Building the IC using Photolithography

- ICs start with the circuit layout of the circuit
- Each device (transistor, inverter) is designed in 2D pattern
- But each part is actually a layer (metal lines, diffusion)
- Photolithography is the process of creating each layer pattern
- Simple chips 8 layers – current ~30 layers
- Each layer pattern is defined with many steps

**Layout of MOS inverter**

- When $V_i = 1 \rightarrow Q_n$ is on $\rightarrow V_o = 0$
- When $V_i = 0 \rightarrow Q_p$ is on $\rightarrow V_o = 1$

<table>
<thead>
<tr>
<th>Truth Table</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

$V_{DD}$ (+ve voltage $= 1$)

$V_{DD}$

$V_o$

$V_i$

$Q_n$ (n-channel MOS)

$Q_p$ (p-channel MOS)

$V_{DD}$

$GND$

**Bipolar NMOS**

**Bipolar PMOS**

**NOT gate**
• To do MOS inverter, at least seven mask steps is needed

- SiO$_2$ is etched using Mask 1.
- Mask 2 creates the active regions where the MOSFETs will be placed.
- Mask 3 is used to deposit the polysilicon gate (most critical step).
- Mask 4 is used to control a heavy arsenic implant and create the source and drain of the n-channel devices.
- Mask 5 is used to control a heavy Boron implant and create the source and drain of the n-channel devices.
- Mask 6 is used to pattern the contact holes.
- Etching opens the holes.
- Mask 7 is used to pattern the interconnection.
- A thin layer of aluminum is evaporated.
The lithographic process

Design => Mask => Wafer
Creation of Photomasks for Photolithography

- Create chip design using CAD (Computer Aided Design) tools
- Laser or e-beam pattern generator writes chip (1:1 or 1:10)

3 possibilities:
- Create whole wafer mask this way (1:1)
- Write Reticule (1 or several chip designs)
  Reticules are 5 or 6 inch in size
  Reticules may cover 3x3 cm chips at reduced magnification 5 or 10x
  Step and repeated reduced pattern (5 or 10x) directly on wafer
- Step and repeat reticule to create whole wafer mask
Photolithography or Patterning

- Creation of 3D structures, eg circuit lines
- Using photographic techniques to transfer the mask pattern
- Derived from creation of printing plates
- Usually starts with thin film on wafer (eg SiO$_2$, metal)
- Coat with photosensitive material (photoresist)
- Exposure: to UltraViolet Light through mask of structure
- Development of resist: leaves pattern of resist with openings
- Etching: removes film unprotected by resist
- Striping Resist: leave only patterned film

**Figure** The areas from which the oxide is to be etched are defined by polymerizing a light-sensitive resist through a photographic negative or mask.
Photolithography Basic Steps
- Creation of 3D structures using photographic techniques

<table>
<thead>
<tr>
<th>Process Step</th>
<th>Purpose</th>
<th>Cross Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Surface Preparation</td>
<td>Clean and dry wafer surface</td>
<td>Top Layer</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wafer</td>
</tr>
<tr>
<td>2. Photoresist Apply</td>
<td>Apply a thin layer of photoresist to the wafer</td>
<td>Photoresist</td>
</tr>
<tr>
<td>3. Softbake</td>
<td>Partial evaporation of photoresist solvents to promote adhesion</td>
<td></td>
</tr>
<tr>
<td>4. Alignment and Exposure</td>
<td>Precise alignment of mask to wafer and exposure to u.v. light. Negative resist is polymerized.</td>
<td></td>
</tr>
<tr>
<td>6. Hard Bake</td>
<td>Final Evaporation of Solvents</td>
<td></td>
</tr>
<tr>
<td>7. Develop Inspection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Etch</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. Photoresist Removal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10. Final Inspection</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Using Patterned Films as Masks

- Photolithography creates 3D patterned film
- Two possibilities
- Patterned film often final structure wanted
- Patterned film acts as a mask for additional processes
  eg oxide mask for doping process
- Sometimes one patterning does both
Two Types of Resist

- Negative: leaves resist where light exposure
- Positive: leaves resist where no light exposure

[Diagram showing the process of photolithography for both negative and positive resists, including light exposure, mask application, and etched film patterns.]
Different Mask Types

- Light field Mask

  ![Light Field Mask Image]

- Dark field Mask

  ![Dark Field Mask Image]

