

Silicon Micro- & Nanofabrication 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 (μ CP), PDMS (polydimethylsiloxane) replica molding (REM), microtransfer molding and nanolithography.

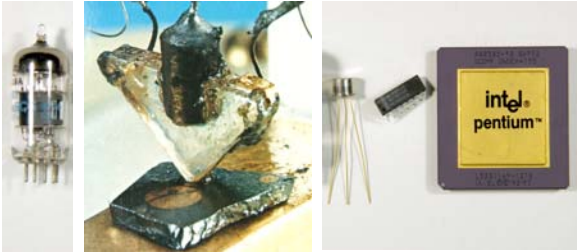
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Micromachining Materials...

- 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.

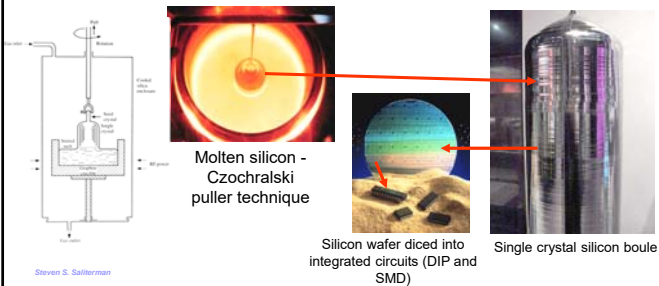
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Microelectronics Revolution



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From Molten Silicon to IC Chips...



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Electronic Grade Silicon (EGS)...

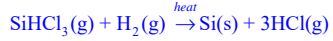
1. Quartzite is placed in a furnace with carbon releasing materials, and reacts as shown, forming metallurgic grade silicon (MGS):



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

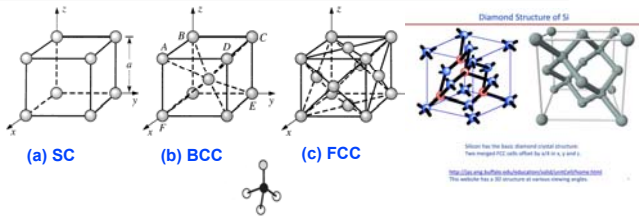


3. Next fractional distillation reduction with hydrogen produces electronic grade silicon (EGS):



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Cubic Crystal System – Unit Cells...

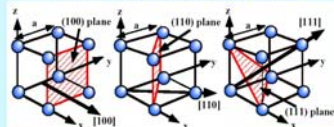


Crystalline silicon forms a covalently bonded structure and coordinates itself tetrahedrally (bottom). Silicon (and germanium) crystallize as two interpenetrating FCC sublattices.

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Image courtesy of Soe, SM.

Silicon Crystal Structure



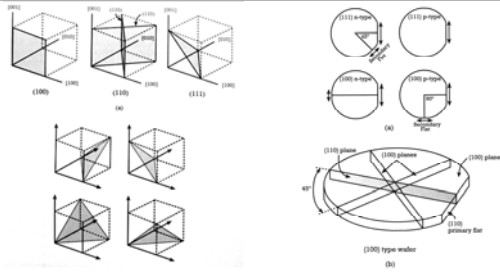
Crystals are characterized by a unit cell which repeats in the x, y, z directions.

- 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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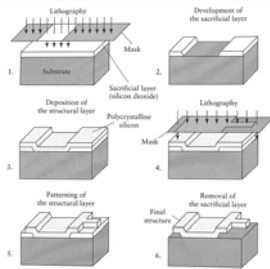
Miller Indices...



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Images courtesy of Madou M.

Basic Surface Micromachining Steps



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Image courtesy of Fatkowi S & Rembold U.

Silicon Wafer Preparation



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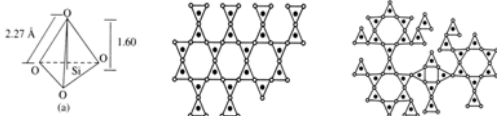
RCA Cleaning Bench...



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Thermal Silicon Oxide...

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



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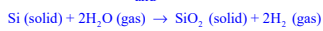
Images courtesy of Gardner JW.

Thermal Silicon Oxide Methods...

- The chemical reaction that occurs is:

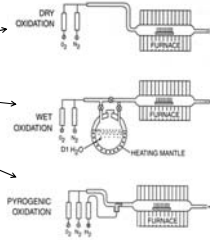


and



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

- Thermal silicon oxide is amorphous.



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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.

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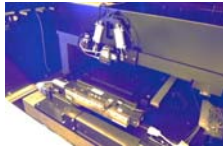
Mask Fabrication



The Heidelberg



Unexposed Masks
(Resist is Pre-applied)

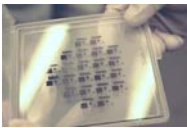


Mask Carriage

Nanolium		
2401 Huntington #100		
Woodside Village, CA 91361		
www.nanolium.com		
Call: LINDY SP MINNESOTA		
Part #	8554-000 BL LRD 100 1010 00 Optical Density	2.0
P.O.	ENERGY CARE	Materials
Photoresist Lot Number	8554	Photo Resist Thickness
Class Type	Blank Carrier	Photo Resist Type
Mask Code 021118		Photo Resist Lot #
		Photo Resist Batch Temp

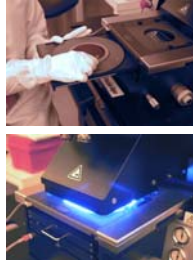
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Contact Alignment...



