CMOS Process - PHOTO

March, 2004 at Hsinchu

Introduction

Photolithography
• Temporarily coat photoresist on wafer
• Transfers designed pattern to photoresist
• Most important process in IC fabrication
• 40 to 50% total wafer process time
• Determines the minimum feature size
Applications of Photolithography

- Main application: IC patterning process
- Other applications: Printed electronic board, nameplate, printer plate, and *et al.*

IC Fabrication

\[
\text{EDA} \rightarrow \text{Mask or Reticle} \rightarrow \text{PR} \rightarrow \text{Chip} \quad \text{Etch}
\]

*Photolithography*

EDA: Electronic Design Automation
PR: Photoresist
Photolithography Requirements

- High Resolution
- High PR Sensitivity
- Precision Alignment
- Precise Process Parameters Control
- Low Defect Density

Photoresist

- Photo sensitive material
- Temporarily coated on wafer surface
- Transfer design image on it through exposure
- Very similar to the photo sensitive coating on the film for camera
Photoresist

**Negative Photoresist**
- Becomes insoluble after exposure
- When developed, the unexposed parts dissolved.
- Cheaper

**Positive Photoresist**
- Becomes soluble after exposure
- When developed, the exposed parts dissolved
- Better resolution

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**Negative and Positive Photoresists**

**Photoresist** → **Substrate**

Mask/reticle

**Negative Photoresist** → **Substrate**

UV light

**Exposure**

After Development

**Positive Photoresist** → **Substrate**
Photoresist Chemistry

- Start with printed circuit
- Adapted in 1950 in semiconductor industry
- Critical to the patterning process
- Negative and positive photoresist

Negative Resist

- Most negative PR are polyisoprene type
- Exposed PR becomes cross-linked polymer
- Cross-linked polymer has higher chemical etch resistance.
- Unexposed part will be dissolved in development solution.
Negative Photoresist

**Disadvantages**

- Polymer absorbs the development solvent
- Poor resolution due to PR swelling
- Environmental and safety issues due to the main solvents xylene.
Comparison of Photoresists

- PR
  Film
  Substrate

+ PR
  Film
  Substrate

Positive Photoresist

- Exposed part dissolve in developer solution
- Image the same that on the mask
- Higher resolution
- Commonly used in IC fabs
Positive Photoresist

- Novolac resin polymer
- Acetate type solvents
- Sensitizer cross-linked within the resin
- Energy from the light dissociates the sensitizer and breaks down the cross-links
- Resin becomes more soluble in base solution

Requirement of Photoresist

- High resolution
  - Thinner PR film has higher the resolution
  - Thinner PR film, the lower the etching and ion implantation resistance
- High etch resistance
- Good adhesion
- Wider process latitude
  - Higher tolerance to process condition change
Photoresist Physical Properties

- Photoresist must be able to withstand process conditions
  - Coating, spinning, baking, developing.
  - Etch resistance
  - Ion implantation blocking

Photoresist Performance Factor

- Resolution
- Adhesion
- Expose rate, Sensitivity and Exposure Source
- Process latitude
- Pinholes
- Particle and Contamination Levels
- Step Coverage
- Thermal Flow
Resolution Capability

- The smallest opening or space that can be produced in a photoresist layer.
- Related to particular processes including expose source and developing process.
- Thinner layer has better resolution.
- Etch and implantation barrier and pinhole-free require thicker layer
- Positive resist has better resolution due to the smaller size of polymer.

Photolithography Process
Basic Steps of Photolithography

- Photoresist coating
- Alignment and exposure
- Development

Basic Steps, Old Technology

- Wafer clean
- Dehydration bake
- Spin coating primer and PR
- Soft bake
- Alignment and exposure
- Development
- Pattern inspection
- Hard bake

PR coating

Development
Basic Steps, Advanced Technology

- Wafer clean
- Pre-bake and primer coating
- Photoresist spin coating
- Soft bake
- Alignment and exposure
- Post exposure bake
- Development
- Hard bake
- Pattern inspection

Track-stepper integrated system

PR coating

Development

Figure 6.5

Previous Process

Clean

Surface preparation

Hard bake

Development

Alignment & Exposure

Track system

Photo Bay

Inspection

Rejected

Approved

Photo cell

ETCH

Ion Implant

Strip PR

Etch

Rejected
Photoresist Coating

- Primer
- Photoresist
- Polysilicon
- STI
- USG
- P-Well

Soft Bake

- Photoresist
- Polysilicon
- STI
- USG
- P-Well
Alignment and Exposure

Gate Mask

Photoresist
Polysilicon
STI
USG
P-Well

Alignment and Exposure

Gate Mask

Photoresist
Polysilicon
STI
USG
P-Well
Post Exposure Bake

Development

Photoresist
Polysilicon
STI
USG
P-Well

PR
Polysilicon
STI
USG
P-Well
Hard Bake

Pattern Inspection
Photoresist Spin Coater

Soft Bake

• Evaporating most of solvents in PR
• Solvents help to make a thin PR but absorb radiation and affect adhesion
• Soft baking time and temperature are determined by the matrix evaluations
• Over bake: polymerized, less photo-sensitivity
• Under bake: affect adhesion and exposure
Soft Bake

