Introduction to BioMEMS & Medical Microdevices

Silicon Microfabrication Part 1 – Lithography & Etching

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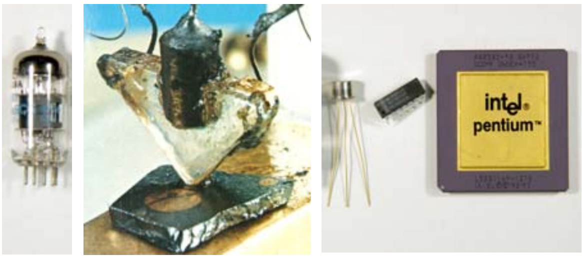
Microfabrication…

1. Microfabrication is the process for the production of devices in the submicron to millimeter range.
2. Micromachining of silicon and other ceramics is similar to integrated circuit fabrication.
3. 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.

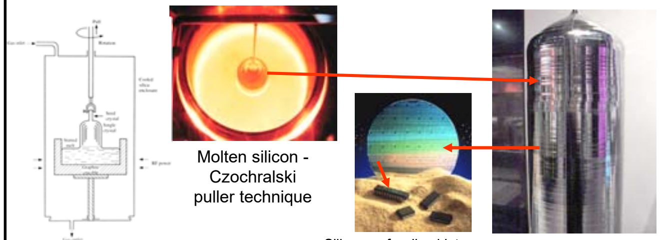
Micromachining Materials…

- 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 (for example, to allow *release* of moving parts, create cantilever, bridge and other 3D structures).
  - 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.

Microelectronics Revolution



From Molten Silicon to IC Chips…



Molten silicon - Czochralski puller technique

Silicon wafer diced into integrated circuits (DIP and SMD)

Single crystal silicon boule

Electronic Grade Silicon (EGS)…

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

$$Si0_2(s) + 2C(s) \xrightarrow{heat} Si(s) + 2CO(g)$$

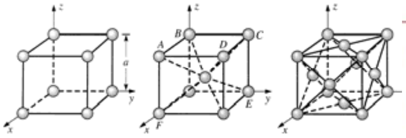
2. MGS is then treated with hydrogen chloride to form trichlorosilane:

$$Si + 3HCl \xrightarrow{heat} SiHCl_3(g) + H_2(g)$$

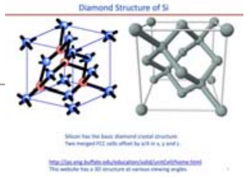
3. Next fractional distillation reduction with hydrogen produces electronic grade silicon (EGS):

$$SiHCl_3(g) + H_2(g) \xrightarrow{heat} Si(s) + 3HCl(g)$$

Cubic Crystal System – Unit Cells…



(a) SC (b) BCC (c) FCC



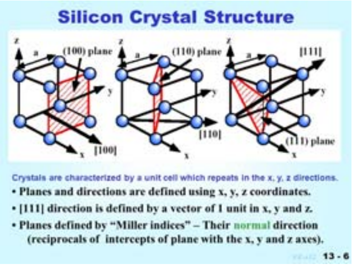
Diamond Structure of Si

Silicon has the basic diamond crystal structure.
Two merged FCC cells offset by a/4 in x, y and z.

http://jas.eng.buffalo.edu/education/solid/unitCell/home.html
This website has a 3D structure at various viewing angles.

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

Image courtesy of Sze, SM.



Silicon Crystal Structure

Crystals are characterized by a unit cell which repeats in the x, y, z directions.

- 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 direction (reciprocals of intercepts of plane with the x, y and z axes).

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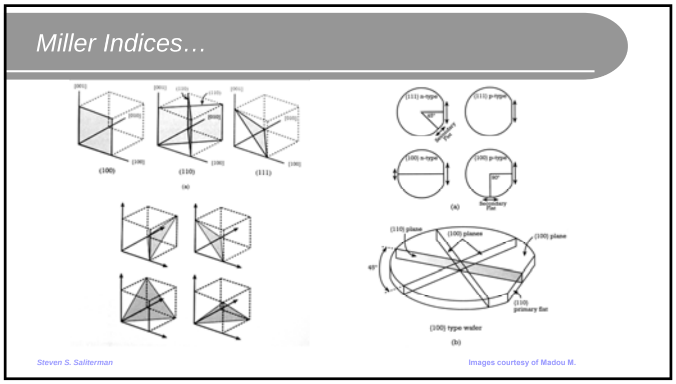

