Fabrication Methods
Methods for Fabrications

- Top down Approach
- Bottom up Approach
Planar technology

- Build on a substrate (typically silicon Wafer)
Top Down - Fabrication Techniques

Planar technology
- Build on a substrate (typically silicon Wafer)
- Build by layers
- Thickness can be much smaller than lateral dimensions
- May “add” materials
Planar technology
- Build on a substrate (typically silicon Wafer)
- Build by layers
- Thickness can be much smaller than lateral dimensions
- May “add” or “remove” materials
Bottom Up Approach

- Chemical and statistical forces can create systems with “natural” scale in the sub-100 nm
- Self-assembly
- Energetic and statistical forces cause crystalline order in solids, can spontaneously form arrays of highly ordered nanostructures
- Examples:
  - Quantum dots
  - Langmuir-Blodgett films
Top Down: Types of Lithography

• Hard Lithography

• Soft Lithography
Hard Microfabrication

Discussion is mainly on
Silicon and related Materials
How do you fabricate a device?

• What do we need?
  • Materials?
  • Tools?
  • Processes?
  • Architecture?
Device Fabrication

What is needed:

• A material to create the device
• A process to follow
• Process Characteristics
  • Reproducible
  • Reliable
  • Scalable
  • Inexpensive
  • Environmentally friendly
• Tools to create the device
• Tools to examine and verify the device
• Packaging
• Integration methods and tools
Device Fabrication

- A material to create the device -- Silicon
- A process to follow -- Micromachining
- Process Characteristics
  - Reproducible
  - Reliable
  - Scalable
  - Inexpensive
  - Environmentally friendly
- Tools to create the device - Lithography
- Tools to examine and verify - Microscopy
- Packaging
- Integration methods and tools
Micromachined Materials

Device Material -- Substrates

- **Silicon**
- GaAs
- Other elemental or compound semiconductors
- Metals (bulk and foils)
- Glasses
- Quartz
- Sapphire
- Ceramics
- Plastics, polymers and other organics
Additive Materials

- Silicon (amorphous, polycrystalline, epitaxial)
- Silicon compounds (oxides, nitrides, carbides, …)
- Metals and metal compounds
- Glass
- Ceramics
- Polymers and other organics
- Biomaterials
Fabrication Processes

Reference materials:
Chapter 1 in Madou’s Book
In Particular pages 1-31
Process needs to be one in a “Cleanroom”

Small Features require “cleanroom” environment

No particles or dust!

Different Classes for different applications
Process to Create Patterns

Design
Process to Create Patterns

- Design
- Pattern Generation
- Wafer
Process to Create Patterns

- Design
- Pattern Generation
- WRITE the Pattern
- Wafer
Process to Create Patterns

Design

Pattern Generation

Direct Write

Mask

Wafer
Process to Create Patterns

Design

Pattern Generation

Direct Write

Mask

Light

Light

Ions

Ions

Electrons

Electrons

X-ray

Wafer
Direct Write
Process to Create Patterns

Design

Pattern Generation

Direct Write

Mask

Light

Ions

Electrons

Wafer

Electrons

Ions

X-ray

Light
Direct Write Hardware

- No mask is needed
- Higher end systems use Direct Write on Wafer (DWW) exposure systems
  - Excimer lasers: geometries down to 1 - 2 \( \mu \text{m} \)
  - Electron beams: geometries down to 0.1 - 0.2 \( \mu \text{m} \)
  - Focused ion beams: geometries down to 0.05 - 0.1 \( \mu \text{m} \)

But, this is a serial process

- wafer cycle time is proportional to the beam writing time, the smaller the spot, the longer it takes
Writing Information by Lithography
Writing Information by Lithography

Several fabrication methods produce sub-100 nm structures
Process to Create Patterns

1. Design
2. Pattern Generation
3. Direct Write
4. Mask
5. Light
6. Ions
7. Electrons
8. Wafer
9. X-ray
Lithographic Technologies

- Submicron Technology
  - Electron
  - Ion
  - Photon
- Nanotechnology
- Atom (Angstrom) Technology

