ENGR 494C and 594C: Microsystems Principles

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: there is no gray-scale, color, nor 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)

Wafer Cleaning - 1

- 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 (minimized by good DI water system)
    - films from other sources:
        - solvent residue
        - H_2O residue
        - photoresist or developer residue
        - oil
        - silicone

Wafer Cleaning - 2

- 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 H_2O with ultrasonic agitation
    - 30 sec. rinse under free flowing DI H_2O
    - spin rinse dry for wafers; N_2 blow off dry for tools and chucks
- For particularly troublesome grease, oil, or wax stains:
    - Start with 2-5 min. soak in 1,1,1-trichloroethane (TCA) or trichloroethylene (TCE) with ultrasonic agitation prior to acetone
- Hazards:
    - TCE is carcinogenic; 1,1,1-TCA is less so
    - acetone is flammable
    - methanol is toxic by skin adsorption

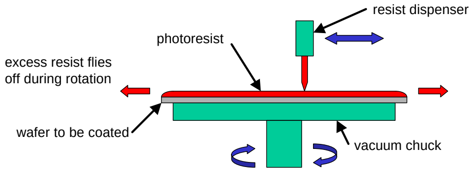
Photoresist Spin Coating

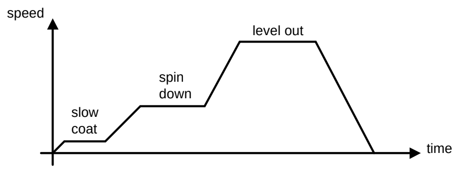
- Wafer is held on a spinner chuck by vacuum and resist is coated to uniform thickness by spin coating.
- Typically 3000-6000 rpm for 15-30 seconds.
- Resist thickness is set by:
  - primarily resist viscosity
  - secondarily spinner rotational speed
- Resist thickness is given by $t = kp^2/w^{1/2}$, where
  - k = spinner constant, typically 80-100
  - p = resist solids content in percent
  - w = spinner rotational speed in rpm/1000
- Most resist thicknesses are 1-2 µm for commercial Si processes.

Wafer Cleaning - 3

- RCA clean: use for new silicon wafers out of the box
  - 1. APW: NH_4OH (1) + H_2O_2 (3) + H_2O (15) @ 70°C for 15 min.
  - 2. DI H_2O rinse for 5 min.
  - 3. 10:1 BOE for 1 min.
  - 4. DI H_2O rinse for 5 min.
  - 5. HPW: HCl (1) + H_2O_2 (3) + H_2O (15) @ 70°C for 15 min.
  - 6. DI H_2O rinse for 5 min.
  - 7. Spin & rinse dry

Photoresist Spin Coating

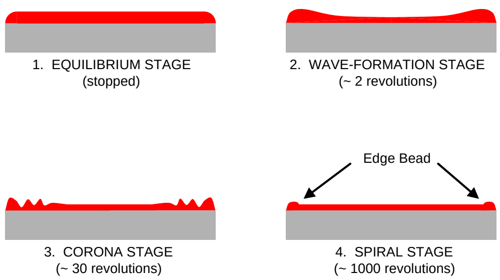




Wafer Priming

- Adhesion promoters are used to assist resist coating.
- Resist adhesion factors:
  - moisture content on surface
  - wetting characteristics of resist
  - type of primer
  - delay in exposure and prebake
  - resist chemistry
  - surface smoothness
  - stress from coating process
  - surface contamination
- Ideally want no H_2O on wafer surface
  - Wafers are given a "singe" step prior to priming and coating
    - 15 minutes in 80-90°C convection oven

Stages of Resist Coating



Wafer Primers

- Used for silicon:
  - 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), $(CH_3)_3SiNCH_3COSi(CH_3)_3$
- Used for gallium arsenide:
  - GaAs already has a polar surface
    - monazoline C
    - trichlorobenzene
    - xylene

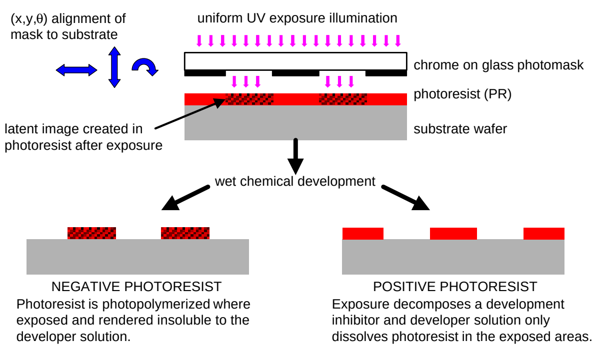
Prebake (Soft Bake) - 3

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

Spinning Artifacts

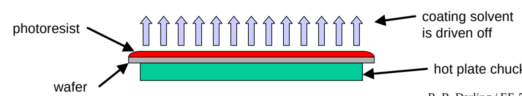
- Striations
  - ~ 30 nm variations in resist thickness due to nonuniform drying of solvent during spin coating
  - ~ 80-100 μm periodicity, radially out from center of wafer
- Edge Bead
  - residual ridge in resist at edge of wafer
  - can be up to 20-30 times the nominal thickness of the resist
  - 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

Overview of Align/Expose/Develop Steps

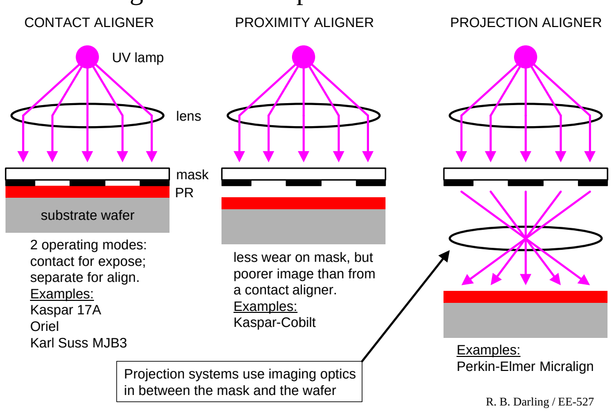


Prebake (Soft Bake) - 1

- 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 solvent like convection oven baking.

