Modulo 3B: Microfabbricazione

Corso di

CARATTERISTICHE MECCANICHE E TECNOLOGICHE DEI MATERIALI NON CONVENZIONALI

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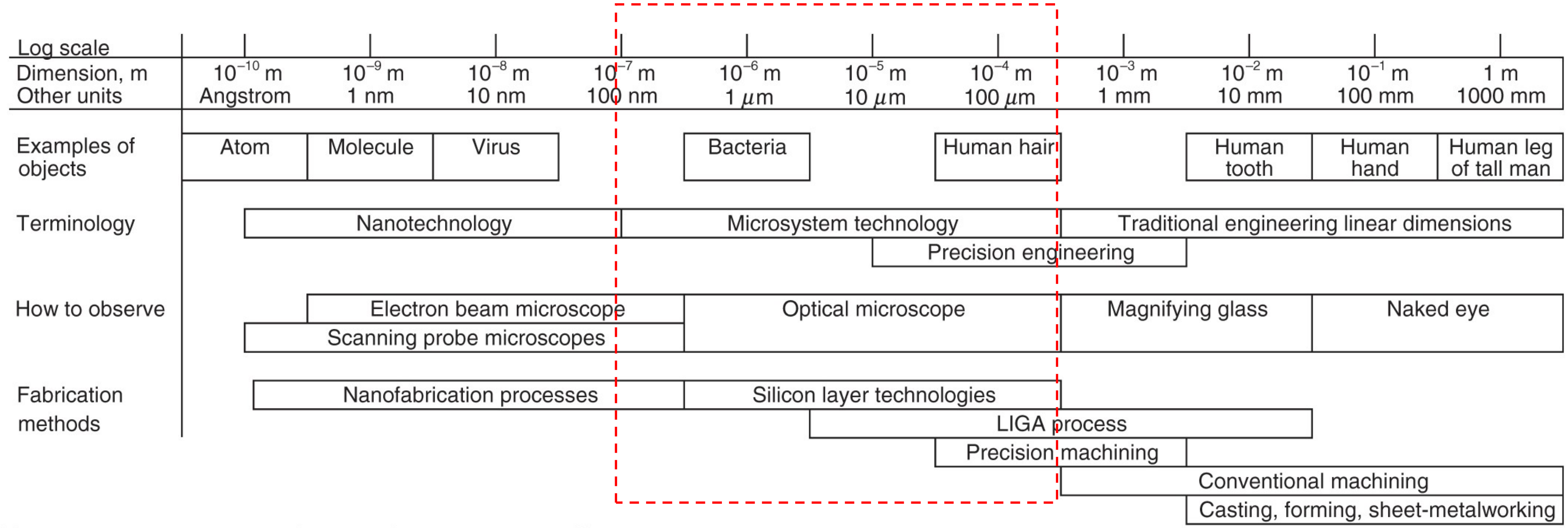
Relative Sizes in Microtechnology and Nanotechnology



Key: nm = nanometer, μm = micron or micrometer, mm = millimeter, m = meter

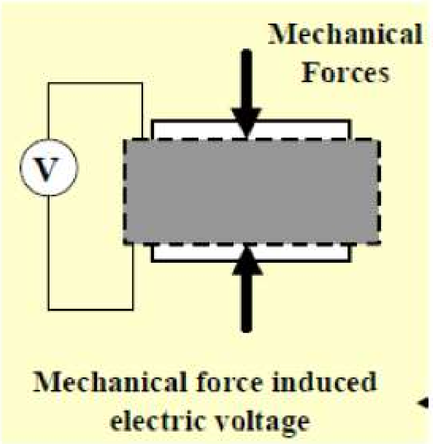
Terminology for micro and nano systems

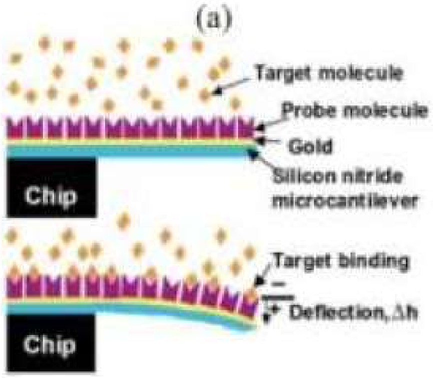
- Miniaturization of products and parts, with features sizes measured in microns (10^{-6} m) or smaller
  - *Microsystem technology* (MST) - refers to the products as well as the fabrication technologies
  - *Microelectromechanical systems* (MEMS) - miniature systems consisting of both electronic and mechanical components
  - *Nanotechnology* - even smaller entities whose dimensions are measured in nanometers (10^{-9} m)

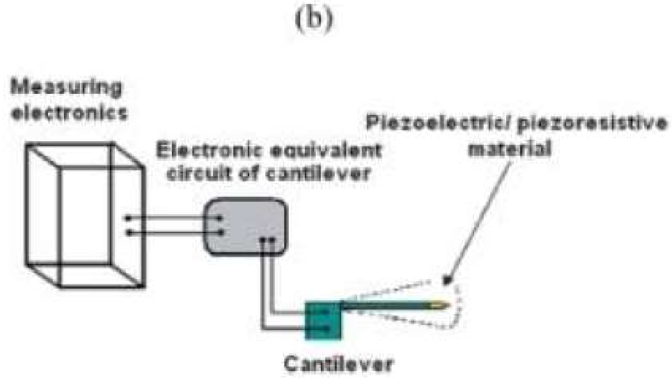
Why miniaturization?

