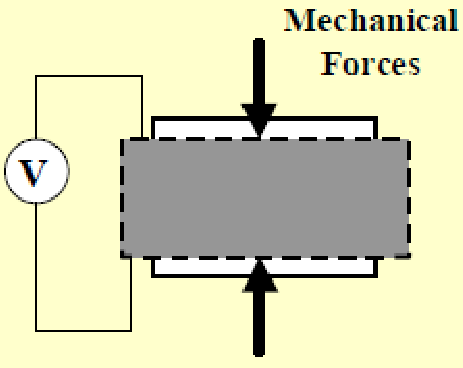
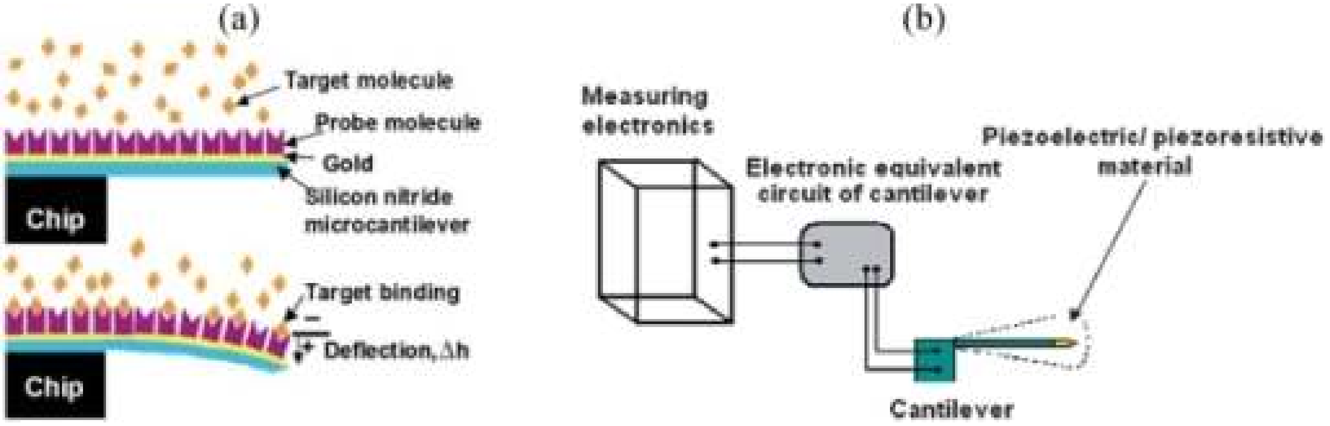
# Microfabrication

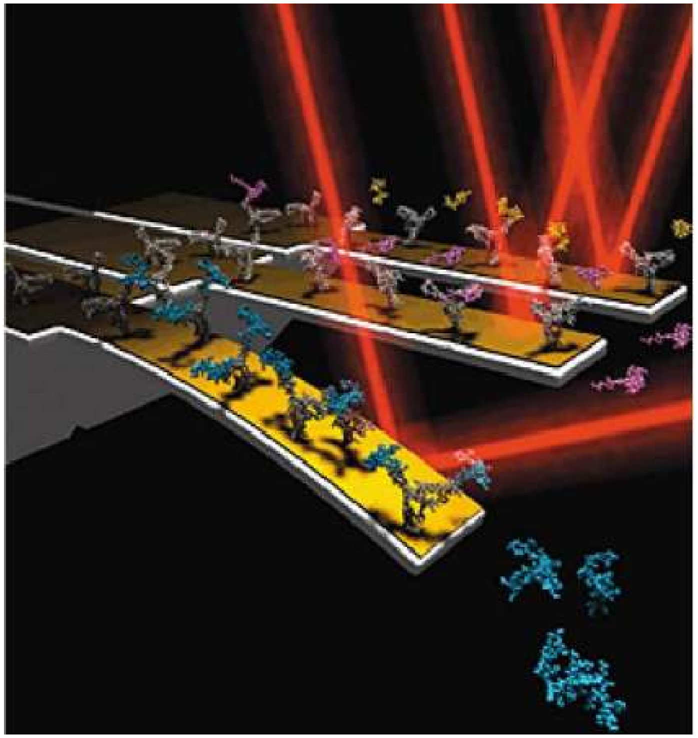
Niraj Sinha
Department of Mechanical Engineering
Indian Institute of Technology Kanpur
nsinha@iitk.ac.in