- The result may have Hole or Island depend on resist and mask types

**Figure** Mask and photoresist polarity results.

<table>
<thead>
<tr>
<th>Photoresist Polarity</th>
<th>Negative</th>
<th>Positive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear Field</td>
<td>Hole</td>
<td>Island</td>
</tr>
<tr>
<td>Dark Field</td>
<td>Island</td>
<td>Hole</td>
</tr>
</tbody>
</table>
### Parts of Photoresist

- **Resist**: photosensitive solid polymer dissolved in solvent
- **Photoresists**: are resins (solids) in solvent
- **Sensitizers and additives**: improve response

<table>
<thead>
<tr>
<th>Component</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Polymer</strong></td>
<td>Changes structure in reaction to energy (polymerization or photosolubilization)</td>
</tr>
<tr>
<td><strong>Solvent</strong></td>
<td>Allows spin application of thin layers</td>
</tr>
<tr>
<td><strong>Sensitizers</strong></td>
<td>Control of modification chemical reaction when exposed</td>
</tr>
<tr>
<td><strong>Additives</strong></td>
<td>Specific Needs</td>
</tr>
</tbody>
</table>

**Figure** Photoresist components.
Negative Photoresist

- Negative resists widely used until 3 micron resolution
- Limitation is that they swell during development hence resolution limited
- Basic material is synthetic rubber (polyisoprene) phenol-formaldehyde polymer (novolak resin)
- Compound is converted to a resin by cyclization
- Cyclized: turned into a benzene ring containing double bonded C atoms
- Sensitizer are PhotoActive Compounds (PAC): added for photosensitivity: eg. bis-aryl diazide

Negative Photoresist Exposure

- Under UV sensitized on one polyisoprene cross links with another sensitizer on another polyisoprene
- Makes a polymer: long chain
- Exposed polymer resists the developer: hydrocarbon solvent: eg. Xylene
- Unexposed resist rapidly dissolved
- Needs light of about 360-400 nm, unaffected by 450 nm
Positive Resist

- VLSI needs positive resist for devices with <2 microns structures
- Again starts with a novolac resin
- PAC sensitized carbon ring added with double bonded N₂ (diazide) and oxygen (ketone) groups
  UV breaks N bond, forms 5 carbon with =C=O bond (ketene): very short lived:
- Ketene reacts with moisture (hydration) forms a carboxylic acid
- Carboxylic acid reacts with alkali to form soluble ester
- Thus exposed areas wash away in water based developer

- Typical resist: Shipley 1350J

![Diagram](image)

**Figure** The positive resist exposure reaction.
Relative Advantages of Resist type

- Positive resists used in almost all processes now
- Positive resist has much higher resolution
- Resist is constantly changing: altered to fit the wavelength used
- Negative resists only used in specialized processes now
- Most important issues for any resist:
  - What is the smallest structure resist can make
  - What wavelengths it responds to
  - How well does the resist cover the devices
  - Low Pinholes – small openings in resist
  - Good step coverage: coverage over structures on the wafer

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Negative</th>
<th>Positive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aspect Ratio</td>
<td></td>
<td>Higher</td>
</tr>
<tr>
<td>Adhesion</td>
<td>Better</td>
<td></td>
</tr>
<tr>
<td>Exposure Speed</td>
<td>Faster</td>
<td></td>
</tr>
<tr>
<td>Pinhole Count</td>
<td></td>
<td>Lower</td>
</tr>
<tr>
<td>Step Coverage</td>
<td></td>
<td>Better</td>
</tr>
<tr>
<td>Cost</td>
<td></td>
<td>Higher</td>
</tr>
<tr>
<td>Developers</td>
<td>Organic Solvents</td>
<td>Aqueous</td>
</tr>
<tr>
<td>Strippers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxide Steps</td>
<td>Acid</td>
<td>Acid</td>
</tr>
<tr>
<td>Metal Steps</td>
<td>Chlorinated Solvent Compounds</td>
<td>Simple Solvents</td>
</tr>
</tbody>
</table>
Photolithography Steps

- Photolithography steps must be carefully followed
- General process is as below
1st Photolithography Step: Substrate Preparation

- Must prepare wafers so resist adheres to surface → wafers must be hydrophobic (hating water)
- After exposure to water vapor in some process, some of wafers becomes hydrophilic → need to Return wafer to hydrophobic by a prebake removal of water. Example 120 °C for 20 min.
- Most commercial also use adhesion promoters, eg: HMDS hexamethyldisilazane
Spin Resist Application
- Place wafer on spinner (held down by vacuum)
- Resist applied to wafer: create a resist pool
- Spin wafer at high speed for thin film
- Rotation ramp up throws off excess resist
- Resist collects at wafer edge: Edge Bead
- Hard to remove edge bead so often add mask to overexpose edge