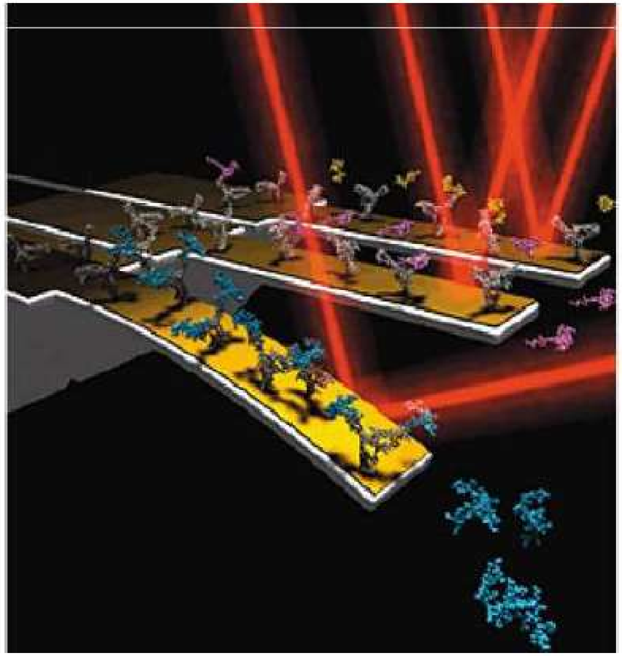
- Taking advantage of scaling: faster devices, improved thermal management, etc.
  - As surface to volume ratio increases a greater amount of a substance comes in contact with surrounding material
- Integration with electronics and other functional components on the same small device
- Miniaturized devices are particularly suited for biomedical and aerospace applications due to their minute size and weight
- Lower amount of sample required for analysis
- Redundancy and arrays
- Exploitation of microfabrication processes already well established for integrated circuitry (IC) technology
- Possibility of production on a large scale

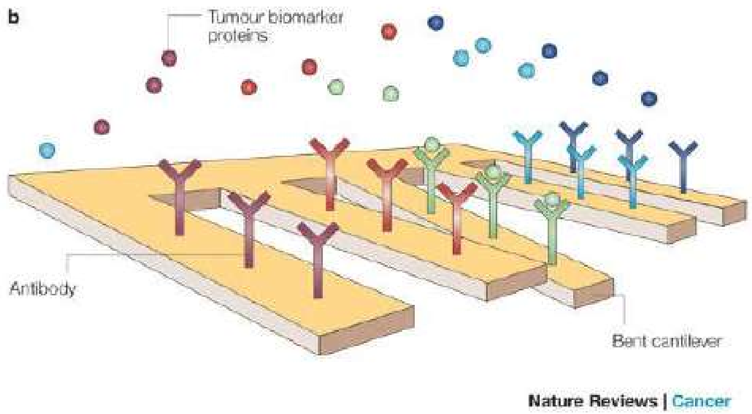
Example: microcantilever based detection



