Chapter 18
LITHOGRAPHY I: PHOTORESIST MATERIALS and PROCESS TECHNOLOGY

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Patterns of IC-Structures are formed by LITHOGRAPHIC PROCESSES

- **SPIN-ON** PhotoResist-Film (PR)
- **ALIGN** Mask-Patterns to Pre-Existing Features on Wafer
- Selectively-Expose Resist (using an EXPOSURE TOOL)
- **DEVELOP** Patterns in PhotoResist
- **ETCH** material under Resist-Film uncovered during Develop-Step
- Remove (**STRIP**) the Resist
PHOTORESISTS

• **Photoresists (or Resists)** are Organic-Polymers Spun-onto Wafers and Soft-Baked to produce Films 0.5-1.0-µm thick

• **Resists Consist of 3-Components:**
  • Inactive-Resin
  • PhotoActive-Compound (PAC)
  • Solvent - used to adjust viscosity

• **After being spun-on, baked, exposed, & developed, the resulting Resist-Features should have the Specified-Width & Vertical-Sidewalls**
MATERIAL PROPERTIES OF PHOTORESISTS

- Resists must perform Two Primary Functions:
  - Precise Pattern-Formation
  - Protect the Substrate During Etch or Ion-Implant
- Resists are Formulated to Satisfy these Roles

- Categories of Resist Material-Characteristics
  - Optical-Properties
    - Resolution
    - Photosensitivity
    - Index-of-Refraction
  - Mechanical/Chemical-Properties
    - Solids-Content
    - Viscosity
    - Etch-Resistance
    - Thermal-Stability
  - Processing/Safety-Related Properties
    - Cleanliness
    - Process-Latitude
    - Shelf-Life
    - Flash-Point
    - Threshold-Limit Value (TLV)
    - Shelf-Life
POSITIVE OPTICAL-PHOTORESISTS

- $g$-line (436-nm) & $i$-line (365-nm)
  Resists are called Optical-Resists
- Positive-Resists produce Positive-Image of Mask when Irradiated (Exposed). Exposed-regions become Soluble in Developer
- Pos-PRs have better Resolution than Neg-PRs
- Base-Resin is Novolac
- PAC is DiazoNapthoQuinone (DNQ)

Absorbance-Spectrum of DNQ Sensitizer & Novolac-Resin

Photochemical-Transformations of PAC in DNQ (Positive-PR)
NEGATIVE OPTICAL-PHOTOURESISTS

- Negative-Image of Mask produced when Irradiated (Exposed)
  Unexposed-Regions remain Soluble
- Workhorse PR in Early-Days of IC Industry
  Excellent Adhesion & PhotoSpeed, Low-Cost
- But, Solvent Penetrates Unexposed-Regions of Negative-Resist
  Causes Swelling → Degrades Resolution
- Replaced by Positive-PRs when Feature-Sizes reached 2.0-µm.
  Positive-Resists have Better Resolution
- Inactive-Resin - Cyclized-Synthetic-Rubber
- PAC - Bis-Arylazide • Solvent - Aromatic Compound
- Light causes Cross-Linking in PAC

Photochemical-Transformations of PAC in DNQ-Positive-PR
CHEMICALLY-AMPLIFIED (CA) DUV-PHOTORESISTS

- When IC Feature-Sizes get \( \leq 0.25\mu m \), Optical-PRs no longer have enough Resolution \( \rightarrow \) Need DUV-CA Resists
- Also Need New Light-Source \( \rightarrow \) DUV-Excimer-Laser
- PAC in DUV-Resist relies on Catalysis (Chemical-Amplification)
  - Photo-Acid-Generator (PAG) - e.g., Onium-Salt - Decomposes into an Acid by Photon-Exposure
  - Later (during Post-Exposure-Bake - PEB) Acid-Molecules react with “Blocking” Molecules on Polymer-Chains - making them Soluble in Developer
  - AND Acid-Molecules are Regenerated so they can React-Again

Photochemical-Transformations in Chemically-Amplified DUV-PR
PROBLEMS OF CHEMICALLY-AMPLIFIED DUV-RESISTS

• Trace-Concentrations (10-ppb) of Amine in fab-air are absorbed by CA-Resist
• Amine reacts with PAG (Acid) at PR Top-Surface - Quenches Catalytic-Process there
• Surface-Region of PR is now Less-Soluble during Develop
• “T-top” Structure forms
• Filtration is used to remove Amines from air
PHOTORESIST PROCESSING-SEQUENCE

- Resist-Process Involves Sequence of Steps
- Goal: Carry-Out Each Step Precisely & Consistently
  - Wafer-to-Wafer, Day-In & Day-Out
- Resist-Processing is “Heartbeat” of IC Fabrication, with up to 25 “Beats” in Advanced ICs
VAPOR PRIMING WITH ADHESION-PROMOTER

