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What is Nanotechnology?

Nanotechnology is the study, design, and application of materials and devices at the nanometer scale (1–100 nm). It involves manipulating matter at the atomic and molecular level to create new materials with unique properties that differ significantly from their bulk counterparts.

Why is Nano Special?

When materials become extremely small, their properties (color, strength, conductivity, and reactivity) change due to quantum effects.

How Small is a Nanometer?
1 nm = meters (one billionth of a meter).
A human hair is about 80,000–100,000 nm thick!
A red blood cell is about 7,000 nm.

Why is the Nanoscale Range 1–100 nm?

The 1–100 nm range is used in nanoscience because materials in this size show new properties due to quantum mechanics. These properties make nanomaterials highly useful in electronics, medicine, energy, and other fields.

How is Nanotechnology Different from Regular Materials?

Example: Gold
Bulk gold is yellow and metallic.
At the nanoscale, gold appears red or blue and behaves differently.
Example: Silver Nanoparticles
Bulk silver is non-toxic.
Silver nanoparticles kill bacteria and viruses, making them useful in medicines and coatings.

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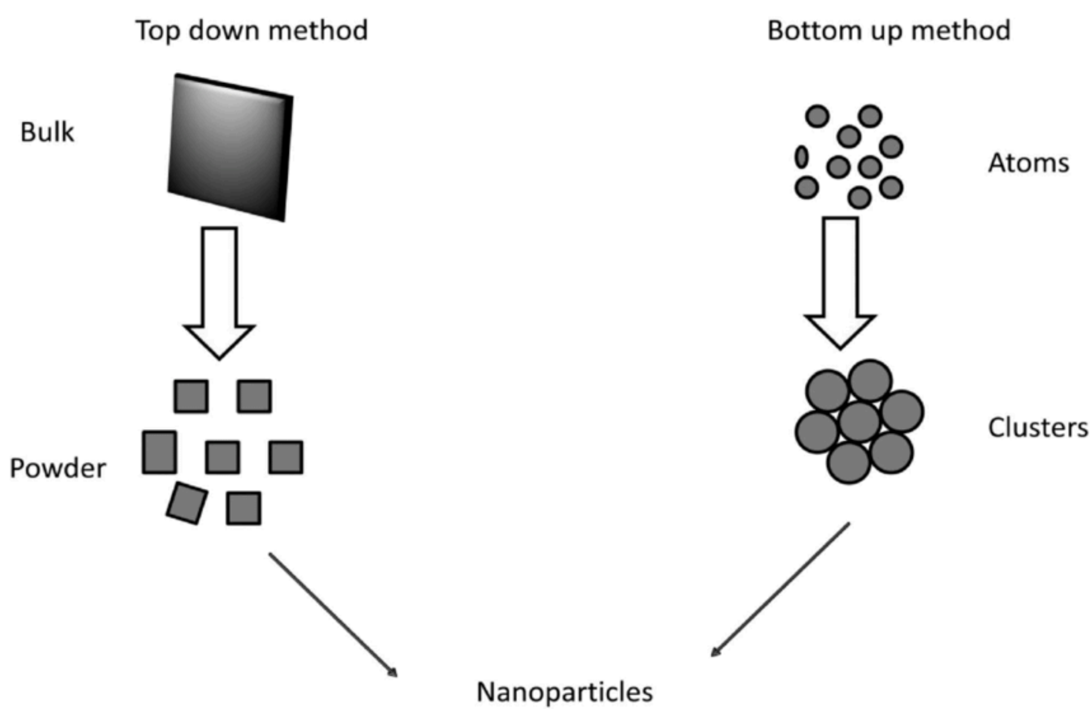
How are Nanomaterials Made?

Top-Down Approach: Breaking large materials into nanoscale parts (e.g., grinding, lithography).

Bottom-Up Approach: Building materials atom by atom (e.g., chemical synthesis, self-assembly).



Why is Nanotechnology Important?

Enhances material properties (stronger, lighter, more conductive).
Helps develop advanced medicines and electronics.
Supports environmental sustainability (clean water, renewable energy).

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Properties of nanomaterial

1.Electrical **2. optical** **3.Structural** **4. Mechanical**

Electrical Properties :

Electrical properties describe how a material conducts electricity, which depends on the behavior of electrons in the material. These properties are influenced by factors like band gap energy, charge mobility, and conductivity.

Classification of Materials Based on Electrical Properties:

Materials are categorized into conductors, semiconductors, and insulators based on their ability to conduct electricity.
This ability depends on the band gap (Eg)- the energy difference between the valence band (where electrons are bound) and the conduction band (where electrons move freely).

Conductors (Metals): No band gap or very small Eg (Eg ≈ 0 eV). Electrons easily move from the valence band to the conduction band, allowing free flow of electricity. Example: Copper, silver.

Semiconductors: Small band gap (Eg ≈ 1–3 eV). Electrons can jump to the conduction band when given enough energy (e.g., heat, light, voltage). Example: Silicon, germanium.

Insulators: Large band gap (Eg > 5 eV). Electrons cannot easily move to the conduction band, so these materials do not conduct electricity. Example: Glass, plastic.

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How Nanotechnology Affects Electrical Properties?

At the nanoscale (1–100 nm), materials exhibit quantum confinement, which significantly affects their electrical behavior.