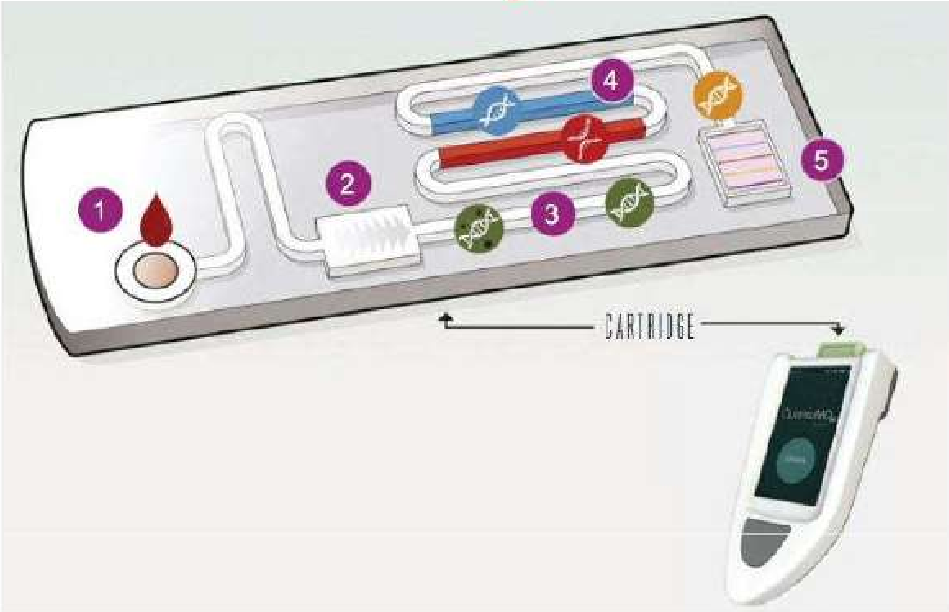


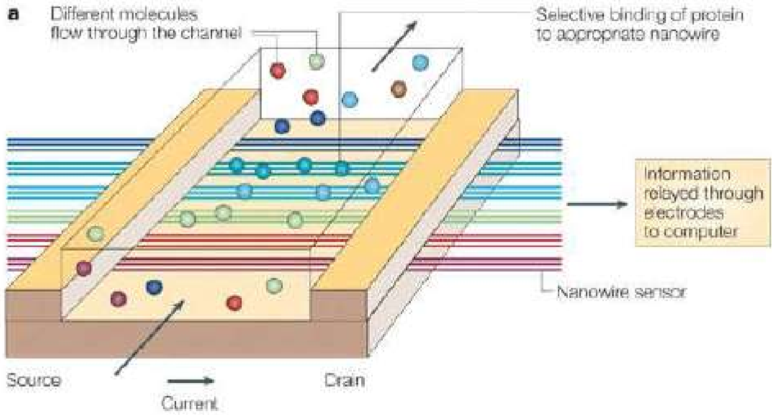


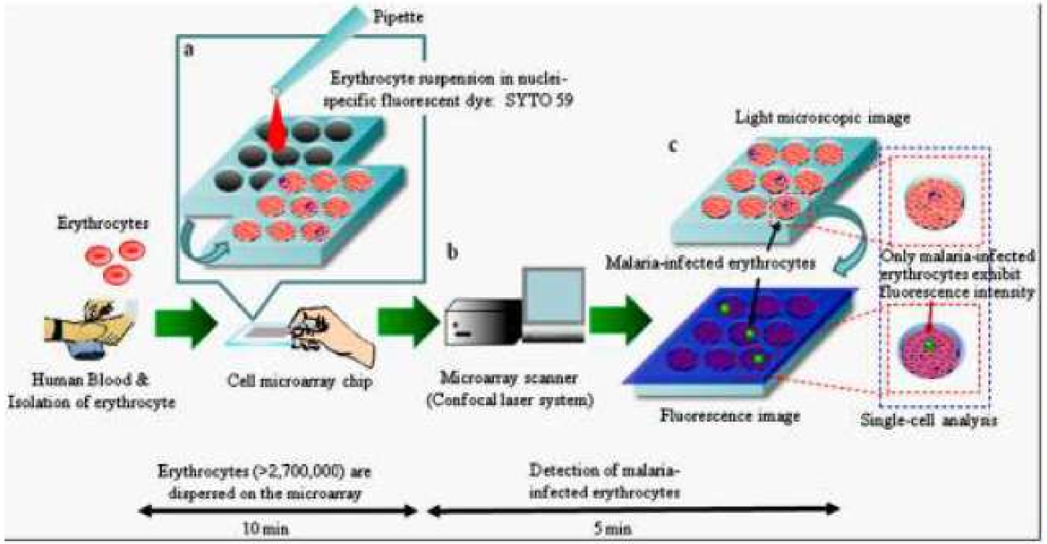


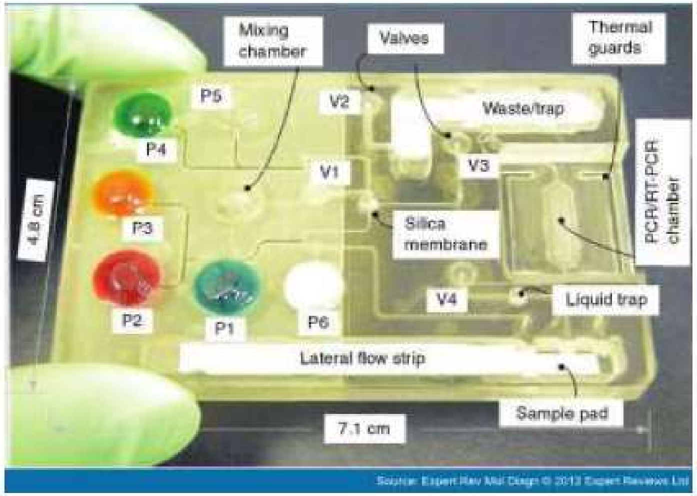


Example: ''Lab on a chip''









Microsystems vs. IC Technologies

Integrated circuits are made by successive deposition, lithography, and then etching of thin film on silicon