- Hot plates
- Convection oven
- Infrared oven
- Microwave oven

Baking Systems

[Diagrams of baking systems: Hot plate, Convection oven, Microwave oven]
Hot Plates

- Widely used in the industry
- Back side heating, no surface “crust”
- In-line track system

Wafer Cooling

- Need to cool down to ambient temperature
- Water-cooled chill plate
- Silicon thermal expansion rate: $2.5 \times 10^{-6}/^\circ C$
- For 8 inch (200 mm) wafer, 1 °C change causes 0.5 µm difference in diameter
Alignment and Exposure

- Most critical process for IC fabrication
- Most expensive tool (stepper) in an IC fab.
- Most challenging technology
- Determines the minimum feature size
- Currently 0.18 \( \mu \)m and pushing to 0.13 \( \mu \)m

Alignment and Exposure Tools

- Contact printer
- Proximity printer
- Projection printer
- Stepper
Stepper

- Most popular used photolithography tool in the advanced IC fabs
- Reduction of image gives high resolution
- 0.25 μm and beyond
- Very expensive

Step-&#38;-Repeat Alignment/Exposure
Step&Repeat Alignment System

Exposure Light Source

- Short wavelength
- High intensity
- Stable

- High-pressure mercury lamp
- Excimer laser
Spectrum of the Mercury Lamp

![Graph of the Mercury Lamp spectrum](image)

### Photolithography Light Sources

<table>
<thead>
<tr>
<th>Name</th>
<th>Wavelength (nm)</th>
<th>Application feature size (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mercury Lamp</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G-line</td>
<td>436</td>
<td>0.50</td>
</tr>
<tr>
<td>H-line</td>
<td>405</td>
<td></td>
</tr>
<tr>
<td>I-line</td>
<td>365</td>
<td>0.35 to 0.25</td>
</tr>
<tr>
<td><strong>Excimer Laser</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>XeF</td>
<td>351</td>
<td></td>
</tr>
<tr>
<td>XeCl</td>
<td>308</td>
<td></td>
</tr>
<tr>
<td>KrF (DUV)</td>
<td>248</td>
<td>0.25 to 0.15</td>
</tr>
<tr>
<td>ArF</td>
<td>193</td>
<td>0.18 to 0.13</td>
</tr>
<tr>
<td><strong>Fluorine Laser</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F₂</td>
<td>157</td>
<td>0.13 to 0.1</td>
</tr>
</tbody>
</table>
Exposure Control

- Exposure controlled by production of light intensity and exposure time
- Very similar to the exposure of a camera
- Intensity controlled by electrical power
- Adjustable light intensity
- Routine light intensity calibration

Standing Wave Effect

- Interference of the incident and reflection lights
- Periodically overexposure and underexposure
- Affects photolithography resolution.
Standing Wave Intensity

- Average Intensity
- Constructive Interference, Overexpose
- Destructive Interference, Underexpose

$\lambda/n_{PR}$

Standing Wave Effect on Photoresist

$\lambda/n_{PR}$

Overexposure

Underexposure
Post Exposure Bake

• Photoresist glass transition temperature $T_g$
• Baking temperature higher than $T_g$
• Thermal movement of photoresist molecules
• Rearrangement of the overexposed and underexposed PR molecules
• Average out standing wave effect,
• Smooth PR sidewall and improve resolution

Post Exposure Bake

• For DUV chemical amplified photoresist, PEB provides the heat needed for acid diffusion and amplification.
• After the PEB process, the images of the exposed areas appear on the photoresist, due to the significant chemical change after the acid amplification
Post Exposure Bake

- PEB normally uses hot plate at 110 to 130 °C for about 1 minute.
- For the same kind of PR, PEB usually requires a higher temperature than soft bake.
- Insufficient PEB will not completely eliminate the standing wave pattern,
- Over-baking will cause polymerization and affects photoresist development

PEB Minimizes Standing Wave Effect
Wafer Cooling

- After PEB the wafer is put on a chill plate to cool down to the ambient temperature before sent to the development process
- High temperature can accelerate chemical reaction and cause over-development,
- PR CD loss

Development

- Developer solvent dissolves the softened part of photoresist
- Transfer the pattern from mask or reticle to photoresist
- Three basic steps:
  - Development
  - Rinse
  - Dry
Development: Immersion

Develop
Rinse
Spin Dry

Developer Solution

• +PR normally uses weak base solution
• The most commonly used one is the tetramethyl ammonium hydride, or TMAH ((CH₃)₄NOH).
Development

Development Profiles

Normal Development

Incomplete Development

Under Development

Over Development
Developer Solutions

Positive PR  Negative PR

Developer  TMAH  Xylene

Rinse  DI Water  n-Butylacetate

Photoresist Flow

- Over baking can causes too much PR flow, which affects photolithography resolution.