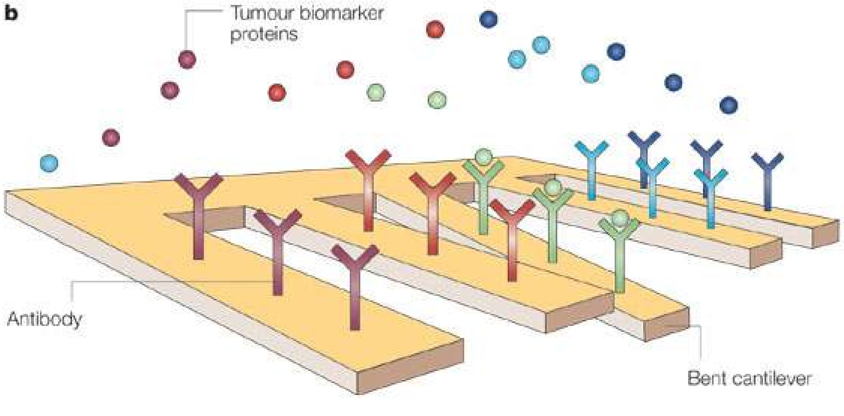
# *Microcantilever Based Detection*



Mechanical force induced electric voltage

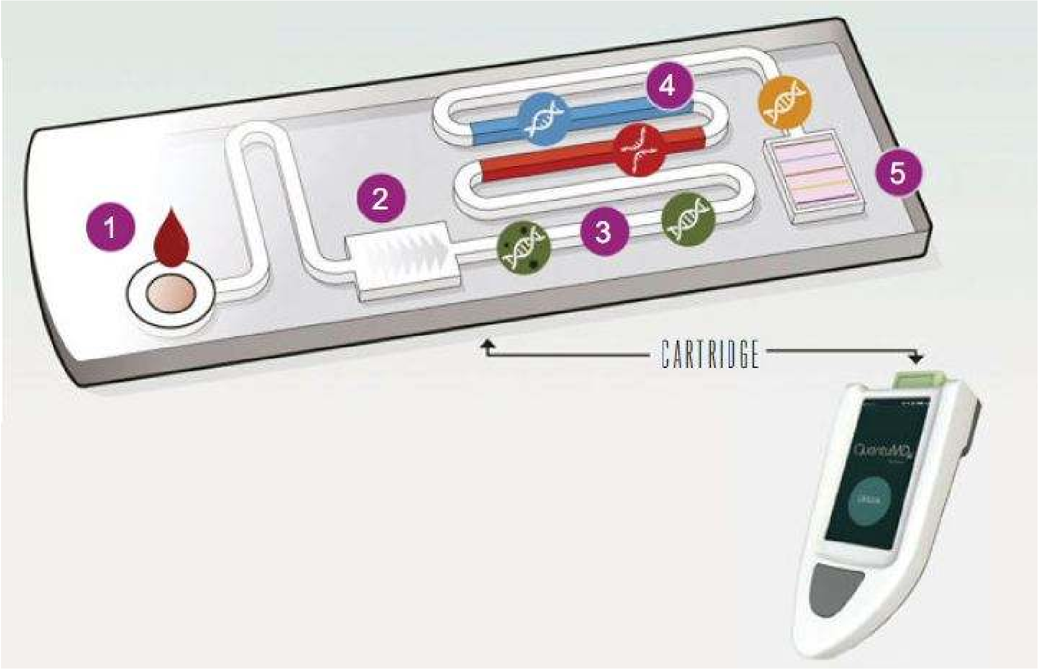


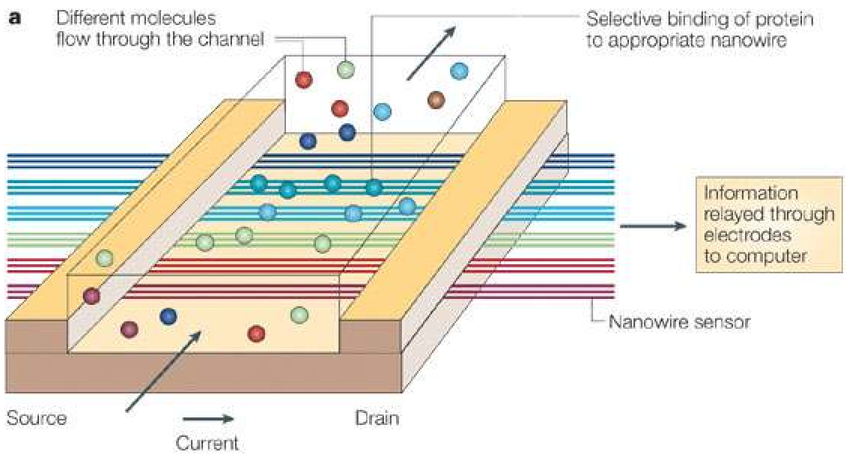


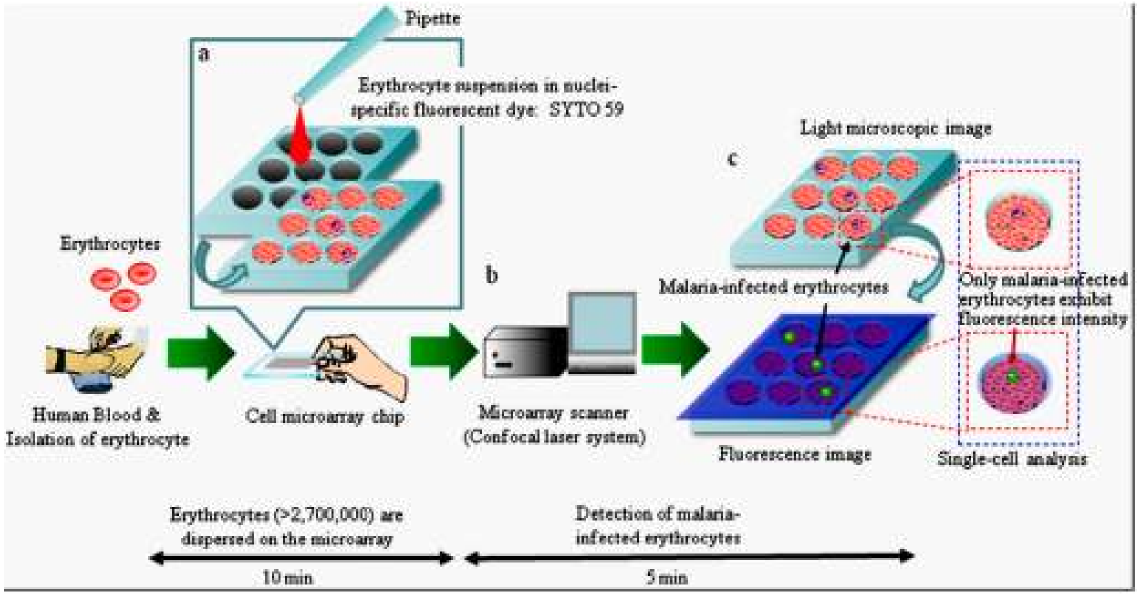


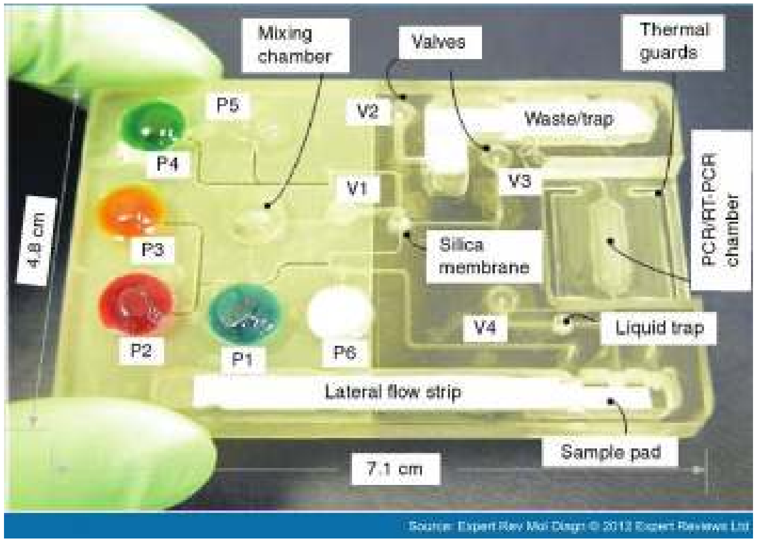
Nature Reviews | Cancer

# Microfluidics Based Detection



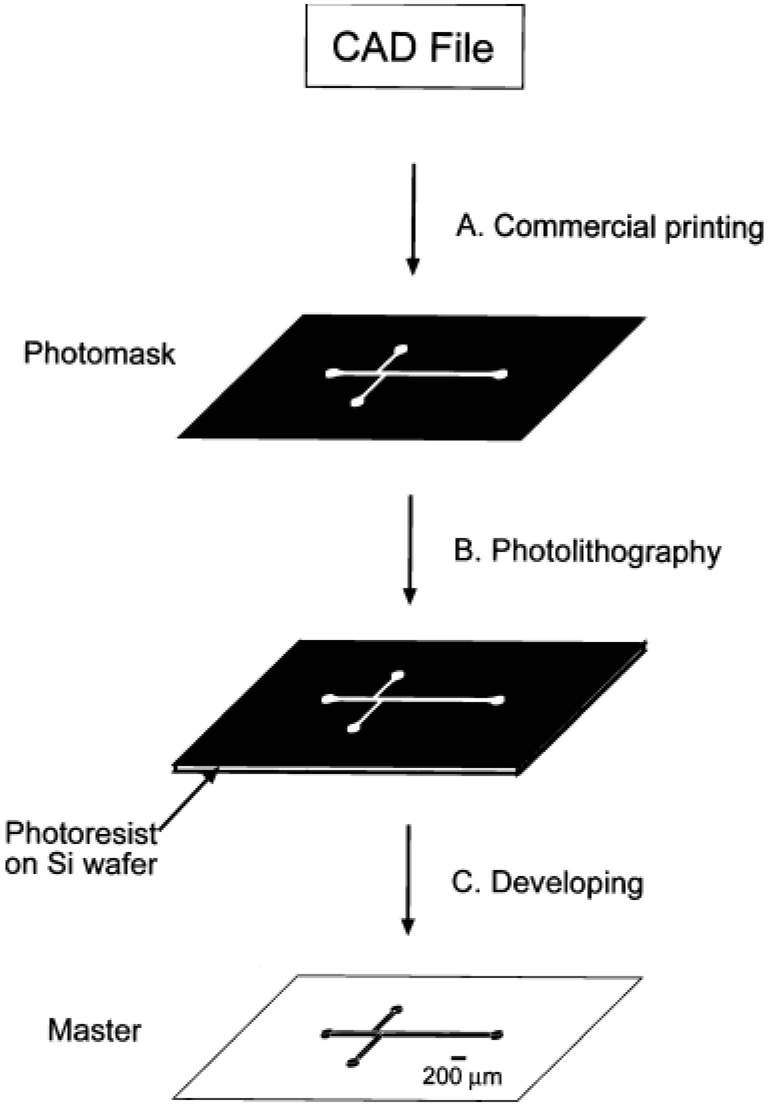






Source: Expert Rev Mol Diagn © 2012 Expert Reviews Ltd

# Microfluidics Based Detection



CAD File

A. Commercial printing

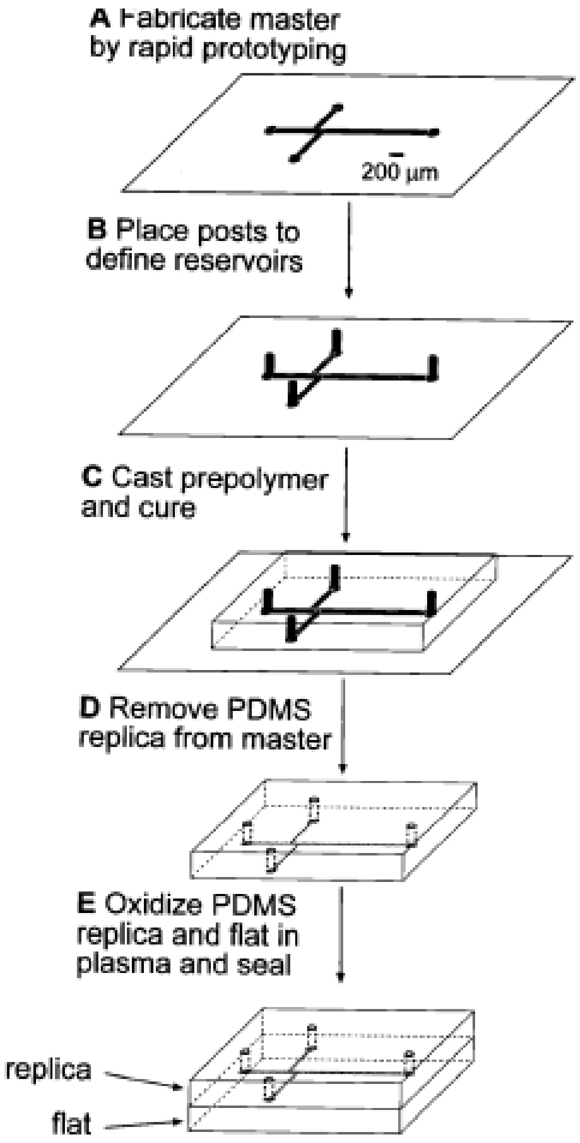
Photomask

B. Photolithography

Photoresist on Si wafer

C. Developing

Master



**A** Fabricate master by rapid prototyping

**B** Place posts to define reservoirs

**C** Cast prepolymer and cure

**D** Remove PDMS replica from master

**E** Oxidize PDMS replica and flat in plasma and seal

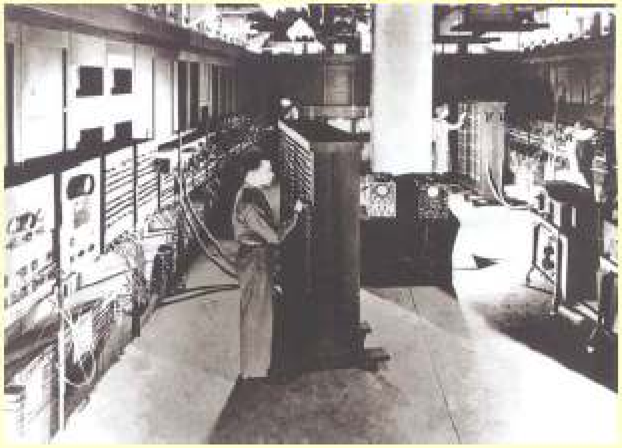
# *Miniaturization of Computers*

http://educationstormfront.wordpress.com/2013/05/17/hardware-innovation-vs-software-innovation/