In ICs these processes are used to create small electrical devices

In microsystems these processes are used to create mechanical structures

With IC technologies, we can

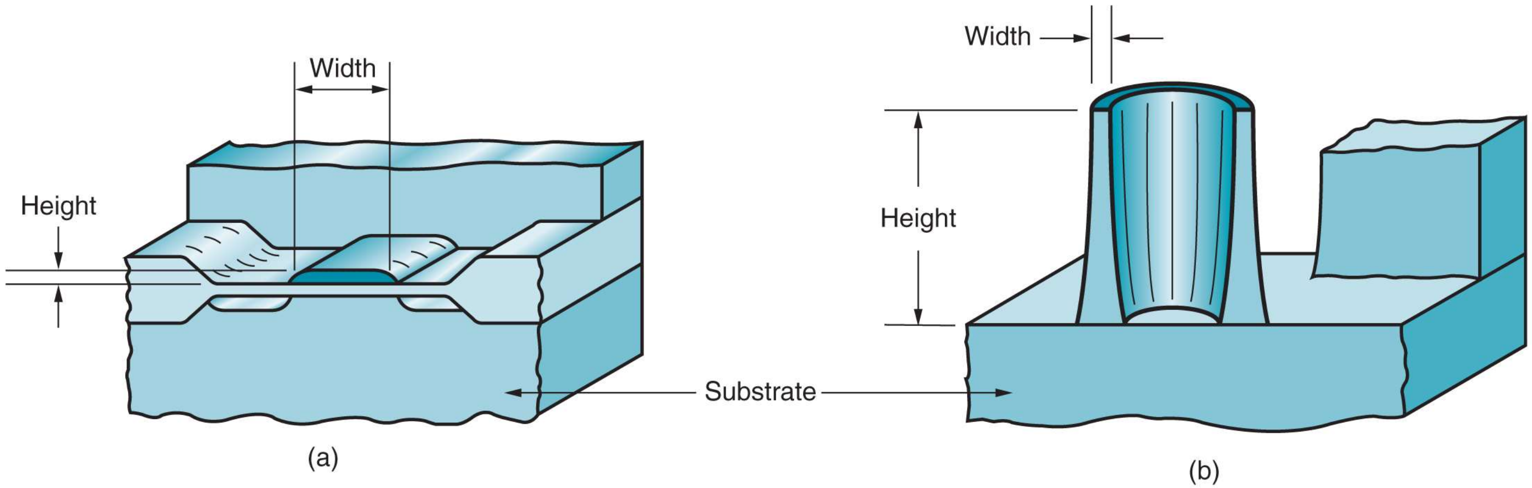
- Miniaturize
- Process sets of wafer in the same batch
- Multiple chips with identical characteristics
- At low cost

But Microsystems technology value adds IC technology by incorporating

- Moving components
- More features (sensors, actuators, bio-applications)

Microfabrication vs. IC Technologies

- Aspect ratios (height-to-width ratio of the features) in microfabrication are generally much greater than in IC fabrication
- The device sizes in microfabrication are often much larger than in IC processing
- The structures produced in microfabrication often include cantilevers and bridges and other shapes requiring gaps between layers
  - These features are not found in integrated circuits



- Aspect ratio (height-to-width ratio) typical in (a) fabrication of integrated circuits and (b) microfabricated components

Types of Microsystem Devices

- Microsensors
- Microactuators
- Microstructures and microcomponents
- Micro-instruments

Microsensors

A sensor is a device that detects or measures some physical phenomenon such as heat or pressure

- Most microsensors are fabricated on a silicon substrate using the same processing technologies as those used for integrated circuits
- Microsensors have been developed to measure force, pressure, position, speed, acceleration, temperature, flow, and various optical, chemical, environmental, and biological variables

Microactuators

An actuator converts a physical variable of one type (e.g. electrical) into another type, and the converted variable usually involves some mechanical action

- An actuator causes a change in position or the application of force
- Examples of microactuators: valves, positioners, switches, pumps, and rotational and linear motors

Microstructures and Microcomponents

Micro-sized parts that are not sensors or actuators

- Examples: microscopic lenses, mirrors, nozzles, gears, and beams
- These items must be combined with other components in order to provide a useful function

Microsystems and micro-instruments

Integration of several of the preceding components with the appropriate electronics package into a miniature system or instrument

- Products tend to be very application-specific
  - Examples: microlasers, optical chemical analyzers, and microspectrometers
- The economics of manufacturing these kinds of systems have made commercialization difficult

