Microfabrication is the process for the production of devices in the submicron to millimeter range.

Machining of silicon and other ceramics is similar to integrated circuit fabrication.

Polymer microfabrication incorporates thick resist lithography, laser ablation, photopolymerization, thermoplastics and "soft" lithography (microcontact printing (µCP), PDMS (polydimethylsiloxane) replica molding (REM), microtransfer molding and nanolithography.
Micromachining Materials…

- MEMS devices are made from the same materials used for microelectronics, including:
  - Single crystal silicon wafers.
  - Deposited layers of polycrystalline silicon (polysilicon) for resistive elements.
  - Gold, aluminum, copper and titanium for conductors.
  - Silicon oxide for insulation and as a sacrificial layer (to allow release of moving parts).
  - Silicon nitride and titanium nitride for electrical insulation and passivation.
- The silicon materials have high strength at small scales which allows higher strain levels and less susceptibility to damage and fracture.

In Contrast to Polymer Microfabrication…

- Thick resist lithography - ie. SU-8.
- Laser ablation with excimer or Nd:YAG lasers.
- 3D Photopolymerization (Also useful in bioprinting.)
- Thermoplastic injection molding & 3D FDM layer by layer printing.
  - Thermoplastic polymers are heated above their glass transition temperature Tg.
- Soft Lithography:
  - Microcontact printing (µCP)
  - PDMS (polydimethylsiloxane) replica molding (REM).
  - Dow Corning Sylgard 184 PDMS (reagent and hardener).
  - Microtransfer molding.
  - Micromolding in capillaries.
  - Solvent-assisted micromolding.
- Nanolithography.

Microelectronics Revolution
From Molten Silicon to IC Chips…

Silicon wafer diced into integrated circuits (DIP and SMD)

Electronic Grade Silicon (EGS)…

1. Quartzite is placed in a furnace with carbon releasing materials, and reacts as shown, forming metallurgical grade silicon (MGS):

\[ \text{SiO}_2(s) + 2\text{C}(s) \underset{heat}{\rightarrow} \text{Si}(s) + 2\text{CO}(g) \]

2. MGS is then treated with hydrogen chloride to form trichlorosilane:

\[ \text{Si} + 3\text{HCl} \underset{heat}{\rightarrow} \text{SiHCl}_3(g) + \text{H}_2(g) \]

3. Next fractional distillation reduction with hydrogen produces electronic grade silicon (EGS):

\[ \text{SiHCl}_3(g) + \text{H}_2(g) \underset{heat}{\rightarrow} \text{Si}(s) + 3\text{HCl}(g) \]

Cubic Crystal System – Unit Cells…

Crystalline silicon forms a covalently bonded structure and coordinates itself tetrahedrally (bottom). Silicon (and germanium) crystallize as two interpenetrating FCC sublattices.
**Silicon Crystal Structure**

- Planes and directions are defined using $x$, $y$, $z$ coordinates.
- $(111)$ direction is defined by a vector of 1 unit in $x$, $y$, and $z$.
- Planes defined by “Miller indices” – Their normal vector (reciprocals of intercepts of plane with the $x$, $y$, and $z$ axes).

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**Miller Indices…**

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**Basic Surface Micromachining Steps**
SiO₂ is a silicon atom surrounded tetrahedrally by four oxygen atoms.

Structure may be crystalline (quartz) or amorphous (thermal deposition).

Images courtesy of Gardner JW.
The chemical reaction that occurs is:

\[ \text{Si (solid)} + \text{O}_2 \text{ (gas)} \rightarrow \text{SiO}_2 \text{ (solid)} \]

Dry oxidation at 900-1500°C in pure oxygen produces a better oxide, with higher density than steam oxidation.

Thermal silicon oxide is amorphous.

Thermal Oxidation...

Choices of oxygen, steam or inert gas.

Spin-Casting Resist...

For spinning positive & negative resists, glass, and i.e. PMMA. Heating plates for soft, hard and dehydration baking.


Both “positive” and “negative” resists can be chosen, depending on whether it is desirable to have the opaque regions of the mask protect the resist, and hence the substrate below, vs. having the transparent regions protect the resist when exposed to UV.