- Resist-Films adhere poorly to many materials - especially SiO$_2$
- To Enhance Resist-Adhesion, Wafer-Surface Must Be Treated
- 3-Step-Treatment is Applied:
  1. Surface-Cleaning
  2. DeHydration-Bake
     - Makes SiO$_2$-Surface Hydrophyllic
  3. Apply Adhesion-Promoter ( Priming )
     - HMDS
     - TMSDEA
     - Applied in a Vapor-Priming Chamber
SPIN-ON RESIST-FILM

• Spin-Coating is how Resist is applied

• **Goals:** Uniform, Adherent, Defect-Free Film of Desired Thickness (0.5-1.5-µm)

• Spin-Coating Sequence
  • Dispense Liquid-Resist (2-5 cm³) onto Wafer held on Vacuum-Chuck
  • Accelerate Wafer to Final Rotation-Speed
  • Spin at constant-speed to final thickness:
    • 3000-7000 rpm
    • 30-60 sec
SOFT-BAKE OF SPUN-ON FILM

- Spun-On-Film must be Solidified (75% Solvent)
- Soft-Bake-Step Drives Solvent from Resist (5% left) & Reduces Film-Thickness by 10-20%
- Develop-Rate is strongly dependent on Solvent in Resist
  - Soft-Bake Step must be Optimized & Tightly-Controlled!
- Soft-Baking Technique: Vacuum-Hot-Plate Baking
  - Single-wafer process
  - 1-2 min/wafer
  - 100-120°C
  - Controlled to ± 0.1°C
- Prior to Soft-Bake, Resist Edge-Bead is Removed

(a) Chemical Edge-Bead Removal  (b) Hot-Plate for Soft-Baking Resist Films
EXPOSE PHOTORESIST

- Resist is next Selectively Exposed to Light, using a Mask & Exposure-Tool
- A specified Dose Irradiates the Resist-Film. It Undergoes Photochemical-Transformation that creates Latent-Image
- Undesirable Exposure-Effects also occur - which Degrade Resist-Line-Resolution
  - Reflected-Light from Wafer Beneath Resist Interferes with Incident Light: Standing-Waves
  - Off-Normal Light Reflects & Exposes Regions of Resist that should not be Exposed: Notching
Anti-Reflective Coatings (ARCs) are Applied to Wafer-Surfaces to Suppress Unwanted Exposure-Effects

- Bottom-ARCs (BARCs) Absorb-Light or Create Optical-Paths that Interfere Destructively with Reflected-Light
- Both Standing-Waves & Notching can thus be Suppressed
- BARCs can be:
  - Spin-On Organic-Films
  - CVD Inorganic-Films
POST-EXPOSURE BAKE (PEB)

Two Functions

1. In DNQ-Resists → Redistributes PAC
2. In CA-DUV-Resists → Produces Catalytic-Reactions that Create Latent-Images

• Non-Uniform Distribution of the PAC in DNQ-PR is eliminated by PEB (5-10°C higher than Soft-Bake Temp)

• In CA-DUV-Resists, PEB decomposes PAG into an Acid, which reacts with polymer to make it Soluble

Standing-Wave Patterns in Resist: (a) After Exposure; (b)-(d) After PEB vs time
DEVELOPING RESIST

- Development after Exposure (& PEB) turns Latent-Images in Resist into Final-Resist-Structures
- Goals of Development-Step:
  - No Decrease of Resist Thickness
  - Specified Pattern-Dimensions are Produced
  - Short Develop-Time
- Positive Developers -
  - Alkaline Solutions (TMAH)
- Negative Developers -
  - Organic Solvents
- Development Methods
  - Immersion
  - Spray
  - Puddle
- Develop Positive-PR
  - Novolac Resin - 200-Å/min
  - Novolac + PAC - 2-Å/min
  - Exposed - 2000-Å/min
POST-DEVELOP INSPECTION

• After Development, Wafers Inspected to ensure Resist-Process performed correctly:
  • Correct Mask
  • Critical-Dimension (CD)
  • Registration
  • Defects

• Inspection Tools:
  • Optical Microscope
  • SEM
  • Laser-System

• Automated Inspections

Wafer-Inspection Station using an Optical Microscope
RESIST-PROCESSING SYSTEMS

- Integrated Resist-Processing Systems automatically-move wafers from one tool to another (Tracks)
- These complex systems contain up to 20 individual Process-Tools
SUMMARY OF KEY CONCEPTS

• Lithography is arguably the single-most important technology in Microchip-Manufacturing
• Lithography is also the Key-Pacing-Item for developing new IC-technology generations
• Patterning Process consists of Mask-Design, Mask-Fabrication, & Wafer-Printing
• $g$ & $i$-line resists are based on DNQ-materials & are used down to 0.35-micron dimensions
• DUV-resists use Chemical-Amplification & are used for features smaller than 0.25-microns
• Aerial-Images are accurately modeled by simulation tools based on Fourier-Optics. But, models of Photoresist-Processes (Exposure, Development, & Postbake) are less accurate, because Chemistry is involved - which is not as well understood
• Etching & Final-Stripping of Resist are Discussed Chaps. 21 & 22