Industrial Applications of Microsystems

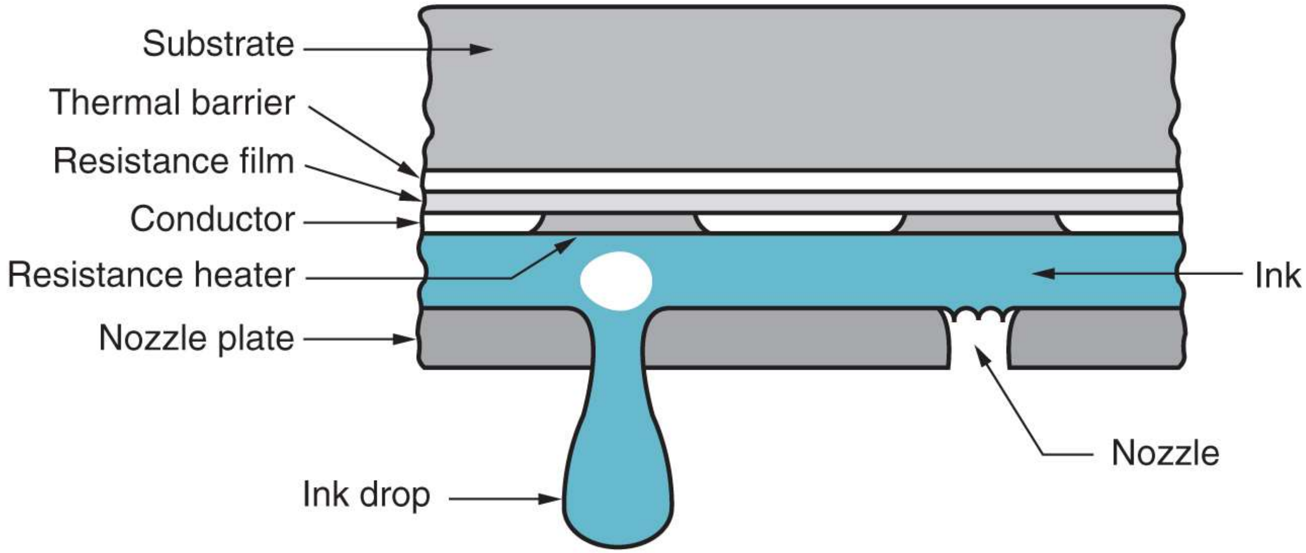
- Ink-jet printing heads
- Thin-film magnetic heads
- Compact disks
- Automotive components
- Medical applications
- Chemical and environmental applications
- Other applications

Ink-Jet Printing Heads

- Currently one of the largest applications of MST
- A typical ink-jet printer uses up several cartridges each year
- Today's ink-jet printers have resolutions of 1200 dots per inch (dpi)
  - This resolution converts to a nozzle separation of only about 21 μm
    - Certainly in the microsystem range

Ink-Jet Printing Heads

- Resistance heater boils ink to create plume that forces drop to be expelled onto paper



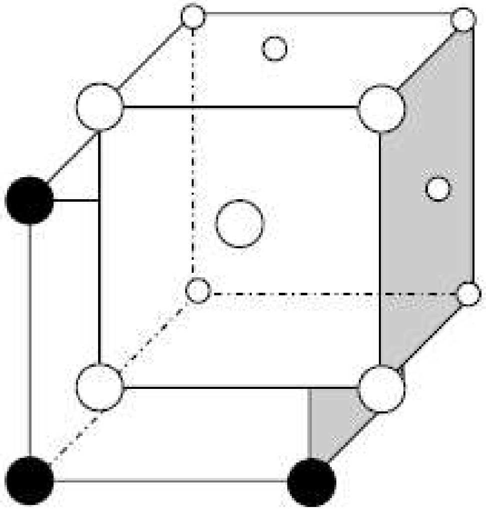
Microfabrication Processes

- Many MST products are based on silicon - Why?
  - Microdevices often include electronic circuits, so both the circuit and the device can be made on the same substrate
  - Silicon has good mechanical properties:
    - High strength and elasticity (about the same as steel, ≈ 200 GPa), good hardness, and relatively low density (as aluminium, 2.3 g/cm^3)
    - It has a melting point at 1400°C, dimensionally stable even at elevated temperature.
    - Its thermal expansion coefficient is about 8 times smaller than that of steel, and more than 10 times smaller than aluminium
    - It shows virtually no mechanical hysteresis. It is thus an ideal candidate material for sensors and actuators

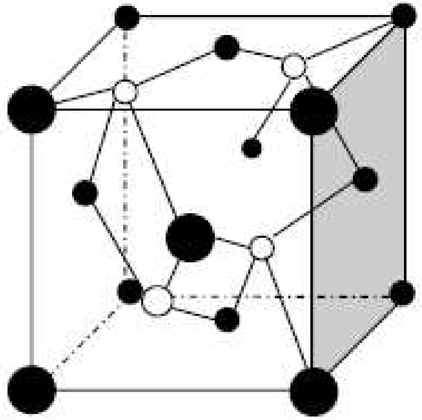
Why silicon?