http://ccatechnohistory.blogspot.in/2010/09/evolution-of-computers.html

# Miniaturization of Digital Computers

## - A remarkable case of miniaturization!

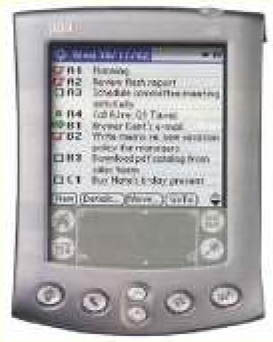


The ENIAC Computer in 1946

Size: $10^6$ down
Power: $10^6$ up

A "Lap-top" Computer in 1996

Size: $10^8$ down
Power: $10^8$ up

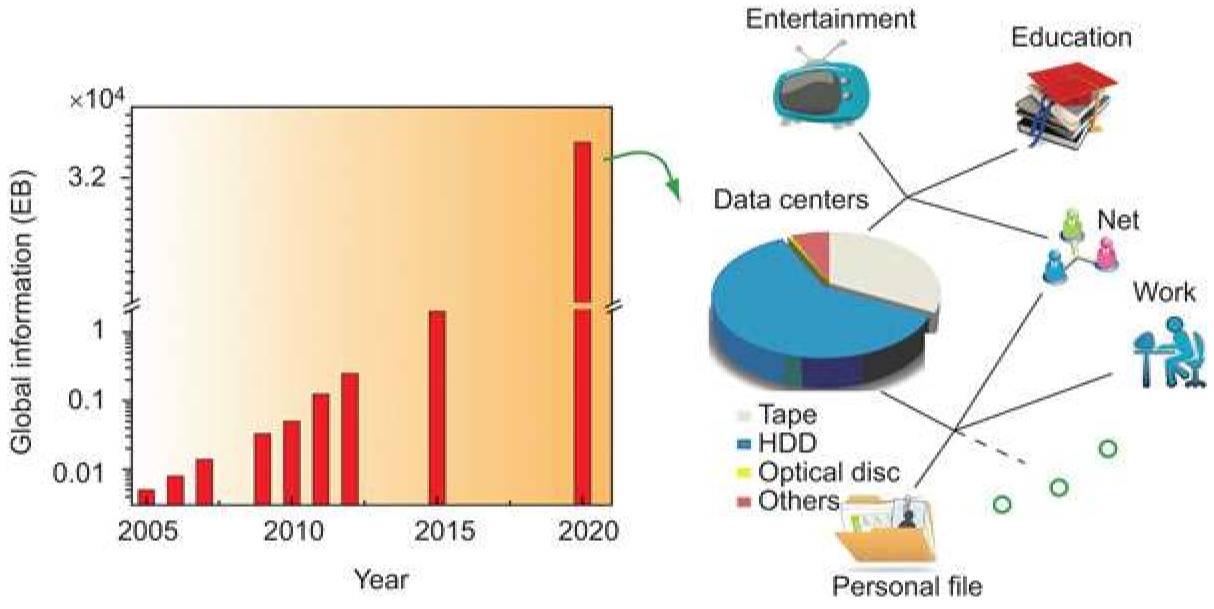


A "Palm-top" Computer in 2001

This spectacular miniaturization took place in 50 years!!

Ref : Hsu, T.R., L.I., 14, 168-171, 1972

# *Miniaturization: Information Storage*



**Data recording on a disc**

❖ The information is transformed to strings of binary digits (0s and 1s, also called bits).

❖ Each bit is then laser “burned” into the disc, using a single beam of light, in the form of dots.

❖ The storage capacity of optical discs is mainly limited by the physical dimensions of the dots.

Fgure Source: International Data Corporation (IDC)

# *Miniaturization: Information Storage*

## How far can we reduce the size of the dots?

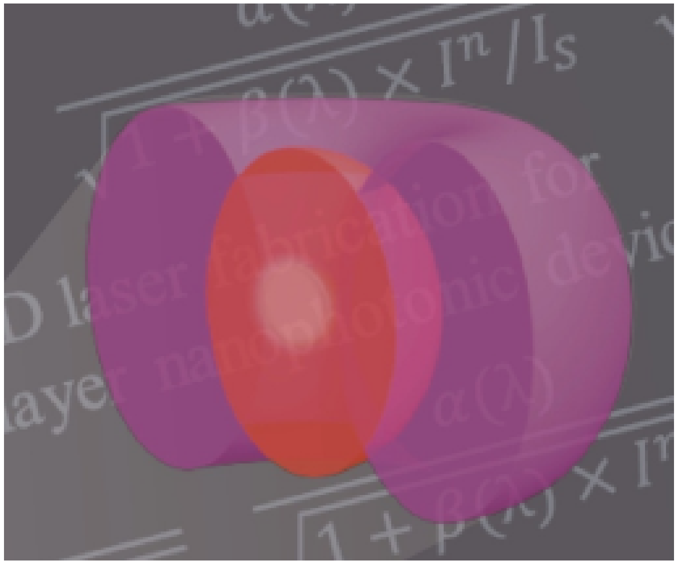
**Abbe's Limit:**

If a light beam is focused through a lens, the diameter of the resulting spot of light can't be smaller than half its wavelength.

**Way to get around the problem**

- ❖The first beam (red, in the figure) has a round shape, and is used to write data.

- ❖ Then, place a doughnut-shaped laser (purple, in the figure) around the initial laser in order to limit the abilities of the first beam. This effectively made the standard laser's diameter smaller, and it could then write smaller bits



http://theconversation.com/more-data-storage-heres-how-to-fit-1-000-terabytes-on-a-dvd-15306

# MINIATURIAZATION – The Principal Driving Force for the 21st Century Industrial Technology

There has been increasing strong market demand for:

**"Intelligent,"**

**"Robust,"**

**"Multi-functional," and**

**"Low-cost"** industrial products.

**Miniaturization** is the only viable solution to satisfy such market demand

# Market Demand for Intelligent, Robusting, Smaller, Multi-Functional Products - the evolution of cellular phones

**Mobil phones 10 Years Ago:**

**Current State-of-the Art:**

**Size reduction**

**Palm-top Wireless PC**

**Transceive voice only**

**Transceive voice+ multi-media + others** (Video-camera, e-mails, calendar, and access to Internet, GPS and a PC with key pad input)

**The only solution is to pack many miniature function components into the device**

# Miniaturization Makes Engineering Sense!!!

- Small systems tend to move or stop more quickly due to low mechanical inertia. It is thus ideal for *precision movements and for rapid actuation.*
- Miniaturized systems encounter less thermal distortion and mechanical vibration due to low mass.
- Miniaturized devices are particularly suited for biomedical and aerospace applications due to their minute sizes and weight.
- Small systems have *higher dimensional stability at high temperature* due to low thermal expansion.
- Smaller size of the systems means less space requirements. This allows the *packaging of more functional components in a single device.*
- Less material requirements mean low cost of production and transportation.
- Ready *mass production in batches.*

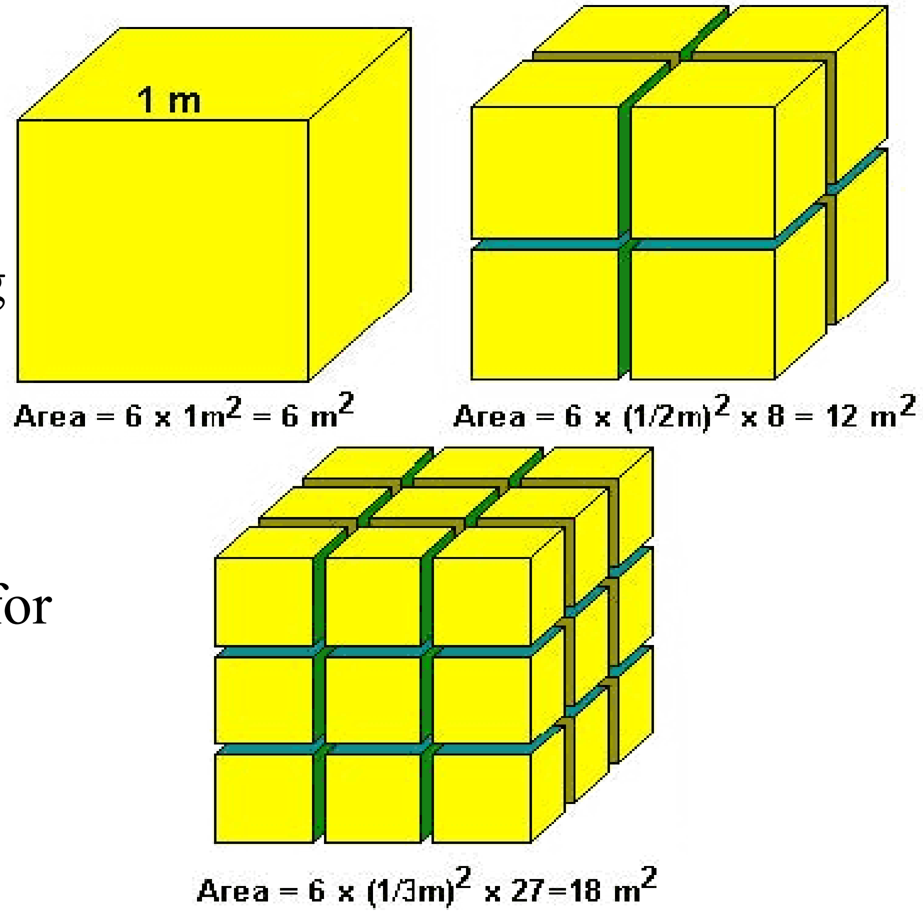
# *Scaling-Surface to Volume Ratio Increases*