Miller Indices…

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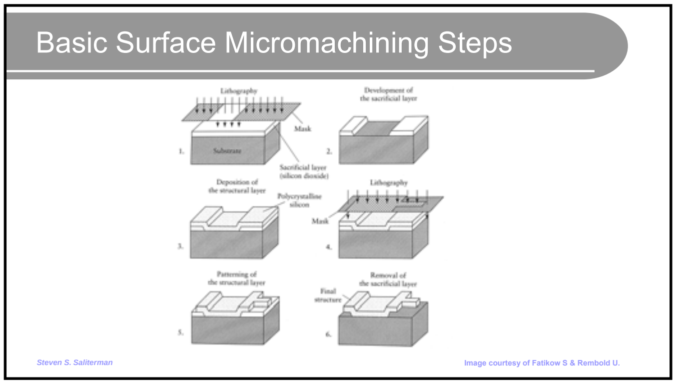
Images courtesy of Madou M.



Basic Surface Micromachining Steps

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Image courtesy of Fatikow S & Rembold U.

Silicon Wafer Preparation

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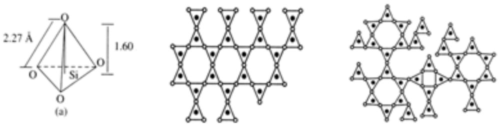
RCA Cleaning Bench…

Thermal Silicon Oxide…

- SiO_2 is a silicon atom surrounded tetrahedrally by four oxygen atoms.
- Structure may be crystalline (quartz) or amorphous (thermal deposition).



Images courtesy of Gardner JW.

Thermal Silicon Oxide Methods…

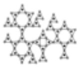
- The chemical reaction that occurs is:

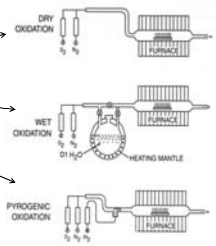
$$\text{Si (solid)} + \text{O}_2 \text{ (gas)} \xrightarrow{900\text{–}1200°C} \text{SiO}_2 \text{ (solid)}$$

and

$$\text{Si (solid)} + 2\text{H}_2\text{O (gas)} \rightarrow \text{SiO}_2 \text{ (solid)} + 2\text{H}_2 \text{ (gas)}$$

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





Images courtesy of Madou M.

Thermal Oxidation Furnace…

Choices of oxygen, steam or inert gas.

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Spin-Casting Resist…

For spinning positive & negative resists, glass, and i.e., PMMA.

Heating plates for soft, hard and dehydration baking.

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Resist Types…

- 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."

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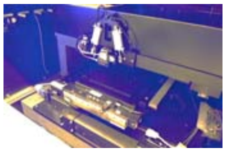
- Positive resists include poly(methyl methacrylate) (PMMA), and a two-part system, diazoquinone ester plus phenolic novolak resin (DQN).
- Negative resists include SU-8, bis(aryl)azide rubber and Kodak KTFR.
- Critical Dimension - this is the smallest feature size to be produced.
- Resolution – smallest line width to be consistently patterned.

Mask Fabrication

The Heidelberg

Unexposed Masks
(Resist is Pre-applied)



Mask Carriage

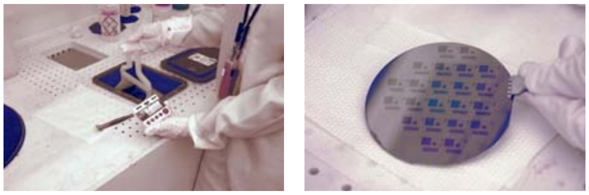
Contact Alignment…

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.

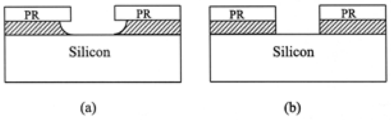
Developing the UV Exposed Wafer…



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).

Etching Profiles…



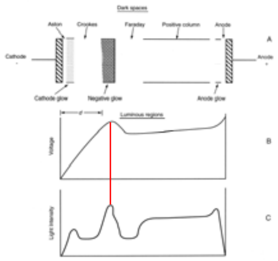
Isotropic Etching Anisotropic Etching

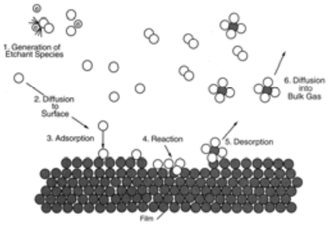
Image courtesy of Ziaie B.