- EB
- FIB
- g, i-line, Excimer, SR
- Si ULSI
  - 1 Gb
  - 256 Mb
  - 64 Mb
  - 16 Mb
  - 4 Mb

- Mesoscopic Devices
  - Quantum Dot
- Sub-0.1μm CMOS
- SET
- Atom-Device

- Hemoglobin
- Benzene
- Insulin
- c-c bond

Scale:
- 1000
- 100
- 10
- 0.1
Photolithography

- A process to transfer a pattern that is created on a “photomask” onto a “photoresist” thin film
- Photo masks are generated by an optical system or an electron system
Pattern Definition

• The desired pattern is defined on a mask
• The patterned mask is opaque to “light” in the shape of the pattern
• Light is projected through this mask to form an image on onto a resist layer (light-activated material)
• The light-activated material (photoresist) defines the pattern that will be transferred to the substrate
• Light: visible -- UV, electron or x-ray beams
Writing Information by Lithography

• Photoresist is spun on a clean substrate – create a nearly uniform layer usually a few hundred nm thick

• The substrate is then baked to drive off the carrier solvent, leaving a hard layer of polymer

• The resist can be removed either with solvents or etching
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
Overview: Device Fabrication

- Surface Preparation
- Coating (Spin Casting)
- Pre-Bake (Soft Bake)
- Mask Alignment
- Exposure
- Development
- Post-Bake (Hard Bake)
- Processing Using the Photoresist as a Masking Film
- Stripping
- Post Processing Cleaning (Ashing)
Silicon Wafer
Fabrication and Characteristics
Atoms are arranged with a certain periodicity
Each side has a length \( (a) \)
There are also Hexagonal structures
Material Structure

Miller indices for a simple Cubic Crystal

[001] [010] [100]
Material Structure

Miller indices for a simple Cubic Crystal
Material Structure

Miller indices for a simple Cubic Crystal

[010]
[001]
[100]
[010]
Material Structure

Miller indices for a simple Cubic Crystal

[001]
[010]
[100]
Crystallographic Surfaces for a simple Cubic Crystal
Silicon Structure
Wafer Preparation
Wafer Fabrication

Czochralski Crystal Growth
Float Zone Process
Gradual pull - from a rotating silicon seed
Wafer Fabrication

Wafers are cut from the ingot:
Sizes varied. The most common now is 8” and 12”
Wafer Preparation

Contaminants must be eliminated

- Dust
  - Atmospheric dust: clean room
  - Scribing or cleaving: laser scribing
  - Abrasive particles from lapping
- Photoresist residue: Oxygen plasma ashing
- Bacteria: DI water system
- Films
  - solvent residue
  - H₂O residue
  - oil and silicone
Particle Size Distribution in a Cleanroom

Different Classes for different applications
Wafer Preparation

- Cleanness promotes adhesion
- Intermediate layer - strong bond with substrate and functional layer
- Noble metal adhere well to other metals, but not to transition metals
- Ti, Cr oxides form very stable oxides
- Metals do not stick well with polymers
- Polymers with polar functional group adheres to metal
Wafer Cleaning
Cleaning Steps

Standard degrease

- Several steps of 2-5 minutes of soak in: Acetone, Methanol, DI water with ultrasonic agitation
- spin rinse dry; and N₂ blow off dry

Aggressive degrease

- Soak in 1,1,1-trichloroethane (TCA) or trichloroethylene (TCE) prior to acetone

Hazards:

- TCE is carcinogenic; 1,1,1-TCA is less so
- Acetone is flammable
- Methanol is toxic by skin adsorption
Polished Wafers
Silicon Oxides
Silicon Oxides: $\text{SiO}_2$

**Uses**
- Diffusion masks
- Surface passivation
- Gate insulator (MOSFET)
- Isolation, insulation

**Formation:**
- Grown / “native”
  - Thermal: “highest” quality
  - Anodization
- Deposited:
  - CVD, evaporate, sputter
Thermal Oxidation of Silicon

Thermal Oxidation is at high temperatures
(900 - 1200 °C)

Two main processes:

