

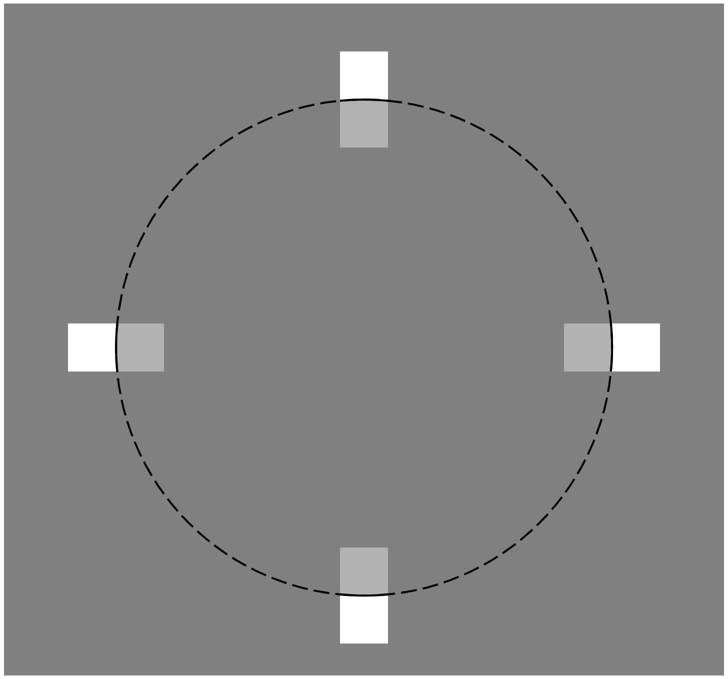
Mask to Wafer Alignment - 2

- This normally requires at least two alignment mark sets on opposite sides of the wafer or the stepped region.
- A split-field microscope is used to make alignment easier:

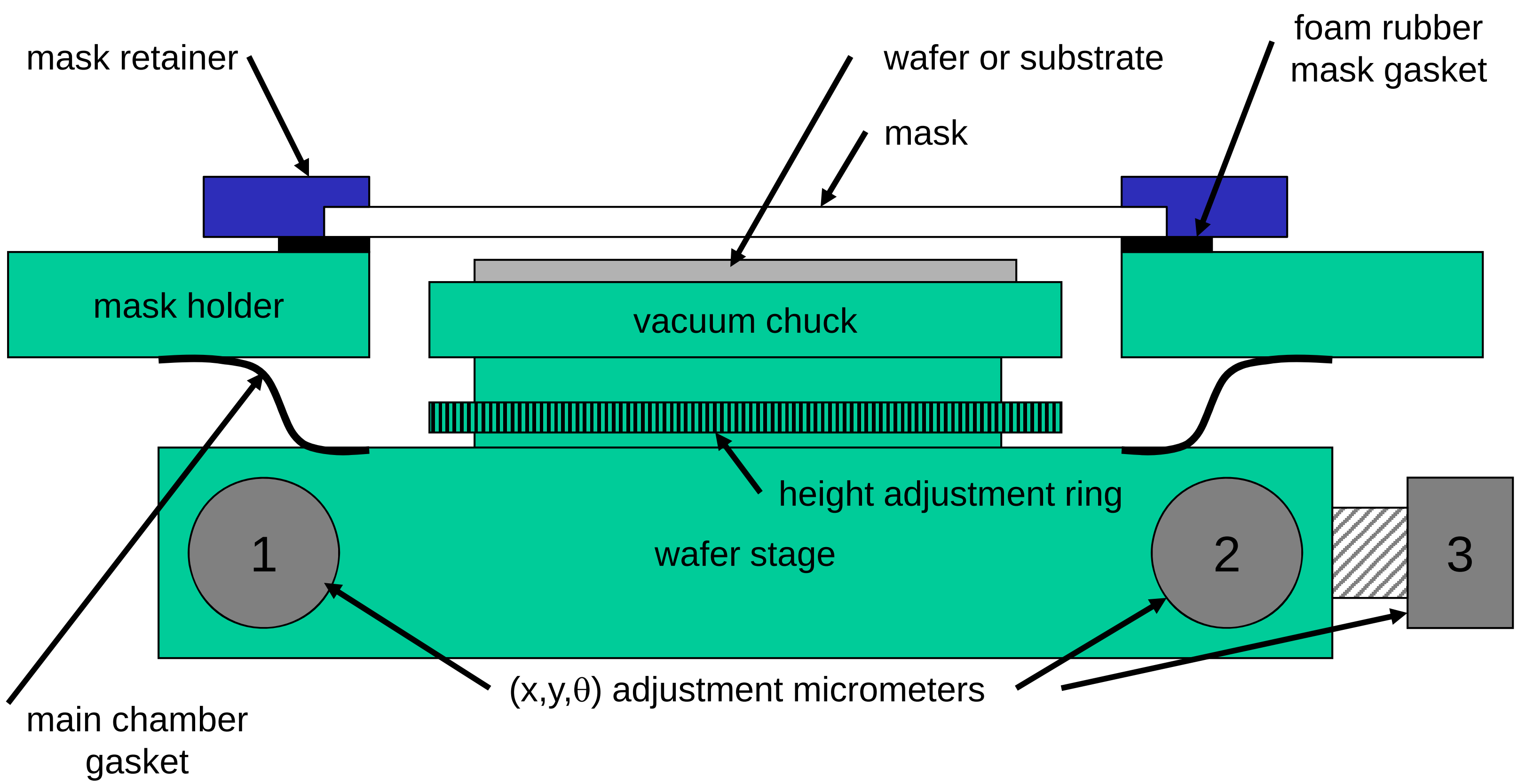


Mask to Wafer Alignment - 3

- Visual alignment:
  - Process of getting the wafer coarsely centered under the mask
  - This is all that is needed for the first mask of the set, since no patterns exist on the wafer yet.
  - This is accomplished by special windows on a dark field mask.

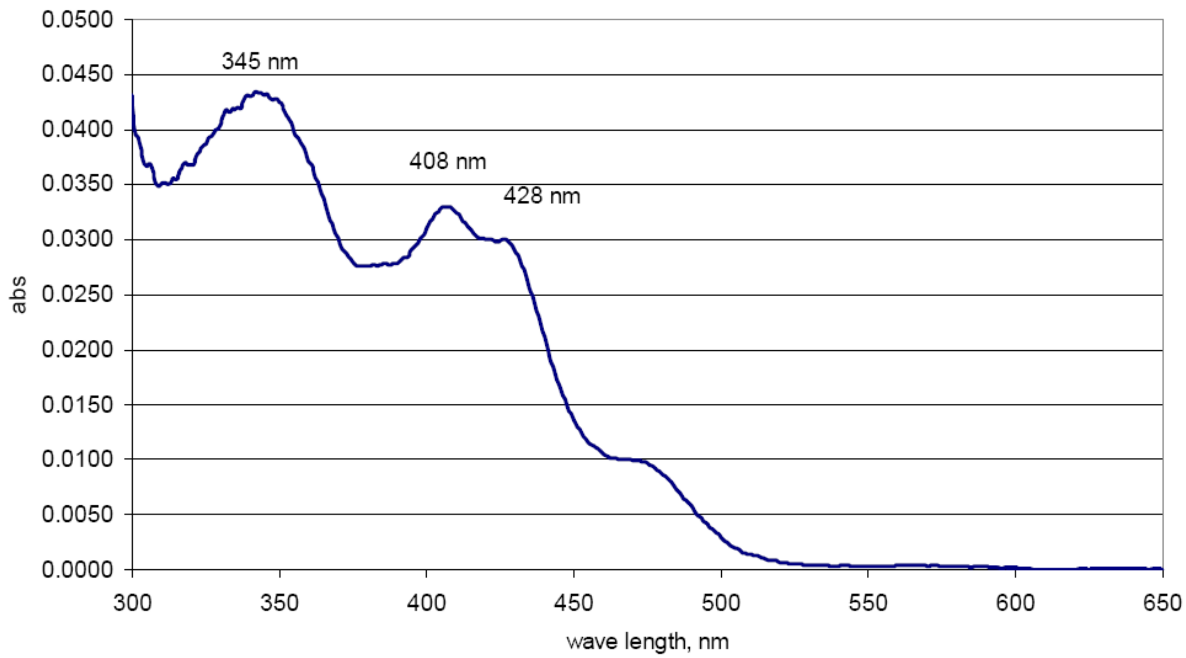


Oriel Alignment Fixture



Photoresist Spectral Absorption

- Most positive photoresists are sensitive to light in the ultraviolet to blue-green range, $\lambda \sim 300$ to 500 nm.
- Photolithography areas must have the light filtered to only 550 – 700 nm (green to red). Because the filters absorb the blue wavelengths, they appear yellow, and photolithography areas appear to have yellow illumination.
- The absorption graph below is for AZ-1500 series positive photoresists.



Graph from AZ Electronic Materials data sheet

Exposure

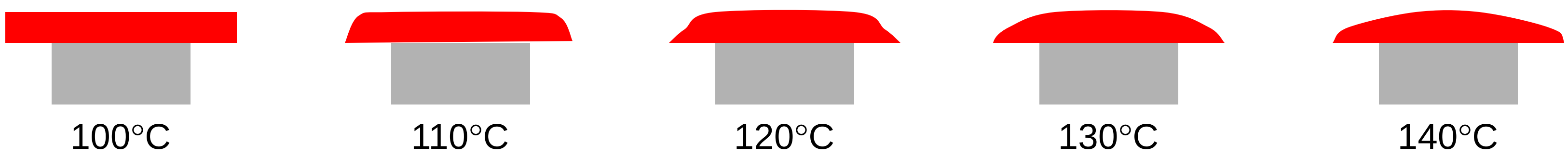
- The exposure dose D is the amount of optical radiation that is applied to the photoresist, usually expressed in mJ/cm^2.
  - The Dose-To-Print (DTP) is the required dose to create a full thickness latent image in the photoresist.
  - The DTP is directly proportional to the photoresist thickness d.
- The exposure intensity I is the optical power density at the photoresist image plane, usually expressed in mW/cm^2.
- The exposure time t_e is the duration of the optical radiation (seconds).
- $D = I*t_e$.
- Example: Oriel 350W 3-inch aligner / high pressure Hg-arc exposure system and 1.2 μm thick AZ-1512 photoresist:
  - $I = 10.0$ mW/cm^2, (check this value periodically, since the lamp ages!)
  - DTP = 200 mJ/cm^2, so set the exposure time for
  - t_e = DTP/I = 20.0 seconds.