Areas where the resist is removed will ultimately be etched. Remember that “positive protects.”

Positive resists include poly(methyl methacrylate) (PMMA), and a two part system, diazoquinone ester plus phenolic novolak resin (DQN).

Negative resists include SU-8, bis(aryl)azide rubber and Kodak KTFR.

Critical Dimension – this is the smallest feature size to be produced.

Resolution – smallest line width to be consistently patterned.

Mask Fabrication

Unexposed Masks (Resist is Pre-applied)
Contact Alignment…

UV Exposure at 350-500 nm…

Cannon Stepper (Alternative to Contact Aligner)…

Projection system. Resolution down to .5 micron, compared to about 3 microns for the contact aligner.
**Etching Methods**

- **Subtractive processes:**
  - Dry etching (plasma),
  - Glow discharge methods (diode setups):
    - Plasma etching (PE),
    - Reactive ion etching (RIE),
    - Physical sputtering (PS),
  - Ion beam methods (triode setups):
    - Ion beam milling (IBM),
    - Reactive ion beam etching (RIBE),
    - Chemical assisted ion beam etching (CAIBE),
  - Deep Reactive Ion Etching (DRIE),
  - Wet etching (chemical liquids).
Energy, Vacuum & Directionality…

- **Plasma Etching** occurs at relatively lower energy and higher pressure (less vacuum), and is isotropic, selective and less prone to cause damage.
- **Reactive Ion Etching** is more middle ground in terms of energy and pressure, with better directionality.
- **Physical Sputtering** and **Ion Beam Milling** rely on physical momentum transfer from higher excitation energies and very low pressures, and result in poor selectivity with anisotropic etching and increased radiation damage.

Plasma Etching (PE)…

Reactive Ion Etching (RIE)…
Reactive Ion Etcher...

The system is designed to etch silicon, silicon nitride, silicon oxide, photoresists, other allowed organics and semiconductor materials.

Gases for the RIE...

Etchant gases available:
- Argon (Ar)
- Trifluoromethane (CHF₃)
- Tetrafluoromethane (CF₄)
- Oxygen (O₂)
- Sulfur hexafluoride (SF₆)
- Methanol (CH₃OH)

Deep Reactive Ion Etching (DRIE)

Sulfur hexafluoride (SF₆) is flowed during the etching cycle and octafluorocyclobutane (C₈F₈) during the sidewall protection cycle.
Physical Sputtering

- Bombarding a surface with inert ions (e.g. argon) has an effect related to the kinetic energy of the incoming particles.
- At energies < 3 eV (electron volts) particles are simply reflected or absorbed.
- At surface energies between 4-10 eV some surface sputtering occurs.
- At surface energies of 10-5000 eV momentum transfer causes bond breakage and ballistic material ejection across the reactor to the collecting surface. A low pressure and long mean free path are necessary to prevent the material from redepositing.
- Implantation (doping) occurs at 10,000-20,000 eV.

Sputter Yield...

- Sputter yield is the number of atoms removed from the surface per incident ion.
- Sputter yield depends on the following:
  - Incident ion energy (max yield 5-50 keV).
  - Mass of the ion
  - Mass of the substrate atom to be etched away.
  - Crystallinity and crystal orientation of the substrate.
  - Temperature of the substrate
  - Partial pressure of oxygen in the residual gas.
Summary

- **Microfabrication** is the process for the production of devices in the submicron to millimeter range.
- **Micromachining** of silicon and other ceramics is similar to integrated circuit fabrication.
- **Crystalline silicon** forms a covalently bonded structure and coordinates itself *tetrahedrally* (bottom). Silicon (and germanium) crystalize as two interpenetrating FCC sub lattices.

Surface micromachining concepts discussed:
- Mask creation,
- Silicon wafer preparation,
- Thin-films deposition such as SiO₂,
- Resist (positive or negative) application,
- UV exposure and development,
- Etching methods (subtractive processes),
- Resist stripping,
- Inspection with profilometer.

- **Dicing and Wire Bonding**