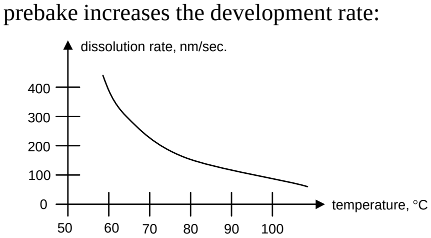


Alignment and Exposure Hardware - 1



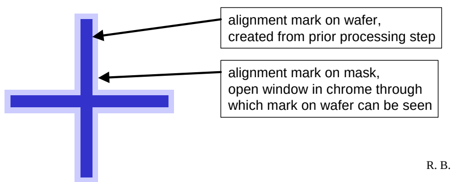
Prebake (Soft Bake) - 2

- 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:



Mask to Wafer Alignment - 1

- 3 degrees of freedom between mask and wafer: (x,y,θ)
- Use alignment marks on mask and wafer 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.
  - Human operators usually take 30-45 seconds with well-designed alignment marks.

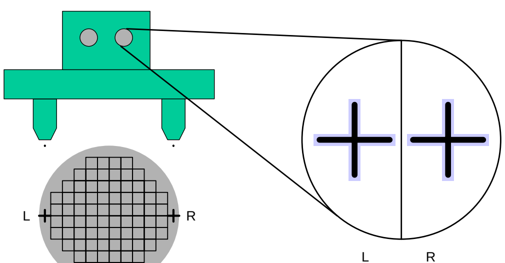


Alignment and Exposure Hardware - 2

- 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.
- 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 (original machine)
- Advantage of steppers: only 1 cell of wafer is needed
- 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.

Mask to Wafer Alignment - 2

- Normally requires at least two alignment mark sets on opposite sides of wafer or stepped region.
- Use a split-field microscope to make alignment easier:

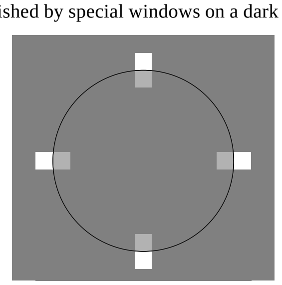


Alignment and Exposure Hardware - 3

- 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
  - Electron beams for geometries down to 0.1-0.2 µm
  - Focused ion beams for geometries down to 0.05-0.1 µm
- No mask is needed for these technologies.
- These are serial processes, and wafer cycle time is proportional to the beam writing time-- the smaller the spot, the longer it takes!

Mask to Wafer Alignment - 3

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



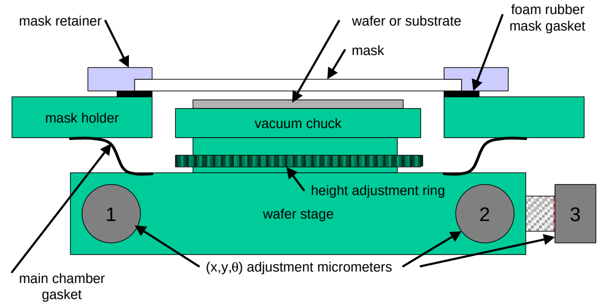
Photomasks

- Master patterns which are transferred to wafers
- Types:
  - photographic emulsion on soda lime glass (cheapest)
  - Fe_2O_3 on soda lime glass
  - Cr on soda lime glass
  - Cr on quartz glass (most expensive, needed for deep UV litho)
- Dimensions:
  - 4” x 4” x 0.060” for 3-inch wafers
  - 5” x 5” x 0.060” for 4-inch wafers
- Polarity:
  - “light-field” = mostly clear, drawn feature = opaque
  - “dark-field” = mostly opaque, drawn feature = clear

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 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.

Oriel Alignment Fixture



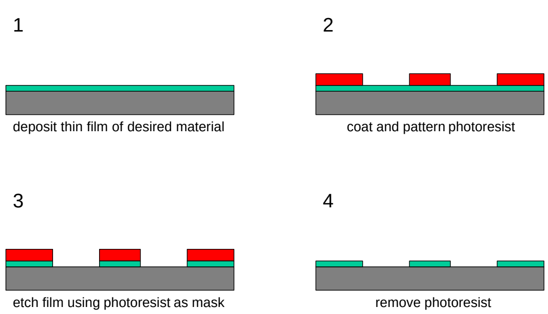
Basics of Photolithography for Processing

- 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
  - Lift-off:
    - patterned layer is deposited over top of the photoresist
    - unwanted material is lifted off when resist is removed

Postbake (Hard Bake) - 1

- Used to stabilize and harden the developed photoresist prior to processing steps that the resist will mask.
- Main parameter is the plastic flow or glass transition temperature.
- 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.

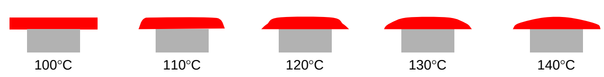
Etch-back



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

Postbake (Hard Bake) - 2

- 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.

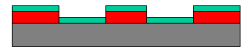


Lift-off

1

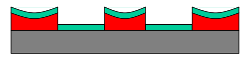
coat and pattern photoresist

2



deposit thin film of desired material

3



swell photoresist with a solvent

4

remove photoresist and thin film above it

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