- Silicon (Si) is the most abundant material on earth. It almost always exists in compounds with other elements
- Silicon has greater flexibility in design and manufacture than other material substrates
- Treatments and fabrication processes for silicon are already well established and documented (IC technology)
- In a perfect crystal, each of silicon’s four outer electrons form covalent bonds, resulting in poor electron mobility (i.e. insulating)
- Doping silicon with impurities alters electron mobility (i.e. semiconducting)
    - Extra electron (“N-type”, with phosphorous, for example)
    - Missing electron (“P-type”, with boron, for example)

Crystal Structure of Silicon



Not all atoms shown
Cube 1: filled circles
Cube 2: empty circles



A typical unit cell showing all atoms within a cube of side a

8/8 at corners
6/2 at face centers
4 from the second fcc

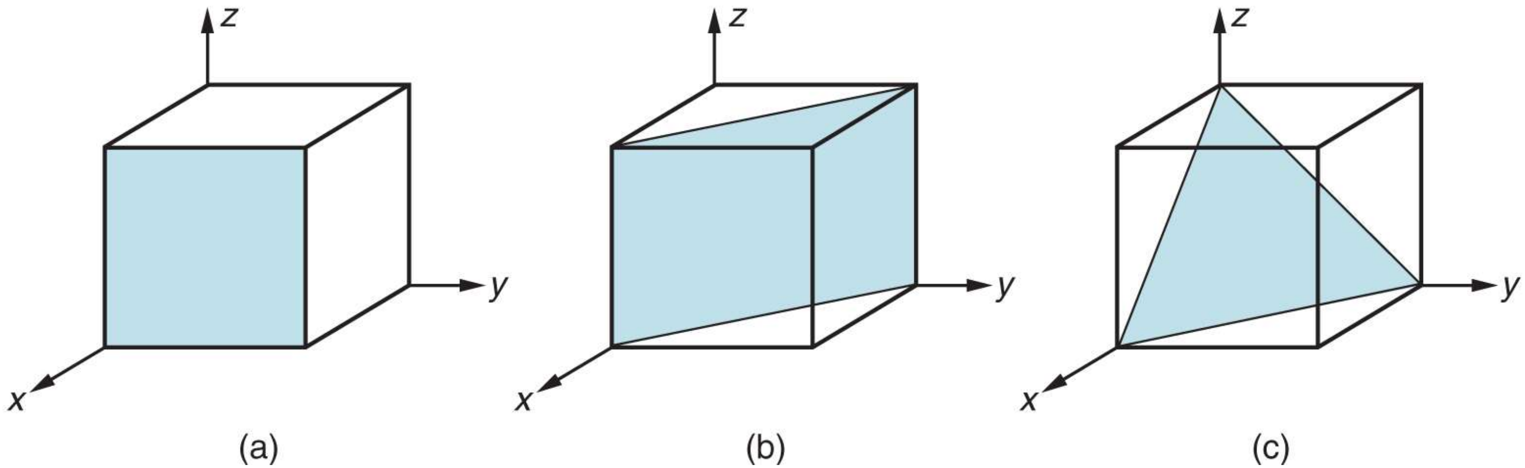
→ Total #: 8 atoms/cell

This is not rotationally symmetric
Properties vary in different directions

→ Anisotropic

Crystal Faces in Cubic Lattice Structure

- Three crystal faces in silicon cubic lattice structure: (a) (100) crystal face, (b) (110) crystal face, and (c) (111) crystal face



Purification of silicon

- Reduction of silica sand (SiO_2) by carbon

  $SiO_2 + 2C \rightarrow Si + 2CO$ (g) (metallurgical grade Si)

- Conversion to gaseous trichlorosilane

  $Si + 3HCl \rightarrow SiHCl_3$ (g) + H_2 (g)

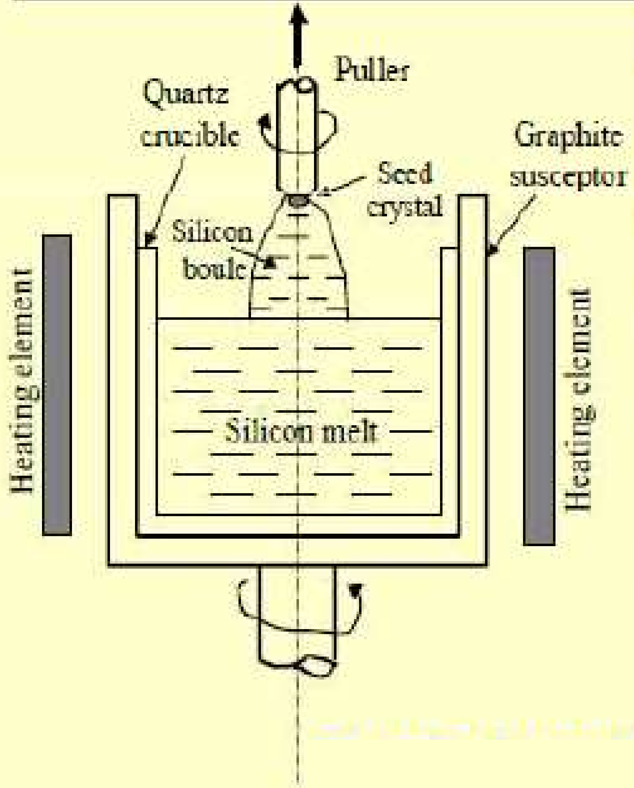
- Distillation of $SiHCl_3$ to separate impurities (Fe, B, P)
- Decomposition of trichlorosilane on hot silicon rods

  $2SiHCl_3 + 2H_2$ (g) $\rightarrow$ 2Si (s) + 6HCl (g) (electronic grade Si)

Single-Crystal Silicon

- For silicon to be used as a substrate material in integrated circuits and MEMS, it has to be in a pure single-crystal form.
- The most commonly used method of producing single-crystal silicon is the Czochralski (CZ) method.