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)…





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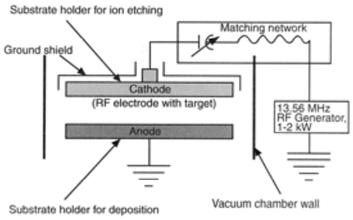
Reactive Ion Etching (RIE)…



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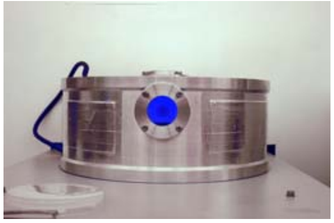
Reactive Ion Etcher…



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

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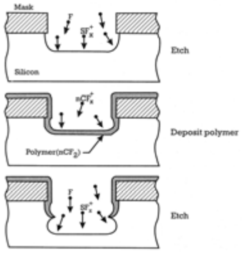
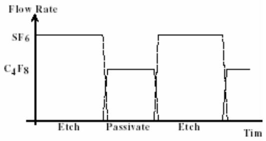
Gases for the RIE…

Etchant gases available:
Argon (Ar),
Trifluoromethane (CHF_3)
Tetrafluoromethane (CF_4)
Oxygen (O_2)
Sulphur Hexafluoride (SF_6)
Methanol (CH_3OH)

Deep Reactive Ion Etching (DRIE)





Sulfur hexafluoride (SF_6) is flowed during the etching cycle then Octafluorocyclobutane (C_4F_8) during the sidewall protection cycle.

Left: Madou M, *Fundamentals of Microfabrication: The Science of Miniaturization, 2nd ed.* CRC Press, Boca Raton, FL (2002).
Right: Reis, A. & R. Bhattacharya, Deep Reactive Ion Etching (DRIE), ENEE416, 3/16/2004.

Deep Reactive Ion Etcher…

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.

Ion Beam Milling (IBM)…

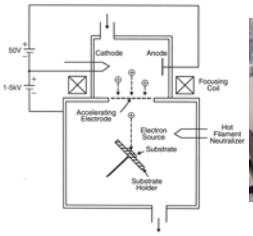


Image courtesy of Madou M.

Resist Stripping…

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Profilometry…

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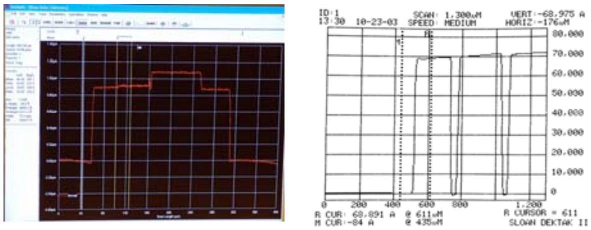
Profilometer Screen Display…



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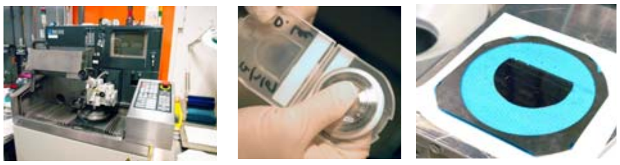
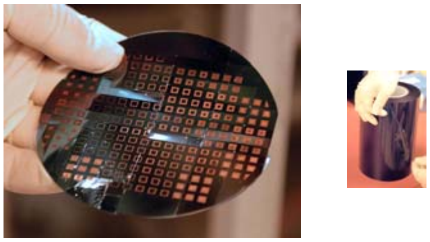
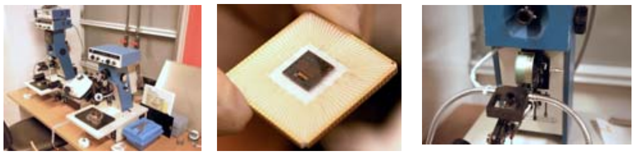
Wafer Cutting - Dicing Chips…





Wire Bonding…



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.

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- Surface micromachining concepts discussed:
  - Mask creation,
  - Silicon wafer preparation,
  - Thin-films deposition such as $SiO_{2,}$
  - Resist (positive or negative) application,
  - UV exposure and development,
  - Etching methods (subtractive processes),
  - Resist stripping,
  - Inspection with profilometer.
- Dicing and Wire Bonding

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