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UV Exposure at 350-500 nm...



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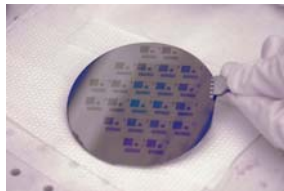
Cannon Stepper (Alternative to Contact Aligner)...



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

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Developing the UV Exposed Wafer...



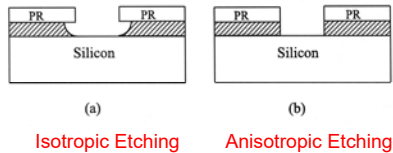
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Etching Methods

- **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).

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Etching Profiles...



Isotropic Etching

Anisotropic Etching

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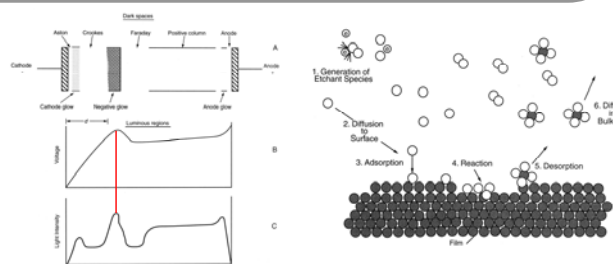
Image courtesy of Zale B.

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.

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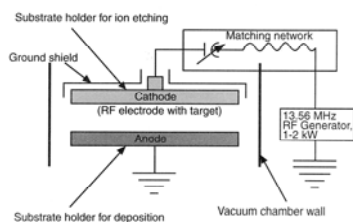
Plasma Etching (PE)...



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Images courtesy of Madou M.

Reactive Ion Etching (RIE)...



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Image courtesy of Madou M.

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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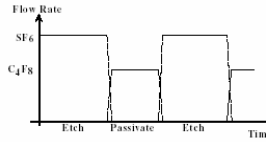
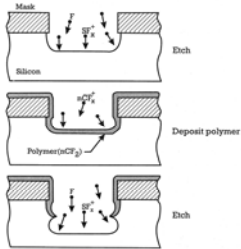
Gases for the RIE...



Etchant gases available:
Argon (Ar),
Trifluoromethane (CHF₃)
Tetrafluoromethane (CF₄)
Oxygen (O₂)
Sulphur Hexafluoride (SF₆)
Methanol (CH₃OH)

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Deep Reactive Ion Etching (DRIE)



Sulfur hexafluoride (SF₆) is flowed during the etching cycle then Octafluorocyclobutane (C₄F₈) during the sidewall protection cycle.

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Left: Madoui 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). ENEC416, 3/10/2004.

Deep Reactive Ion Etcher...



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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.

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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.

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Ion Beam Milling (IBM)...

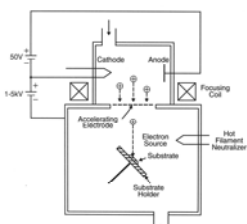
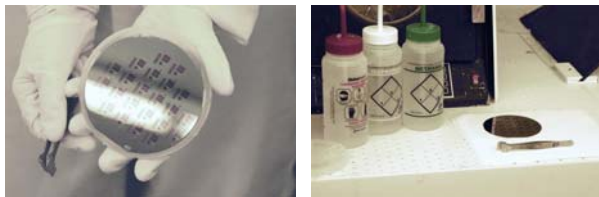


Image courtesy of Madou M.

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Resist Stripping...



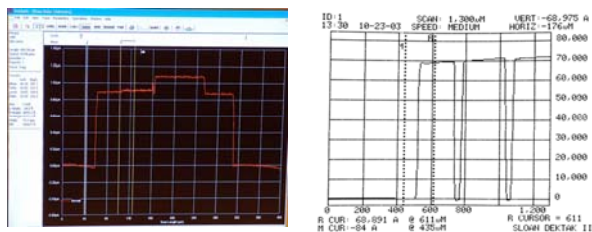
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Profilometry...



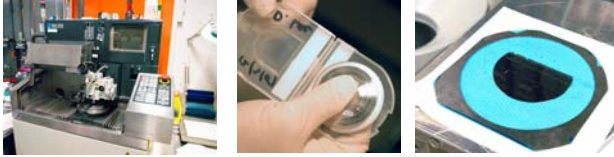
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Profilometer Screen Display...

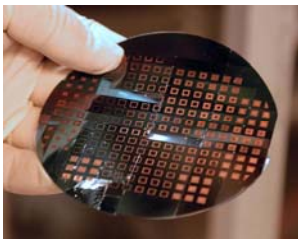


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Wafer Cutting - Dicing Chips...

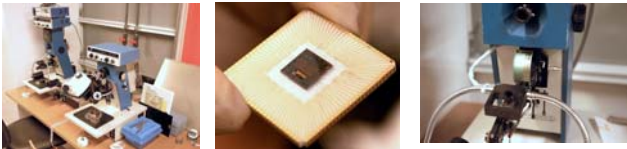


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Wire Bonding...



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Key Points

- **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 includes:**
 - 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 for interfacing.**

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