As surface to volume ratio increases

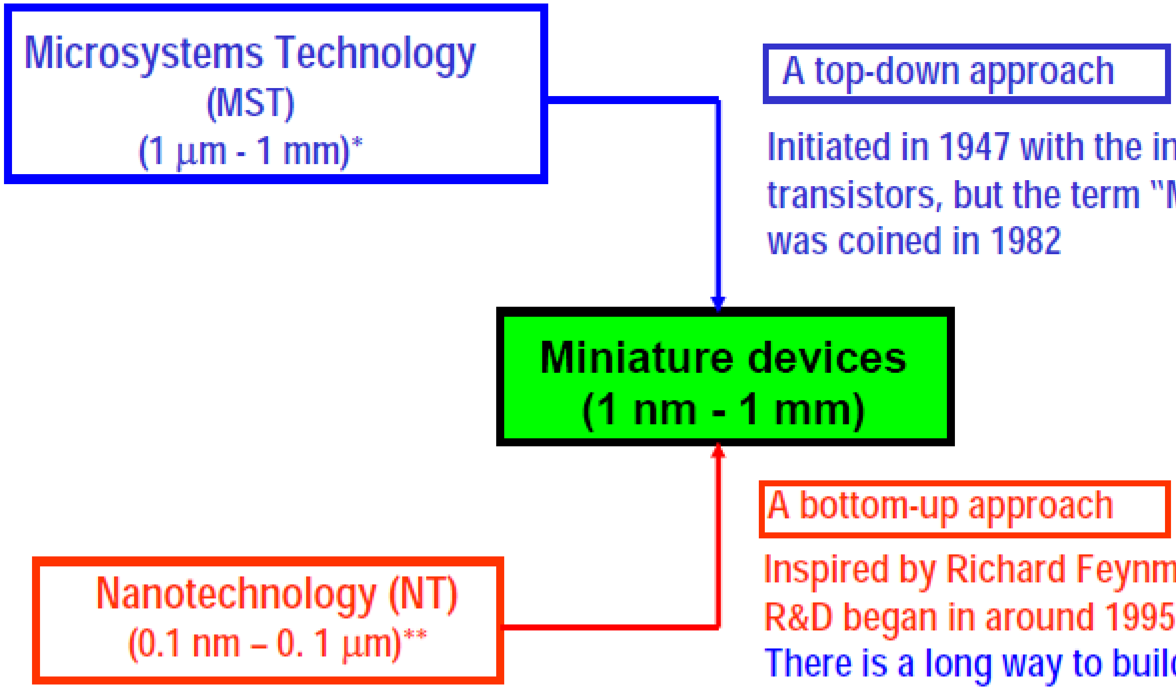
- A greater amount of a substance comes in contact with surrounding material.

- This helps in loading more drugs for drug delivery.

- Also, elephant and dragonfly example.



# Enabling Technologies for Miniaturization



Microsystems Technology
(MST)
(1 $\mu$m - 1 mm)*

A top-down approach

Initiated in 1947 with the invention of transistors, but the term "Micromachining" was coined in 1982

**Miniature devices**
**(1 nm - 1 mm)**

A bottom-up approach

Inspired by Richard Feynman in 1959, with active R&D began in around 1995

There is a long way to building nano devices!

Nanotechnology (NT)
(0.1 nm – 0. 1 $\mu$m)**

*** 1 $\mu$m = $10^{-6}$ m ≈ one-tenth of human hair**

**** 1 nm = $10^{-9}$ m ≈ span of 10 $H_2$ atoms**

# MEMS = a pioneer technology for Miniaturization –

A leading technology for the 21st Century, and

an inevitable trend in industrial products and systems development

# WHAT IS MEMS?

**MEMS = MicroElectroMechanical System**

**Any engineering system that performs *electrical* and *mechanical* functions with *components* in *micrometers* is a MEMS. (1 μm = 1/10 of human hair)**

**Available MEMS products include:**

- **Micro sensors** (acoustic wave, biomedical, chemical, inertia, optical, pressure, radiation, thermal, etc.)
- **Micro actuators** (valves, pumps and microfluidics;
  electrical and optical relays and switches;
  grippers, tweezers and tongs;
  linear and rotary motors, etc.)
- **Read/write heads** in computer storage systems.
- **Inkjet printer heads**.
- **Micro device components** (e.g., palm-top reconnaissance aircrafts, mini robots and toys, micro surgical and mobile telecom equipment, etc.)

# Commercial MEMS and Microsystems Products

**Micro Sensors:**

Acoustic wave sensors
Biomedical and biosensors
Chemical sensors
Optical sensors
Pressure sensors
Stress sensors
Thermal sensors

**Micro Actuators:**

Grippers, tweezers and tongs
Motors - linear and rotary
Relays and switches
Valves and pumps
Optical equipment (switches, lenses & mirrors, shutters, phase modulators, filters, waveguide splitters, latching & fiber alignment mechanisms)

**Microsystems = sensors + actuators + signal transduction:**

- Microfluidics, e.g. Capillary Electrophoresis (CE)
- Microaccelerometers (inertia sensors)

# Evolution of Microfabrication

- 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.

**Significant technological development towards miniaturization was initiated with the invention of transistors by three Nobel Laureates, W. Schockley, J. Bardeen and W.H. Brattain of Bell Laboratories in 1947.**

**This crucial invention led to the development of the concept of integrated circuits (IC) in 1955, and the production of the first IC three years later by Jack Kilby of Texas Instruments.**

**ICs have made possible for miniaturization of many devices and engineering systems in the last 50 years.**

**The invention of transistors is thus regarded as the beginning of the *3rd Industrial Revolution* in human civilization.**

# *Introduction to MEMS Fabrication*

## Microfabrication
by physical-chemical processes

## Traditional Manufacturing
by machine tools

# *Materials for fabricating Micro/ Nano-systems*

- Silicon and microelectronic materials
- Glass, Quartz
- Polymers
  - Poly (dimethylsiloxane) (PDMS)
  - Poly (methyl methacrylate) (PMMA)
  - Teflon, etc.

# *Materials for MEMS*

## Silicon – an ideal substrate material for MEMS

- Silicon (Si) is the most abundant material on earth. It almost always exists in compounds with other elements.

- Single crystal silicon is the most widely used substrate material for MEMS and microsystems.

- The popularity of silicon for such application is primarily for the following reasons:

  (1) It is mechanically stable and it is feasible to be integrated into electronics on the same substrate (b/c it is a semiconducting material).

  (2) Electronics for signal transduction such as the p or n-type piezoresistive can be readily integrated with the Si substrate-ideal for transistors.

  (3) Silicon is almost an ideal structure material. It has about the same Young's modulus as steel (~ $2\times10^5$ MPa), but is as light as aluminum with a density of about 2.3 g/cm$^3$.

# Silicon – an ideal substrate material for MEMS-Cont'd

(4) It has a melting point at 1400°C, which is about twice higher than that of aluminum. This high melting point makes silicon dimensionally stable even at elevated temperature.

(5) Its thermal expansion coefficient is about 8 times smaller than that of steel, and is more than 10 times smaller than that of aluminum.

(6) Silicon shows virtually no mechanical hysteresis. It is thus an ideal candidate material for sensors and actuators.

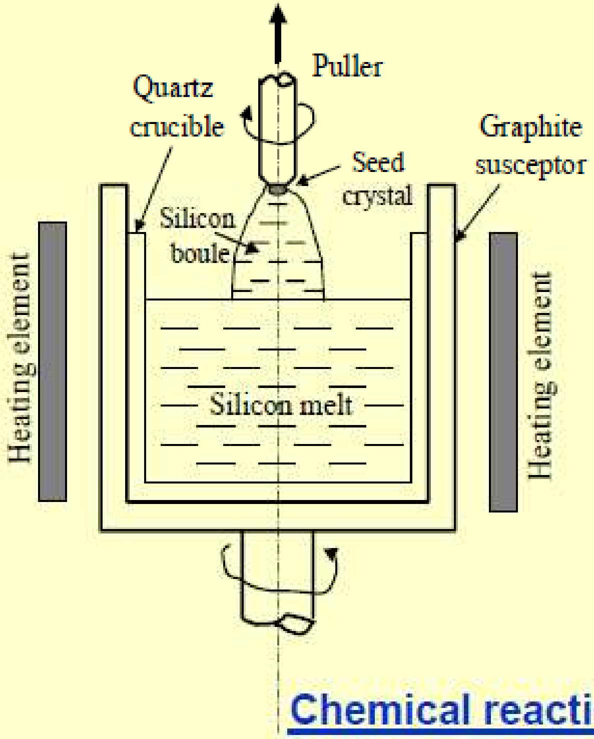
(7) Silicon wafers are extremely flat for coatings and additional thin film layers for either being integral structural parts, or performing precise electromechanical functions.

(8) There is a greater flexibility in design and manufacture with silicon than with other substrate materials. Treatments and fabrication processes for silicon substrates are well established and documented.

# 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) Raw Si (quartzite) + coal, coke, woodchips) are melted in the crucible.

(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.

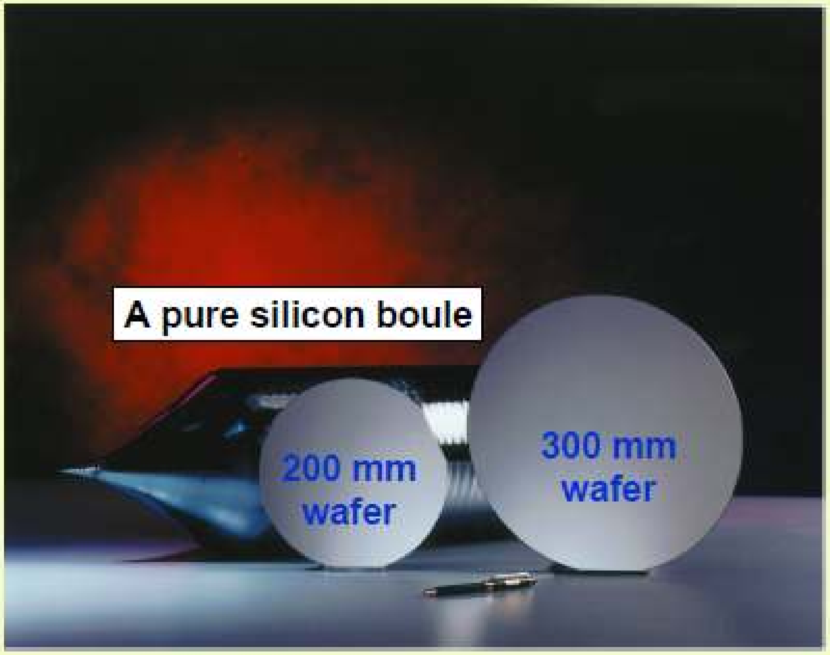
(4) The diameters of the "bologna-like" boules vary from 100 mm (4") to 300 mm (12") in diameters.