Figure Spin coating of resist. (a) Resist puddle applied to substrate. (b) Profile view of this step, showing some details of the spin coating equipment. (c) Spinning begins, throwing off most of resist. (d) Profile view of this step, showing waves in resist and function of catch cup. (e) Spinning complete, substrate coated. (f) Profile view of coated substrate, showing edge bead. Resist thickness is greatly exaggerated.
Resist Thickness

- Resist thickness is set by:
  - primarily resist viscosity
  - secondarily spinner rotational speed

- Resist thickness in \( \mu m \) is given by \( t = \frac{kp^2}{w^{1/2}} \), 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 \( \mu m \) for commercial Si processes.

Spin Speed Curve for AZ 1500 Photoresist Products

[Graph showing spin speed curve for AZ 1500 photoresist products with different symbols for AZ 1505, AZ 1512, AZ 1518, and AZ 1529.]
## Typical Commercial Resists

- Shipley, Hoechst, Hunt, Kodak

<table>
<thead>
<tr>
<th>Resist</th>
<th>Solids content (%)</th>
<th>Viscosity</th>
<th>Specific gravity</th>
<th>Index of refraction</th>
<th>Flash point (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kodak Microresist 809</td>
<td>$32 \pm 1$</td>
<td>23</td>
<td>1.045</td>
<td>1.560</td>
<td>58</td>
</tr>
<tr>
<td>Hunt Waycoat HPR 204</td>
<td>$28$</td>
<td>17.5</td>
<td>1.036</td>
<td>1.469</td>
<td>110</td>
</tr>
<tr>
<td>Hunt Waycoat HPR 206</td>
<td>$33$</td>
<td>41</td>
<td>1.055</td>
<td>1.482</td>
<td>110</td>
</tr>
<tr>
<td>MIT Superfine IC 528</td>
<td>$28.5 \pm 0.5$</td>
<td>$5 \pm 0.5$</td>
<td>1.010</td>
<td>1.484</td>
<td>—</td>
</tr>
<tr>
<td>Tokyo OKHA OFPR-800</td>
<td>Three available</td>
<td>$20 \pm 1.5$</td>
<td></td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$30 \pm 1.5$</td>
<td></td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$50 \pm 1.5$</td>
<td></td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Shipley AZ-1370†</td>
<td>27</td>
<td>$17 \pm 1.5$</td>
<td>1.025</td>
<td>$1.64 \pm 0.01$</td>
<td>41</td>
</tr>
<tr>
<td>Shipley AZ-1350J</td>
<td>31</td>
<td>$30.5 \pm 2.0$</td>
<td>1.040</td>
<td>$1.64 \pm 0.01$</td>
<td>41</td>
</tr>
<tr>
<td>Shipley AZ-1470</td>
<td>27</td>
<td>15.7–18.3</td>
<td>1.025</td>
<td>$1.64 \pm 0.01$</td>
<td>41</td>
</tr>
<tr>
<td>Shipley AZ-1450J</td>
<td>31</td>
<td>$28.0–33.1$</td>
<td>1.040</td>
<td>$1.64 \pm 0.01$</td>
<td>41</td>
</tr>
<tr>
<td>Shipley AZ-1115</td>
<td>20</td>
<td>$24.5 \pm 1.5$</td>
<td>0.990</td>
<td>1.555</td>
<td>34</td>
</tr>
<tr>
<td>Shipley AZ-111H</td>
<td>25</td>
<td>70 ± 5</td>
<td>1.017</td>
<td>1.555</td>
<td>39</td>
</tr>
<tr>
<td>Shipley AZ-2400</td>
<td>26</td>
<td>16.7–20.0</td>
<td>1.000–1.030</td>
<td>—</td>
<td>44</td>
</tr>
</tbody>
</table>
**Wafer Track Spin Coaters**

- Modern production uses wafer track system
- Automatic, cassette to cassette spin coaters
- All steps done automatically: unloaded from cassette
- Moved to prebake oven, then cooled on cooling plate
- Loads on spinner, automatically coated, then postbake to dry
- Then reloaded into the cassette

**Figure** An automated spin-coater for photoresist.