- **Dry Oxidation**
  \[
  \text{Si} + \text{O}_2 \rightarrow \text{SiO}_2 \quad @ 1 \text{ atm, 1000 °C}
  \]

- **Wet Oxidation**
  \[
  \text{Si} + 2\text{H}_2\text{O} \rightarrow \text{SiO}_2 + 2\text{H}_2
  \]

- Dry oxidation produces a better (more dense) oxide as compared to wet oxidation.
Method for Creating Features
Si Etching and Characteristics
Etchant Properties

Selectivity to masking layer(s)
Selectivity to metals (e.g., Al)
**Etch rate**

Anisotropy (crystal plane selectivity)
Surface roughness
Control of etch parameters
Etching Plans

(100)

(110)

(111)
Etching

- Silicon etching: different rates

Anisotropic

Isotropic
Isotropic and Anisotropic Etching

- Isotropic is diffusion limited
- Anisotropic are rate limiting
- Isotropic is used for removing work-damaged areas, remove roughness
- \( \text{Si} + \text{HNO}_3 + 6 \text{HF} \rightarrow \text{H}_2\text{SiF} + \text{HNO}_2 + \text{H}_2\text{O} + \text{H}_2 \)
  \( \text{H}_2\text{SiF} \) is water soluble
- Anisotropic wet etching creates geometric shapes
  \[
  \text{Si} + 2\text{OH}^- \rightarrow \text{Si(OH)}_2^{2+} + 4\text{e}^- \\
  4 \text{H}_2\text{O} + 4\text{e}^- \rightarrow 4\text{OH}^- + 2\text{H}_2 \\
  \text{Si(OH)}_2^{2+} + 4\text{OH}^- \rightarrow \text{SiO}_2(\text{OH})_2^{2+} + 2\text{H}_2\text{O}
  \]
  so: \( \text{Si} + 2\text{OH}^- + 2\text{H}_2\text{O} \rightarrow \text{Si(OH)}_2^{2+} + 2\text{H}_2 \)
Anisotropic Si Etchants

**Alkali Hydroxides (KOH, NaOH, etc.)**
very smooth walls, can use isopropyl alcohol to increase selectivity (111) vs. (100), attacks aluminum, oxide etches somewhat, nitride good mask.

**Ethylene Diamine Pyrochatechol (EDP)**
similar to KOH but much more toxic, does not attack metals (even Al in some cases) nor oxide.

**Tetramethyl Ammonium Hydroxide (TMAH)**
similar to EDP but safer, in some cases will not attack Al, can be masked with oxide.

**HNA**
HF + HNO₃ + Acetic acid
KOH Etching

Etching Rate: Varies with Temperature and Concentration

(110) > (100) > (111)

(100) > (110) > (111)
Anisotropic Etching
Dopant-Etch Stops

Many anisotropic etchants slow down markedly at high boron concentrations (\(10^{20} \text{ cm}^{-3}\)). Can diffuse or grow boron-containing epitaxial silicon.

Figure 9. Bulk micromachining along crystallographic planes.
Etching SiO$_2$ and SiN$_4$

- CHF$_3$ removes Polysilicon and Si oxides
- SiO$_2$: HF
- SiN$_4$: HF, H$_3$PO$_4$
Masking with Photoresist
Creating a Mask

- The mask is the “stencil” of the required pattern
- CAD systems are used to create the patterns
- Pattern is created by photo projection exposure
Masks

Create master patterns are transferred to wafers

- Both glass and quartz are used
  - Photographic emulsion on soda-lime glass (cheap)
  - Fe$_2$O$_3$ on soda-lime glass
  - Cr on soda-lime glass
  - Cr on quartz glass (expensive, used with deep UV)

Polarity

- “light-field”: mostly clear, drawn feature are opaque
- “dark-field”: mostly opaque, drawn feature are clear
Photoresist
Materials and Application
Photoresist

• Photoresist: Radiation-sensitive compound
• Requirements
  • Etch resistance
  • Thermal stability
  • Ease of development
  • Good adhesion
• Difficult to achieve in the UV region
Components of Photoresist