Chemical reaction for the process: $SiC + SiO_2 \rightarrow Si + CO + SiO$

# Pure silicon wafers

Pure silicon boules of 300 mm diameter and 30 ft long, can weigh up to 400 Kg.

These boules are sliced into thin disks (wafers) using diamond saws.

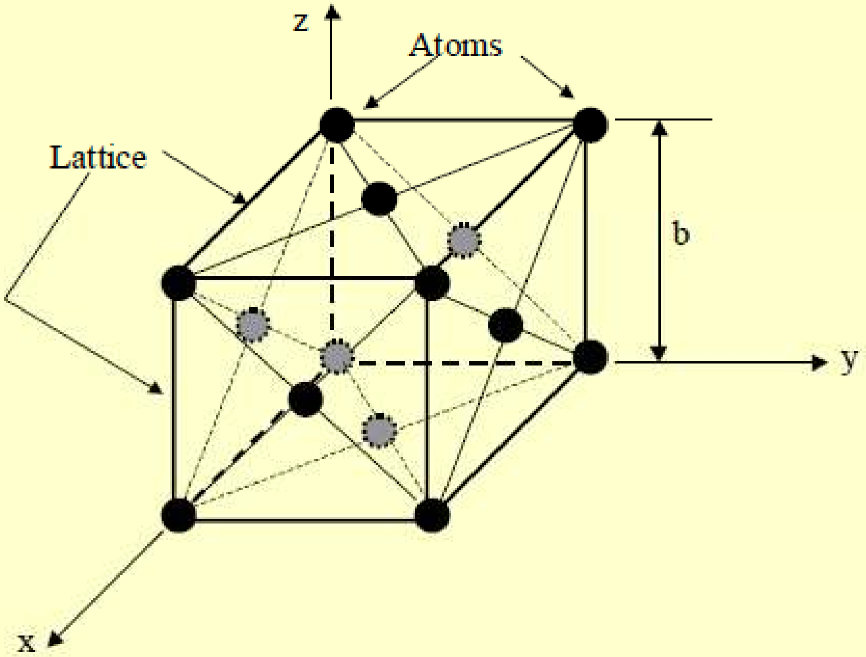


Standard sizes of wafers are:

100 mm (4") diameter x 500 μm thick.
150 mm (6") diameter x 750 μm thick.
200 mm (8") diameter x 1 mm thick
300 mm (12") diameter x 750 μm thick (tentative).

# Single Silicon Crystal Structure

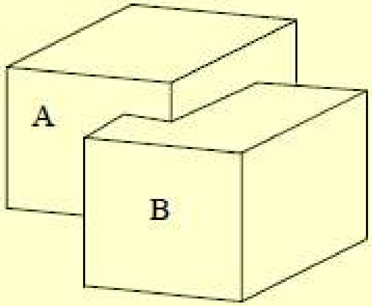
- Single silicon crystals are basically of "face-cubic-center" (FCC) structure.
- The crystal structure of a typical FCC crystal is shown below:



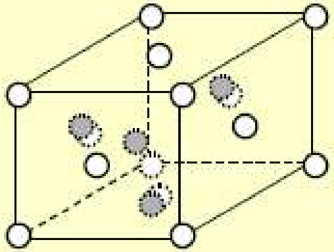
**Note:** Total number of atoms: 8 at corners and 6 at faces = **14 atoms**

# Single Silicon Crystal Structure-Cont'd

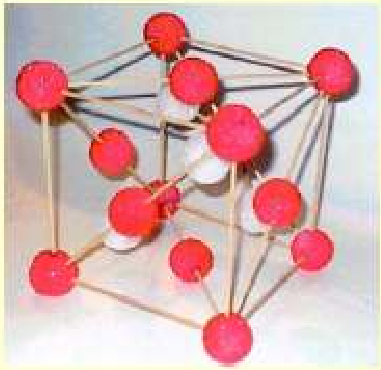
- Single crystal silicon, however has 4 extra atoms in the interior.
- The situation is like to merge two FCC crystals together as shown below:



(a) Merger of two FCC



(b) Merged crystal structure



- Total no. of atoms in a single silicon crystal = 18.

- The unsymmetrical distribution of atoms within the crystal make pure silicon anisotropic in its mechanical properties.

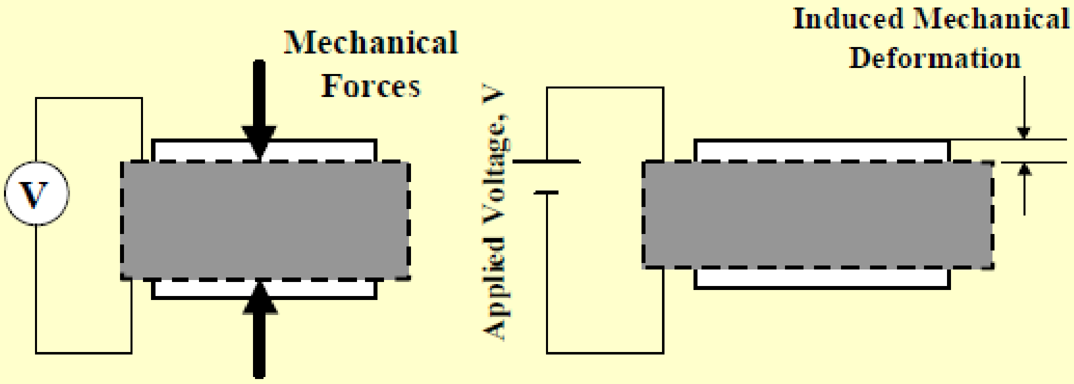
- In general, however, we treat silicon as an isotropic material.

## Quartz

- Quartz is a compound of $SiO_2$.
- Quartz is ideal material for sensors because of its extreme dimensional stability.
- It is used as piezoelectric material in many devices.
- It is also excellent material for microfluics systems used in biomedical applications.
- It offers excellent electric insulation in microsystems.
- A major disadvantage is its hard in machining. It is usually etched in HF/NH4F into desired shapes.
- Quartz wafers up to 75 mm diameter by 100 µm thick are available commercially.

# Piezoelectric Crystals

- Piezoelectric crystals are solid ceramic compounds that produce piezoelectric effects:



Mechanical force induced electric voltage ↔ Electric voltage induced mechanical deformation

- Natural piezoelectric crystals are: quartz, tourmaline and sodium potassium tartrate.

- Synthesized crystals are: Rochelle salt, barium titanate and lead zirconate.

# Polymers

**What is polymer?**

Polymers include: Plastics, adhesives, Plexiglass and Lucite.

**Principal applications of polymers in MEMS:**

- Currently in biomedical applications and adhesive bonding.
- New applications involve using polymers as substrates with electric conductivity made possible by doping.

**Molecular structure of polymers:**

- It is made up of long chains of organic (hydrocarbon) molecules.
- The molecules can be as long as a few hundred nm.

**Characteristics of polymers:**

- Low melting point; Poor electric conductivity
- Thermoplastics and thermosets are common industrial products
- Thermoplastics are easier to form into shapes.
- Thermosets have higher mechanical strength even at temperature up to 350°C.

## Polymers as industrial materials

Polymers are popular materials used for many industrial products for the following advantages:

- Light weight
- Ease in processing
- Low cost of raw materials and processes for producing polymers
- High corrosion resistance
- High electrical resistance
- High flexibility in structures
- High dimensional stability

## Polymers for MEMS and microsystems

(1) Photo-resist polymers are used to produce masks for creating desired patterns on substrates by photolithography technique.
(2) The same photoresist polymers are used to produce the prime mold with desirable geometry of the MEMS components in a LIGA process in micro manufacturing.
(3) Conductive polymers are used as “organic” substrates for MEMS and microsystems.
(4) The ferroelectric polymers that behave like piezoelectric crystals can be used as the source of actuation in micro devices such as in micro pumping.
(5) The thin Langmuir-Blodgett (LB) films can be used to produce multilayer microstructures.
(6) Polymers with unique characteristics are used as coating substance to capillary tubes to facilitate effective electro-osmotic flow in microfluidics.
(7) Thin polymer films are used as electric insulators in micro devices, and as dielectric substance in micro capacitors.
(8) They are widely used for electromagnetic interference (EMI) and radio frequency interference (RFI) shielding in microsystems.
(9) Polymers are ideal materials for encapsulation of micro sensors and the packaging of other microsystems.

# Conductive Polymers

- Polymers are poor electric conducting materials by nature.