Postbake (Hard Bake) - 1

- Used to stabilize and harden the developed photoresist prior to processing steps that the resist will mask.
- An important parameter is the plastic flow or glass transition temperature.
- The postbake removes any remaining traces of the coating solvent or developer.
- This eliminates the solvent burst effects in vacuum processing.
- Postbake introduces some stress into the photoresist.
- Some shrinkage of the photoresist may occur.
- Longer or hotter postbake makes resist removal much more difficult.

Postbake (Hard Bake) - 2

- A firm postbake is needed for acid etching, e.g. BOE.
- Postbake is not needed for processes in which a soft resist is desired, e.g. metal liftoff patterning.
- Photoresist will undergo plastic flow with sufficient time and/or temperature:
  - Resist reflow can be used for tailoring sidewall angles.



Photoresist Removal (Stripping)

- Want to remove the photoresist and any of its residues.
- Simple solvents are generally sufficient for non-postbaked photoresists:
  - Positive photoresists:
    - acetone
    - trichloroethylene (TCE)
    - phenol-based strippers (Indus-Ri-Chem/EKC J-100)
  - Negative photoresists:
    - methyl ethyl ketone (MEK), $CH_3COC_2H_5$
    - methyl isobutyl ketone (MIBK), $CH_3COC_4H_9$
- Plasma etching with O_2 (ashing) is also effective for removing organic polymer debris.
  - Also: Shipley 1165 stripper (contains n-methyl-2-pyrrolidone), which is effective on hard, postbaked resist.
  - Also: SC1 and/or SC2 standard cleans.

Basics of Photolithography for Processing

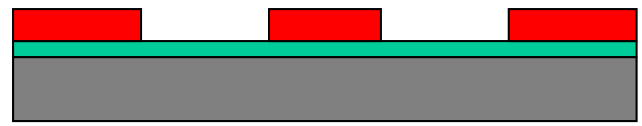
- Microfabrication processes:
  - Additive → deposition
  - Subtractive → etching
  - Modifying → doping, annealing, or curing
- Two primary techniques for patterning additive and subtractive processes:
  - Etch-back:
    - Photoresist is applied overtop of the layer to be patterned.
    - Unwanted material is etched away using the photoresist as a mask.
  - Lift-off:
    - The patterned layer is deposited over top of the photoresist.
    - Unwanted material is lifted off when the resist is stripped.

Etch-back

1

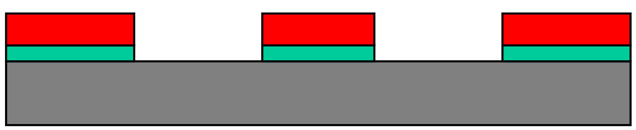
deposit thin film of desired material

2



coat and pattern photoresist

3



etch film using photoresist as mask

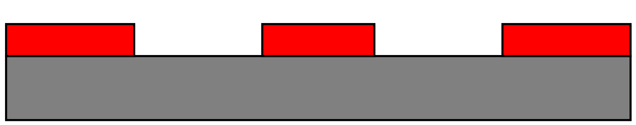
4

remove photoresist

NOTE: photoresist has same polarity as final film; photoresist never touches the substrate wafer.

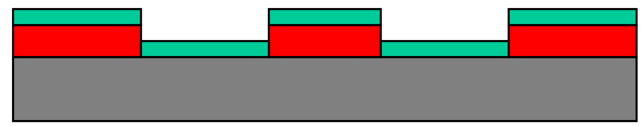
Lift-off

1



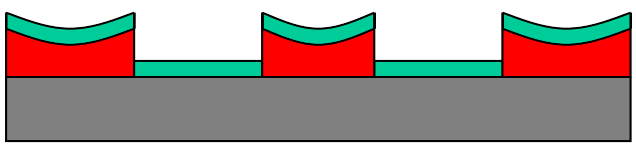
coat and pattern photoresist

2



deposit thin film of desired material

3



swell photoresist with a solvent

4

remove photoresist and thin film above it

NOTE: photoresist has opposite polarity as final film; excess deposited film never touches the substrate wafer.

(Somewhat) Useful References

- Britney Spear's Guide to Semiconductor Physics:
    - http://britneyspears.ac/lasers.htm
  - Section on photolithography: (references EE-527 course notes)
    - http://britneyspears.ac/physics/fabrication/photolithography.htm