Conventional optical photoresist has **three components**

- 1) Matrix material
- 2) Sensitizer
- 3) Solvent

- Sensitizer (also called inhibitor)
- Photoactive compound (PAC) - Insoluble without radiation - preventing resist to be dissolved
- Take photochemical reaction upon exposing to light, transferring from dissolution inhibitor to dissolution enhancer
Photoresist -Types

• Positive resists
  • Exposed region becomes more soluble
  • Patterns are the same as those on the mask

• Negative resists
  • Exposed regions become less soluble
  • Patterns are the reverse of the mask patterns
Positive and Negative Photoresist

**Positive Resist**
The solubility of exposed regions is much higher than the unexposed region in a solvent (developer) produces a positive image of the mask.

**Negative Resist**
The solubility of exposed regions is much lower than the unexposed region in developer produces a negative image of the mask.
## Commercial Photoresist

<table>
<thead>
<tr>
<th>Lithography</th>
<th>Name</th>
<th>Type</th>
<th>Sensitivity</th>
<th>$\gamma$</th>
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<tr>
<td>Optical</td>
<td>Kodak 747</td>
<td>Negative</td>
<td>9 mJ/cm$^2$</td>
<td>1.9</td>
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<td></td>
<td>AZ-1350J</td>
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<td>90 mJ/cm$^2$</td>
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<td></td>
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<td>140 mJ/cm$^2$</td>
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<td>e-beam</td>
<td>COP</td>
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<td>0.3 $\mu$C/cm$^2$</td>
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<tr>
<td></td>
<td>GeSe</td>
<td>Negative</td>
<td>80 $\mu$C/cm$^2$</td>
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<td></td>
<td>PBS</td>
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<td>1 $\mu$C/cm$^2$</td>
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<td>PMMA</td>
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<td>X-ray</td>
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<td>DCOPA</td>
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<td></td>
<td>PMMA</td>
<td>Positive</td>
<td>1000 mJ/cm$^2$</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Applying the Photoresist
Spin Coating
Photoresist Spin Coating

- Wafer is held on a spinner chuck by vacuum
- Resist is coated to uniform thickness by spin coating
- Typically 3000-6000 rpm for 15-30 seconds
- Resist thickness is set by
  - Resist viscosity
  - Spinner rotational speed
- Resist thickness is given by
  \[ t = \frac{kp^2}{\sqrt{w}} \]
  - \( k \) = spinner constant, typically 80-100
  - \( p \) = resist solids content in percent
  - \( w \) = spinner rotational speed in rpm/1000
Spin Coating Machine
Wafer Baking
Pre-Bake

• Pre-bake
  • evaporate coating solvent
  • Increase the density of the resist after spin coating.

• Typical thermal cycles
  90-100°C for 20 min. in a convection oven
  75-85°C for 45 seconds on a hot plate

• Microwave heating and IR lamps are also used in production lines
Hard Bake

- Removes all traces of the coating solvent or developer.
- Harden the developed photoresist prior to the processing steps - e.g. metal deposition, acid etching
- Main parameter is the plastic flow or glass transition temperature
- Some shrinkage of the photoresist may occur; introduces some stress into the photoresist
Photoresist Removal

Simple solvents are generally sufficient for none hard baked photoresists

- Positive photoresist
  - acetone
  - trichloroethylene (TCE)
  - phenol-based strippers (Indus-Ri-Chem J-100)

- Negative photoresist:
  - methyl ethyl ketone (MEK), CH\(_3\)COC\(_2\)H\(_5\)
  - methyl isobutyl ketone (MIBK), CH\(_3\)COC\(_4\)H\(_9\)

- Plasma etching with O\(_2\) is effective for removing organic polymer debris

- Shipley 1165 stripper (contains n-methyl-2-pyrrolidone) - effective on hard baked resist
Exposure
Exposure Methods