Some polymers can be made electrically conductive by the following 3 methods:

## (1) Pyrolysis:

at 600°C

Pyropolymer-base Phthalonitrile resin + Amine = Conductive polymer as high as $2.7 \times 10^4$ S/m

## (2) Doping:

Introducing metal atoms into molecular matrices of polymers

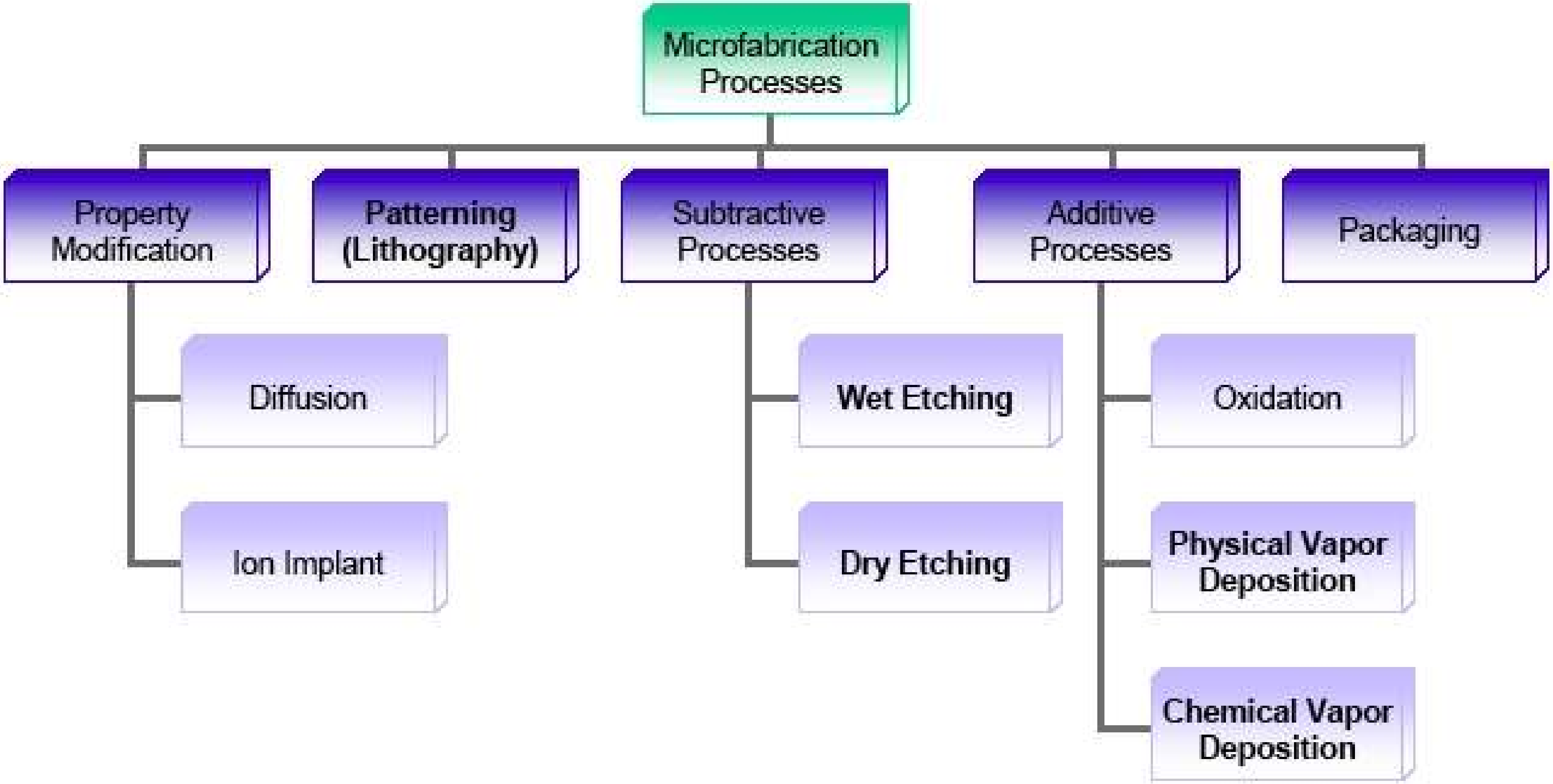
→ Conductive polymers

| Polymers groups | Dopants |
|---|---|
| Polyacetylenes (PA) | $Br_2$, $I_2$, $AsF_5$, $HClO_4$ and $H_2SO_4$ for p-type<br>Sodium naphthalide in tetrahydrofuran for n-type |
| Polyparaphenylenes (PPP) | $AsF_5$ for p-type; alkali metals for n-type |
| Polyphenylene sulfide (PPS) | $AsF_5$ |

## (3) Insertion of conductive fibers:

Fibers made of Au, Ag, stainless steel, aluminum fibers and flakes.

# *Taxonomy of Microfabrication Processes*



Microfabrication Processes

Property Modification

Diffusion

Ion Implant

Patterning (Lithography)

Subtractive Processes

Wet Etching

Dry Etching

Additive Processes

Oxidation

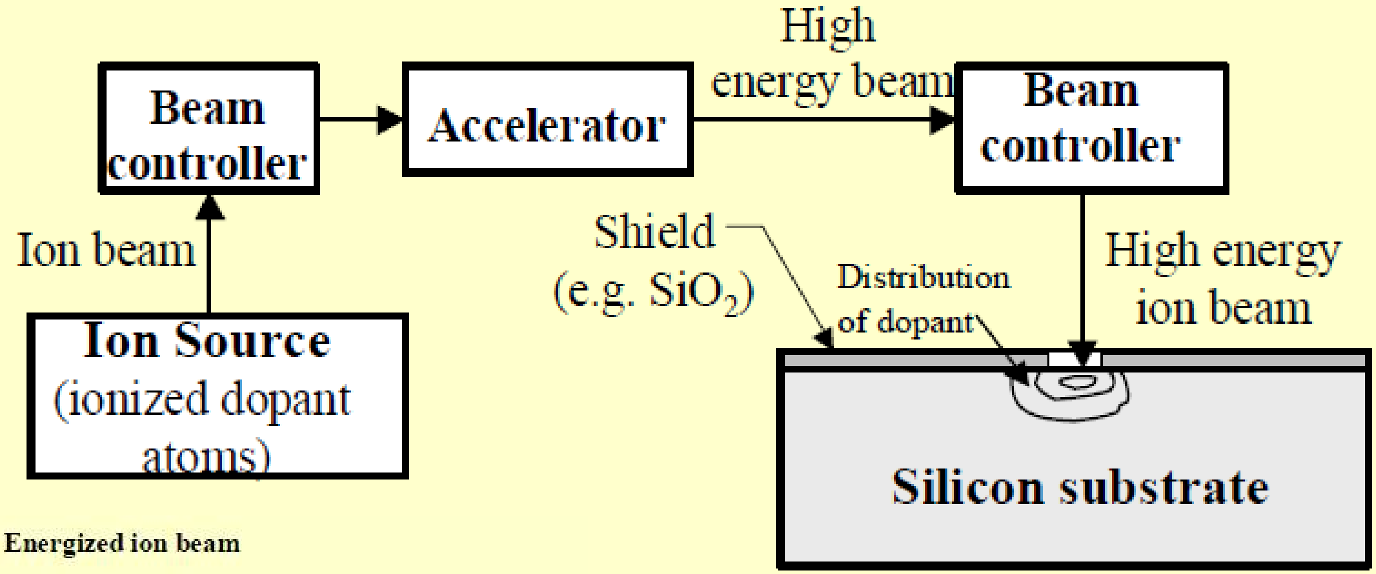
Physical Vapor Deposition

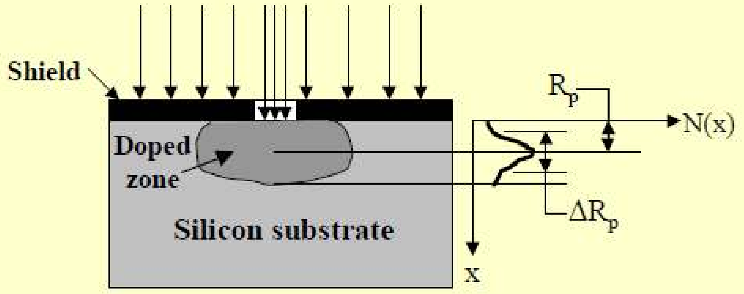
Chemical Vapor Deposition

Packaging

# *Ion Implantation*

- It is physical process used to dope silicon substrates.
- It involves “forcing” free charge-carrying ionized atoms of B, P of As into silicon crystals.
- These ions associated with sufficiently high kinetic energy will be penetrated into the silicon substrate.
- Physical process is illustrated as follows:

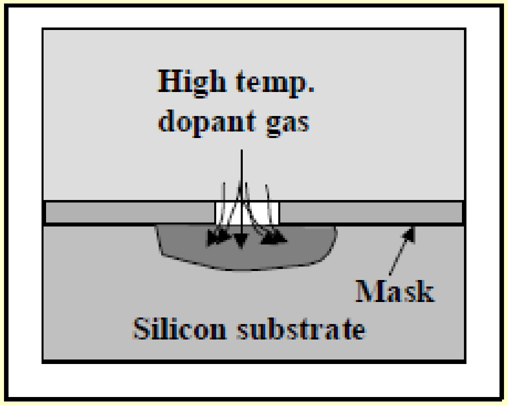




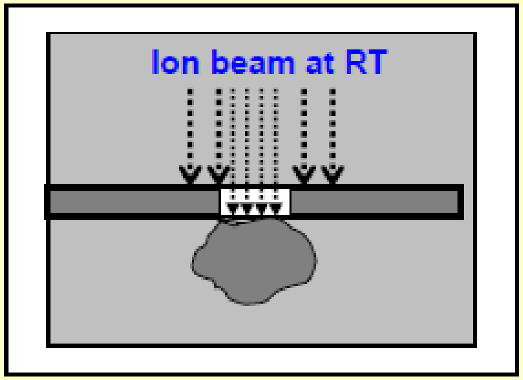
$$N(x)=\frac{Q}{\sqrt{2\pi}\,\Delta R_p}\exp\left[\frac{-\left(x-R_p\right)^2}{2\Delta R_p^2}\right]$$

# Diffusion

- Diffusion is another common technique for doping silicon substrates.
- Unlike ion implantation, diffusion takes place at high temperature.
- Diffusion is a chemical process.
- The profile of the spread of dopant in silicon by diffusion is different from that by ion implantation:



Dopant profile by Diffusion

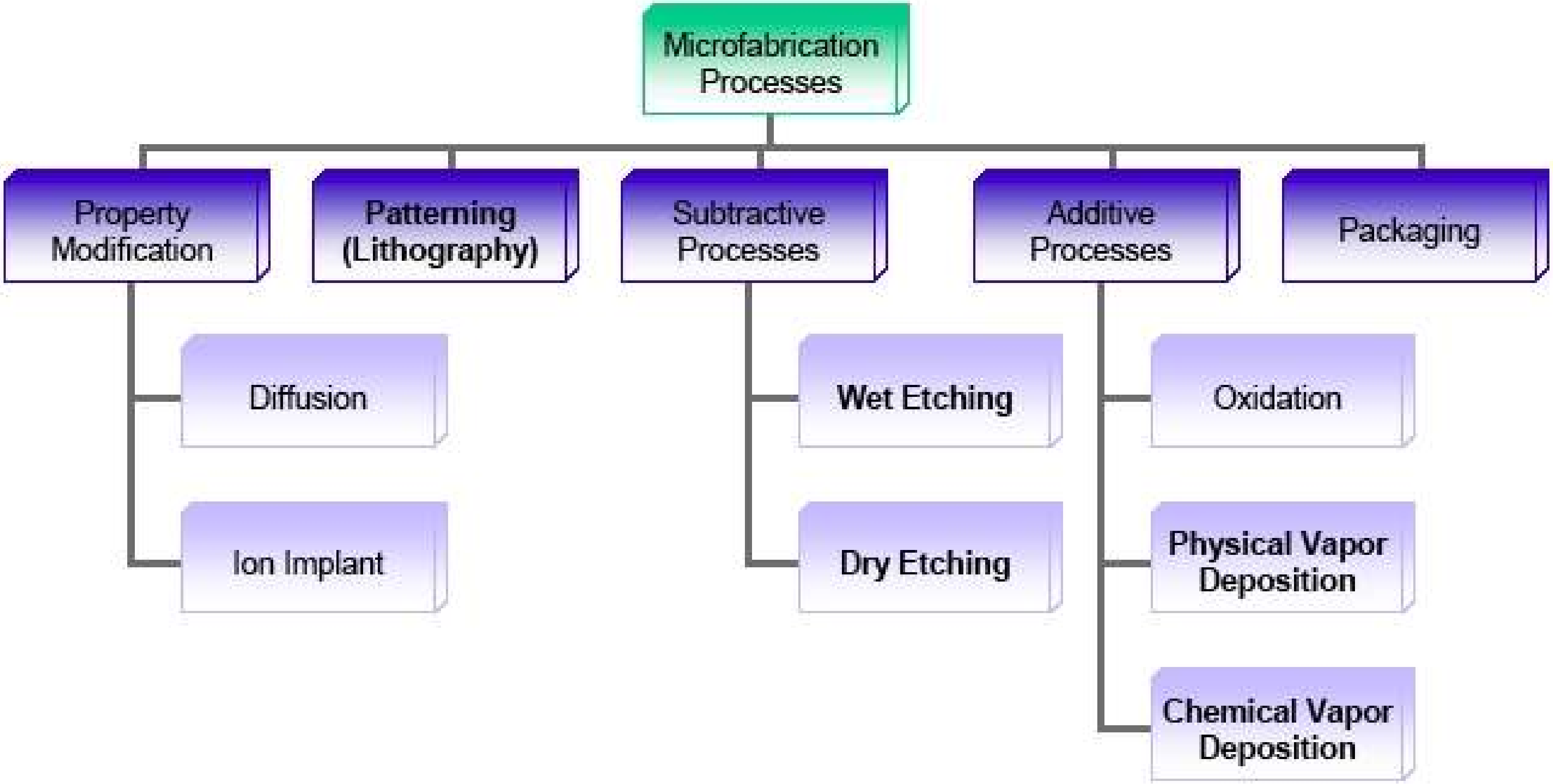


Dopant profile by ion implantation

**Fick's Law:** $$F = -D\frac{\partial N(x)}{\partial x}$$

$F$: dopant flux
$D$: diffusion coefficient
$N$: dopant concentration

# Taxonomy of Microfabrication Processes



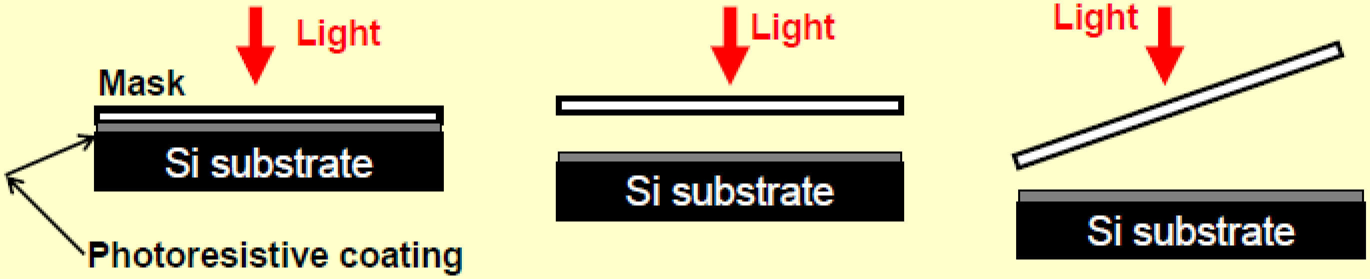
# *Photolithography*

**Photolithography** process involves the use of an **optical image** and a **photosensitive film** to produce **desired patterns** on a substrate.

The **desired patterns are first printed on light-transparent mask**, usually made of quartz.

The mask is then placed above the top-face of a silicon substrate coated with thin film of **photoresistive** materials.

The mask can be in contact with the photoresistave material, or placed with a gap, or inclined to the substrate surface:



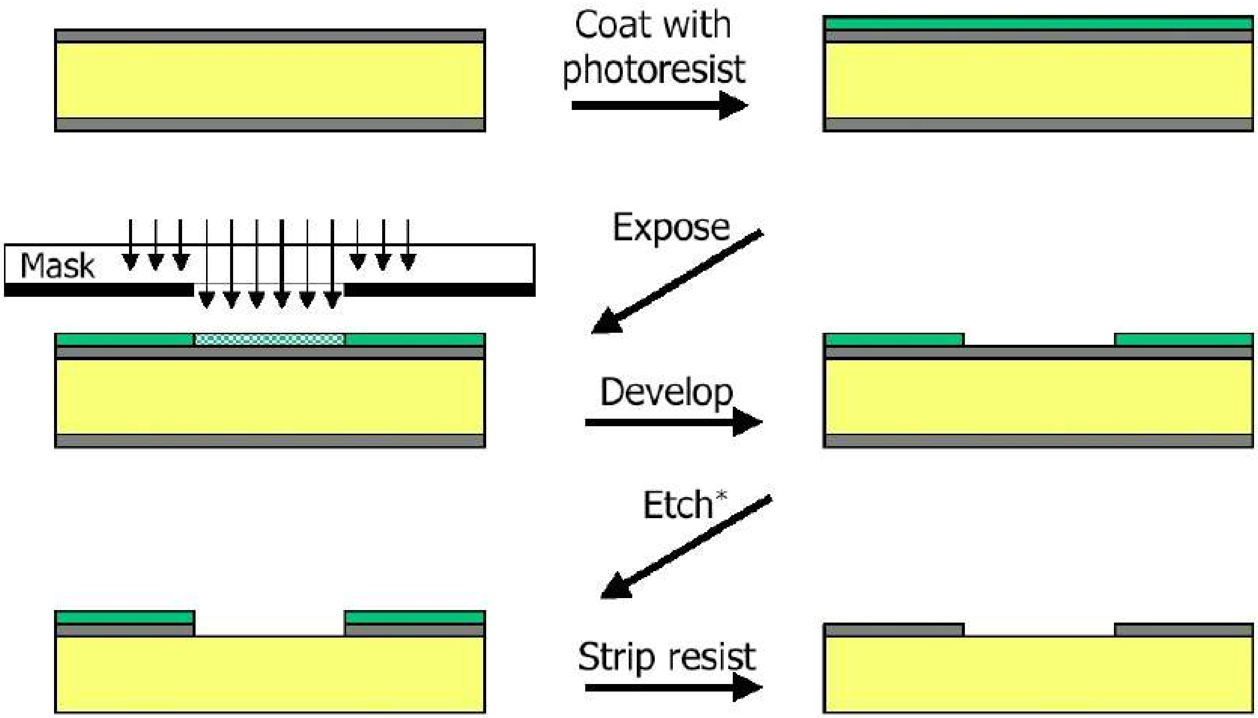
# INTRODUCTION TO THE LITHOGRAPHY PROCESS

## Ten Basic Steps of Photolithography

1. Surface Preparation
2. Photoresist Application
3. Soft Bake
4. Align & Expose*
5. Develop
6. Hard Bake
7. Inspection
8. Etch
9. Resist Strip
10. Final Inspection