![Diagram showing PR flow during normal and over baking]
Pattern Inspection

- Fail inspection, stripped PR and rework
  - Photoresist pattern is temporary
  - Etch or ion implantation pattern is permanent.
- Photolithography process can rework
- Can’t rework after etch or implantation.
- Scanning electron microscope (SEM)
- Optical microscope

Electron Microscope

[- Diagram showing electron beam and its interaction with PR and Substrate with labels: More secondary electrons on the corners, Less secondary electrons on the sidewall and plate surface]
Pattern Inspection

• Overlay or alignment
  – run-out, run-in, reticle rotation, wafer rotation, misplacement in X-direction, and misplacement in Y-direction
• Critical dimension (CD)
• Surface irregularities such as scratches, pin holes, stains, contamination, etc.

Misalignment Cases

- Run-out
- Run-in
- Reticle rotation
- Wafer rotation
- Misplacement in x-direction
- Misplacement in y-direction
Resolution

- The achievable, repeatable minimum feature size
- Determined by the wavelength of the light and the numerical aperture of the system. The resolution can be expressed as
Resolution

\[ R = \frac{K_1 \lambda}{NA} \]

- \( K_1 \) is the system constant, \( \lambda \) is the wavelength of the light, \( NA = 2 \frac{r_o}{D} \), is the numerical aperture
- \( NA \): capability of lens to collect diffraction light

To Improve Resolution

- Increase NA
  - Larger lens, could be too expensive and unpractical
  - Reduce DOF and cause fabrication difficulties
- Reduce wavelength
  - Need develop light source, PR and equipment
  - Limitation for reducing wavelength
  - UV to DUV, to EUV, and to X-Ray
- Reduce \( K_1 \)
  - Phase shift mask
Wavelength and Frequency of Electromagnetic Wave

<table>
<thead>
<tr>
<th>RF</th>
<th>MW</th>
<th>IR</th>
<th>UV</th>
<th>X-ray</th>
<th>γ-ray</th>
<th>f (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^4$</td>
<td>$10^6$</td>
<td>$10^8$</td>
<td>$10^{10}$</td>
<td>$10^{12}$</td>
<td>$10^{14}$</td>
<td>$10^{16}$</td>
</tr>
<tr>
<td>$10^4$</td>
<td>$10^2$</td>
<td>$10^0$</td>
<td>$10^{-2}$</td>
<td>$10^{-4}$</td>
<td>$10^{-6}$</td>
<td>$10^{-8}$</td>
</tr>
</tbody>
</table>

**RF:** Radio frequency; **MW:** Microwave; **IR:** infrared; and **UV:** ultraviolet

Depth of focus

- The range that light is in focus and can achieve good resolution of projected image
- Depth of focus can be expressed as:

$$DOF = \frac{K_2 \lambda}{2(NA)^2}$$
Depth of Focus

- Smaller numerical aperture, larger DOF
  - Disposable cameras with very small lenses
  - Almost everything is in focus
  - Bad resolution
- Prefer reduce wavelength than increase NA to improve resolution
- High resolution, small DOF
- Focus at the middle of PR layer

\[ DOF = \frac{K_2 \lambda}{2(NA)^2} \]
Focus on the Mid-Plain to Optimize the Resolution

Surface Planarization Requirement

- Higher resolution requires
  - Shorter $\lambda$
  - Larger $NA$.
- Both reduces $DOF$
- Wafer surface must be highly planarized.
- CMP is required for 0.25 $\mu m$ feature patterning.
Future Trends

Summary

- Photolithography: temporary patterning process
- Most critical process steps in IC processing
- Requirement: high resolution, low defect density
- Photoresist, positive and negative
- Process steps: Pre-bake and Primer coating, PR spin coating, soft bake, exposure, PEB, development, hard bake, and inspection
- NGL: EUV and e-beam lithography
Chemically Amplified Photoresists

- Deep ultraviolet (DUV), $\lambda \leq 248$ nm
- Light source: excimer lasers
- Light intensity is lower than I-line (365 nm) from high-pressure mercury lamp
- Need different kind of photoresist

Chemically Amplified Photoresists

- Catalysis effect is used to increase the effective sensitivity of the photoresist
- A photo-acid is created in PR when it exposes to DUV light
- During PEB, head-induced acid diffusion causes amplification in a catalytic reaction
- Acid removes protection groups
- Exposed part will be removed by developer
Chemically Amplified Photoresist

Before PEB

Exposed PR + H⁺ → Heat → Exposed PR + H⁺

Protecting Groups

After PEB

Protecting Groups

Photoresist Characteristics

Summary

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Negative</th>
<th>Positive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymer</td>
<td>Polyisoprene</td>
<td>Novolac Resin</td>
</tr>
<tr>
<td>Photo-reaction</td>
<td>Polymerization</td>
<td>Photo-solubilization</td>
</tr>
<tr>
<td>Sensitizer</td>
<td>Provide free radicals for polymer cross-link</td>
<td>Changes film to base soluble</td>
</tr>
<tr>
<td>Additives</td>
<td>Dyes</td>
<td>Dyes</td>
</tr>
</tbody>
</table>