The Czochralski method for producing single-crystal silicon



Equipment: a crucible and a "puller".

Procedure:

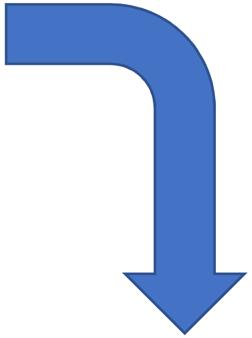
(1) Electronic grade Si is melted in a crucible at 1420°C

(2) A "seed" crystal is brought to be in contact with molten Si to form larger crystal.

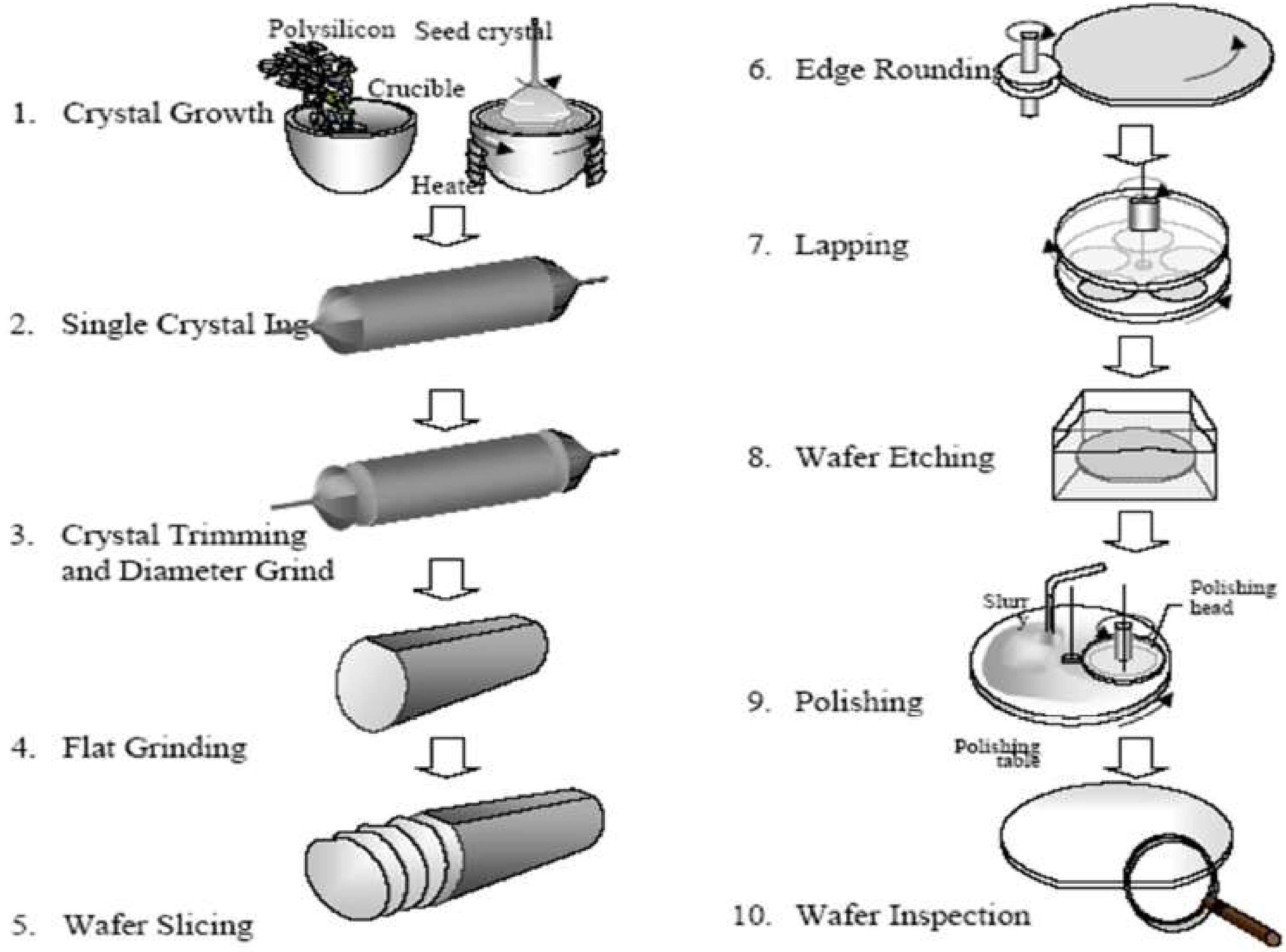
(3) The "puller" slowly pulls the molten Si up to form pure Si "boule" after the solidification.