** Some processes may include a Post-exposure Bake*

# Photolithography



Coat with photoresist

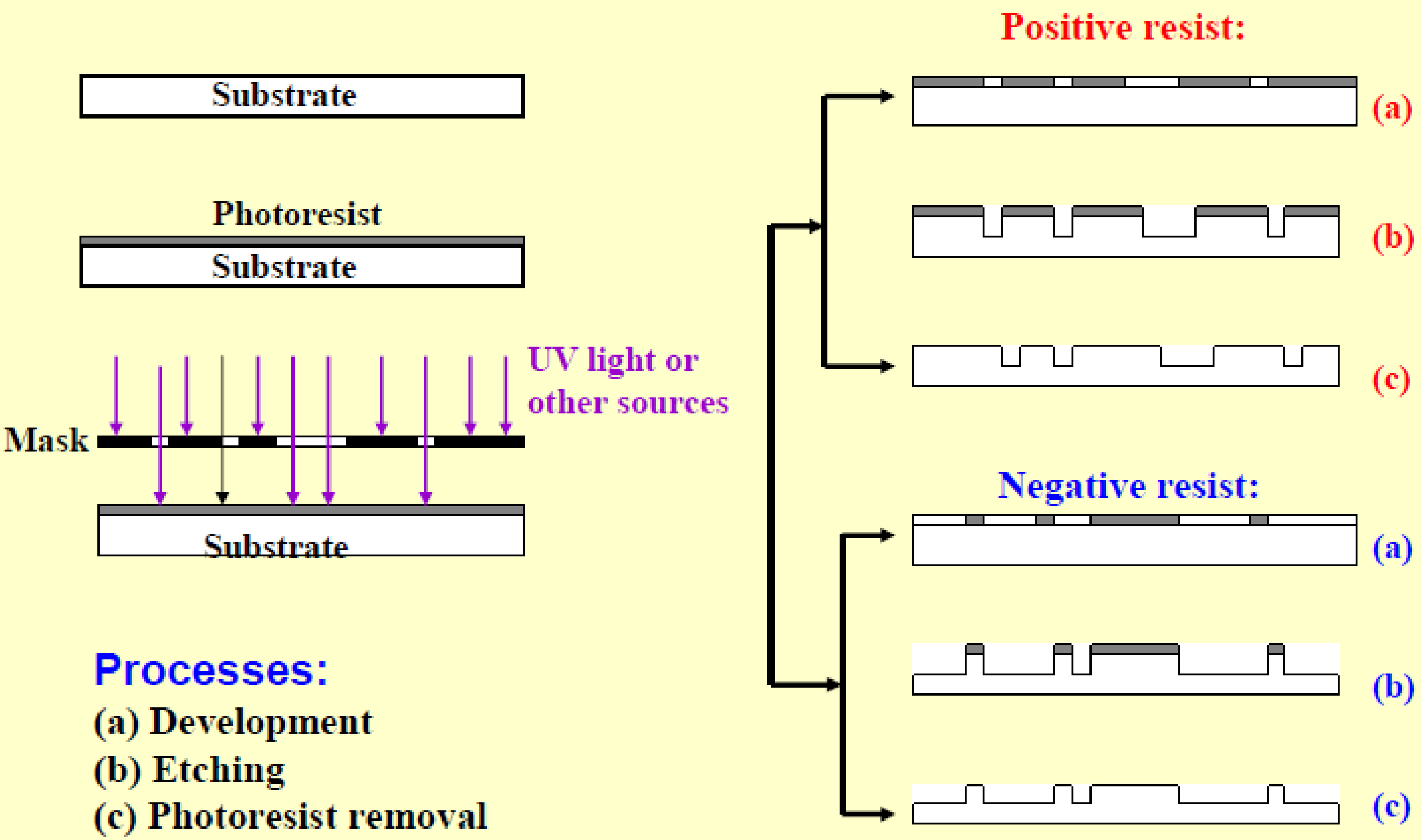
Expose

Develop

Etch*

Strip resist

# *Photolithography*

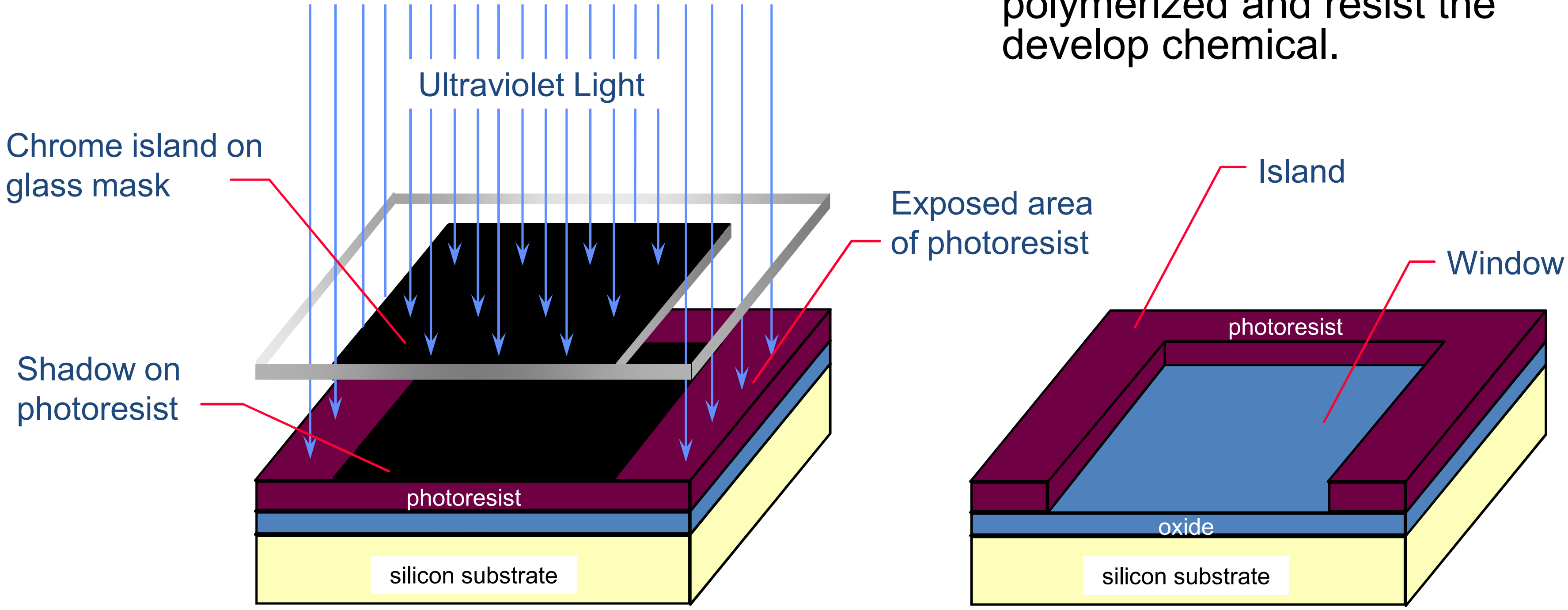


**Processes:**

(a) Development
(b) Etching
(c) Photoresist removal

# *Negative Lithography*

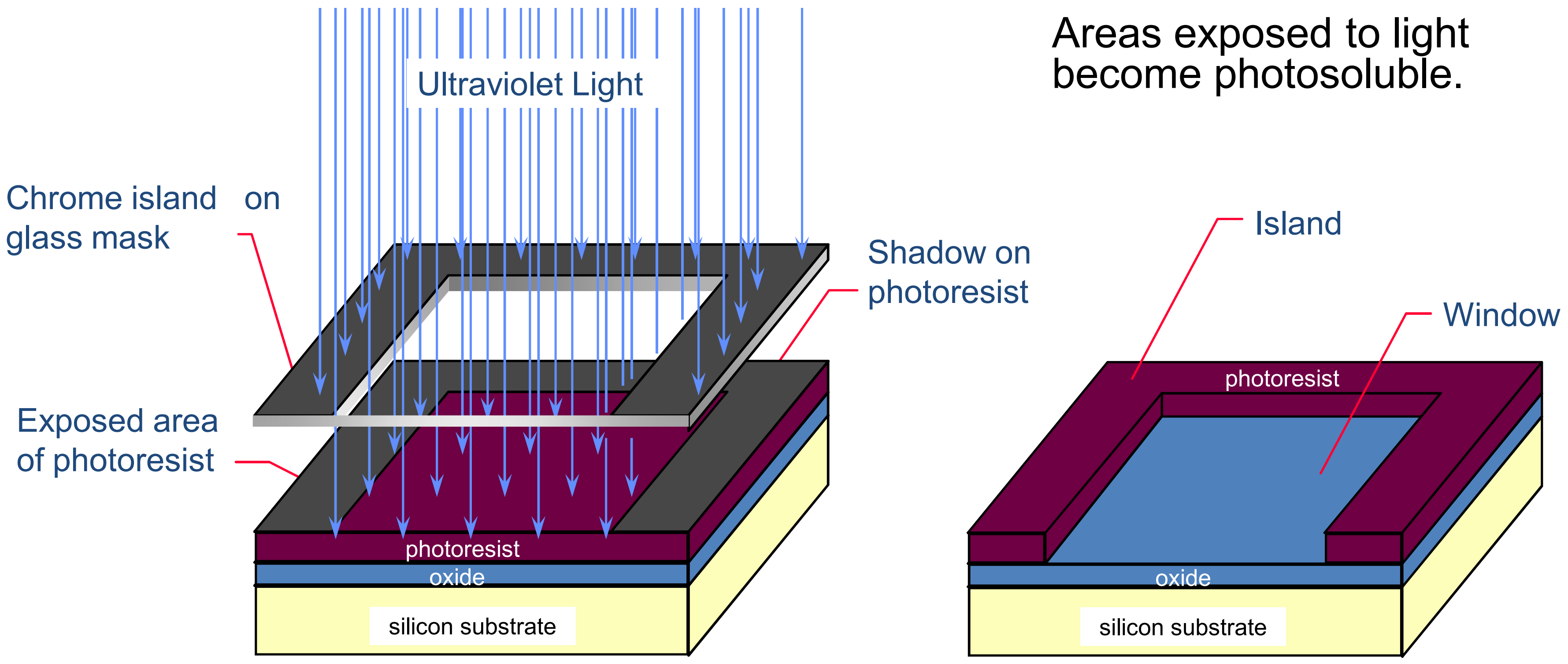
Areas exposed to light become polymerized and resist the develop chemical.



Resulting pattern after the resist is developed.

# *Positive Lithography*

Areas exposed to light become photosoluble.



Resulting pattern after the resist is developed.