Contact Aligner:
- UV lamp
- Lens
- Mask
- PR
- Substrate wafer

Operating modes:
- Contact for exposure
- Separate for alignment

Examples:
- Kaspar 17A
- Oriel
- Karl Suss MJB3

Proximity Aligner:
- Less wear on mask
- Poorer image than from contact aligner

Examples:
- Kaspar-Cobilt

Projection Aligner:
- Imaging optics in between the mask and the wafer

Examples:
- Perkin-Elmer Micralign
Light Transmission Near the Edges

\[ d = \text{the thickness of the photoresist} \]
\[ 2b = \text{the minimum pitch of line spacing} \]
\[ Z = \text{the spacing} \]

For Contact Imaging:
\[ 2b = 3 \sqrt{(0.5 \, d \, \lambda)} \]

For Proximity Imaging:
\[ 2b = 3 \sqrt{\lambda (Z + 0.5 \, d)} \]
Other Exposing Beams

Electron and X-rays Beams
Other Methods
Electron-beam lithography

- The most common method to create very small features
- Electron beam exposure alters the chemistry of the resist instead of light exposure.
Schematic of E-Beam System

- Electron Emitter
- 1st Condense Lens (Electrostatic or magnetic)
- Blanking Electrode
- 2nd Condense Lens
- Beam Limiting Aperture
- Deflector
- Final Lens
- Substrate
E-Beams and X-ray Lithography

- DoF and resolution are improved with short wave illumination
- Throughput is an issue. So, these are used to create the masks
- Early 80s, deep UV (248 nm and 193 nm) was used with ArF and KrF excimer lasers
- X-ray required using synchrotron generators
Electron-Beam Lithography (EBL)

- Diffraction is not a limitation on resolution
- Resolution depends on beam size, can reach \( \sim 5 \text{ nm} \)
- Two applications:
  - Direct Writing
  - Projection (step and repeat)

Issues:
- Throughput of direct writing is very low – research tool or low pattern density production
- Projection stepper is in development stage. Mask making is the biggest challenge.
- Back-scattering and second electron reduce resolution with dense patterns
E-Beam Issues - Proximity Effect

MTF is greatly reduced at high pattern density - requires

• Use thin resist and thin substrate
• Adjust acceleration voltage
• Split pattern into several writings using different doses
• Adjust pattern size and shapes
• Adjust dose level to compensate scattering
Reactive Ion Etching
Reactive Ion Etching (RIE and DRIE)

**RIE**: chemical etching is accompanied by ionic bombardment

- Bombardment opens areas for reactions
- Ionic bombardment:
- No undercutting since side-walls are not exposed
Deep Reactive Ion Etching (DRIE)

DRIE uses lower energy ions --> less damage and higher selectivity

In this process, etch depths of hundreds of microns can be achieved with almost vertical sidewalls
DRIE

BOSCH Patent

Locus Nova
Thin Film
Deposition and Etching
Material
Deposition and Etching

Reference: Madou’s Book
Deposition: page 72
Si Structure: page 187
Etching: Pages 210 -222
Deposition
Deposition Methods

- **Evaporation**
  - Thermal
  - E-beam
  - Flash
- **Sputtering**
- **Chemical Vapor Deposition (CVD)**
  - Low pressure
  - Plasma Enhanced
- **Epitaxy**
  - Vapor
  - Liquid
  - Molecular Beam
Deposition From Gas Phase

Morphology of generated surface depends on usability

- Low mobility: unordered arrangement, amorphous structure.
- High mobility: condensation and crystallization centers – multigrain column-like structure
- Low deposition rate: dendritic structure – sponge like
- Epitaxial: single crystalline surface requires preconditioning - seed surface
Evaporation

- Heat a source in vacuum: material evaporates
- (source – substrate distance)
- Mechanical Shutter

Heated material

Vacuum $10^{-6}$ to $10^{-10}$ torr
Support Materials

Must Stand the temperature need to evaporate materials

• Tungsten melting point = 3380 °C
• Alumina (Al₂O₃) melting point = 3700 °C
• Boron Nitride melting point = 2500 °C
Resistance Heaters
Evaporated Materials

Common ones

• Au, Ag, Al, Sn, Cr, Sb, Ge, In, Mg, Ga,..
• CdS, PbS, CdSe, NaCl, KCl,…
E-Beam System