(4) The diameters of the "bologna-like" boules vary from 100 mm (4") to 300 mm (12") in diameters.

From boule to wafer



Fabrication of silicon wafers



Other substrate materials…

- Gallium Arsenide

  - Second most common semiconductor

  Disadvantages

  - Does not form sufficient quality native oxide;
  - Thermally unstable above 600°C due to As evaporation;
  - Mechanically fragile

- Quartz (SiO_2)

  - Extreme dimensional stability;
  - It offers excellent electric insulation in microsystems/IC;
  - Excellent material for microfluidic systems in biomedical applications

  Disadvantages

  - Hard in micromachining, needs for chemical attacks (HF/NH4F)

Other substrate materials…

- Polymers
  - Poly (dimethylsiloxane) (PDMS)
  - Poly (methyl methacrylate) (PMMA)
  - Teflon, etc.

Performance of various substrates (for general MEMS / IC applications)

Substrate	Cost	Metallization	Machinability
Ceramic	medium	fair	poor
Plastic	low	poor	fair
Silicon	high	good	very good
Glass	low	good	poor

Introduction to μfab processes

- There is no machine tool with today's technology can produce any device or MEMS component of the size in the micrometer scale (or in mm sizes).
- The complex geometry of these minute MEMS components can only be produced by various physical-chemical processes – the microfabrication techniques originally developed for producing integrated circuit (IC) components.

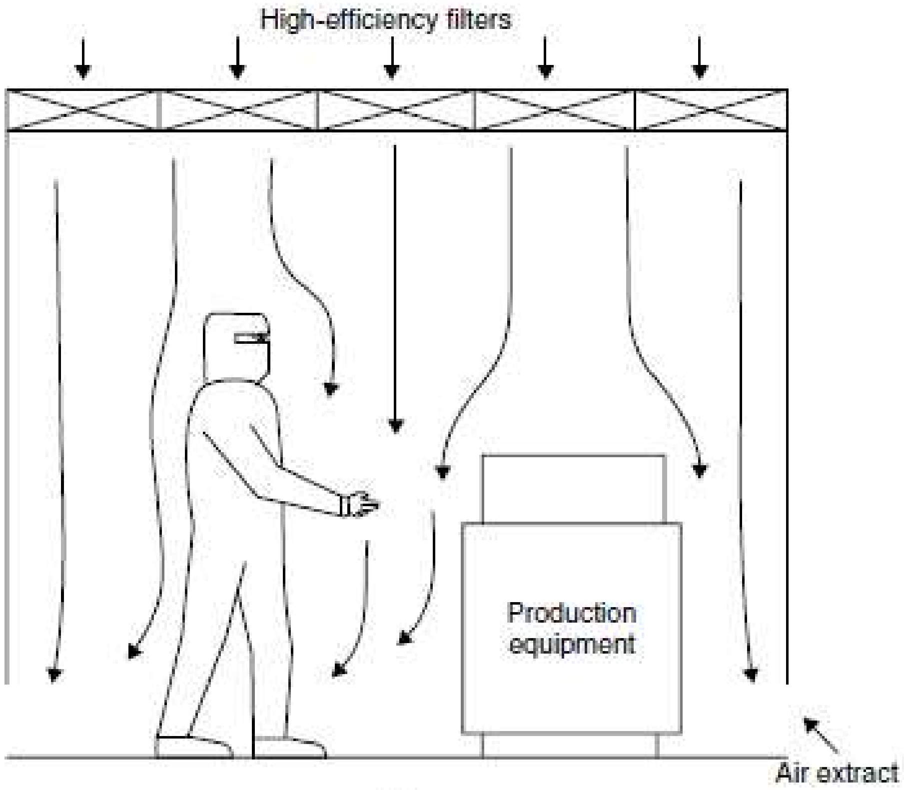
Microfabrication
by physical-chemical processes

Traditional Manufacturing
by machine tools

Clean room environment

Microfabrication is performed in a close environment with strict control of:

- Temperature
- Humidity
- Illumination
- Air flux
- Dust density



(a)

Clean room classification

Table 2.1 – *Clean room classification based on US FED STD 209E and ISO 14644-1 standards.*

FED STD 209E classification	maximum number of particles/m^3						ISO 14644-1 classification
	≥ 0.1 µm	≥ 0.2 µm	≥ 0.3 µm	≥ 0.5 µm	≥ 1 µm	≥ 5 µm	
Class 1	1000	237	102	35	8.3	0.29	ISO 3
Class 10	10000	2370	1020	352	83	2.9	ISO 4
Class 100	100000	23700	10200	3520	832	29	ISO 5
Class 1000	1000000	237000	102000	35200	8320	293	ISO 6

Microfabrication steps