(a) Quantum Confinement and Band Gap Expansion :- As a material's size decreases to the nanoscale, the energy gap (Eg) increases.This means more energy is required to move electrons from the valence band to the conduction band.
Effect: Some conductors behave like semiconductors, and semiconductors require higher energy to conduct.
Example: Gold (a good conductor in bulk form) can become a semiconductor at the nanoscale.

(b) Blue Shift in Optical Properties:- When band gap increases, a material absorbs higher-energy (shorter wavelength) light.This results in a blue shift where emitted light moves toward the blue end of the spectrum.
Application: Used in quantum dots for display technologies (e.g., QLED TVs).

(c) Surface Effects on Conductivity :- Nanomaterials have a higher surface-to-volume ratio, leading to increased electron interactions.This affects charge mobility, making nanomaterials more sensitive to external electric fields.

Applications of Nano-Engineered Electrical Properties

1. Nano-sized semiconductors improve speed and efficiency in microchips.
2. Quantum dots improve light absorption and efficiency
3. Nanomaterials enhance energy storage capacity.
4. Carbon nanotubes enable bendable electronic devices

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Optical properties :-

Optical properties describe how nanomaterials interact with light, including absorption, reflection, transmission, and scattering. These properties are different from bulk materials due to the small particle size and quantum effects. The unique behavior of nanomaterials is used in sensors, imaging, coatings, and optoelectronic devices.

1. Size Dependence: The interaction of light with nanoparticles changes as the particle size decreases, leading to color variations and increased transparency.

2. Scattering of Light: Smaller nanoparticles scatter light differently than larger particles, affecting color perception and making materials appear white (e.g., milk) or transparent (e.g., nanosized ZnO in sunscreen).

3. Localized Surface Plasmon Resonance (LSPR): In metal nanoparticles (e.g., gold and silver), free electrons oscillate at a specific frequency when exposed to light, producing intense colors like red, purple, or orange.

4. Quantum Confinement: In semiconductor nanoparticles (e.g., quantum dots), energy levels become discrete, altering light absorption and emission. Smaller particles have a higher energy band gap, leading to a blue shift in emission.

5. Interference Effects: In nanostructures like butterfly wings or photonic crystals, light waves interfere constructively and destructively, producing iridescent colors.

6. Transmission and Transparency: In nanomaterials, reducing particle size increases light transmission, making materials more transparent (e.g., nanosized TiO_2 in sunscreen).

Examples and Applications

1. Metal Nanoparticles (Gold/Silver): Used in biosensors, imaging, and color-changing materials due to LSPR effects.
2. Quantum Dots: Used in LED displays, bio-imaging, and solar cells due to tunable light emission.
3. Photonic Crystals (Butterfly Wings): Inspire anti-counterfeiting measures and optical coatings.
4. Nanocoatings in Sunscreens: Enhance UV protection while maintaining transparency.

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Structural properties:-

Nanomaterials exhibit unique structural properties, including high surface area to volume ratio, quantum effects, and size-dependent properties, which lead to enhanced mechanical, optical, electrical, and chemical characteristics compared to their bulk counterparts.

1.High Surface Area to Volume Ratio:-
As the size of a material decreases, its surface area increases compared to its volume.
This leads to higher reactivity, better adsorption, and enhanced catalytic properties.
Example: Gold nanoparticles act as excellent catalysts because more atoms are available for reactions.

2. Quantum Effects (Quantum Confinement):-
When the size of a nanoparticle becomes smaller than the wavelength of electrons, its energy levels become discrete (quantized).
This alters optical, electrical, and magnetic properties.
Example: Quantum dots emit different colors depending on their size due to changes in electron energy levels.

3. Size-Dependent Properties:-
At the nanoscale, properties like strength, conductivity, and color change with size.
Example: Bulk gold is yellow, but gold nanoparticles appear red or blue due to quantum confinement.
Mechanical strength increases in nanomaterials due to lattice strain and more grain boundaries.

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Mechanical properties :-

Mechanical properties describe how materials respond to applied forces. In nanomaterials, these properties change significantly due to their small size, high surface area, and quantum effects. Compared to bulk materials, nanomaterials often exhibit higher strength, hardness, elasticity, and wear resistance.

1.High Strength – Nanomaterials are much stronger than bulk materials due to fewer defects. (Example: Carbon nanotubes are stronger than steel.)

2.Increased Hardness – Small grain size increases hardness, making nanomaterials resistant to scratches and wear. (Example: TiN coatings in cutting tools.)

3.Better Elasticity – Some nanomaterials can stretch without breaking. (Example: Graphene can stretch up to 20%.)

4.Ductility & Brittleness

Nanometals → More ductile (flexible).
Nano ceramics → Brittle but sometimes tougher.

5.Toughness – Can resist cracks and fractures better than bulk materials. (Example: Nanostructured titanium alloys in aerospace.)

6.Wear Resistance – Less surface damage, making them ideal for coatings. (Example: Protective coatings in aerospace & medical implants.)

7.Fatigue Resistance – Can withstand repeated stress without failure. (Example: Nanometals in automobile engines.)

8.Superplasticity – Can be easily shaped at high temperatures. (Example: Nano ceramics in heat-resistant materials.)

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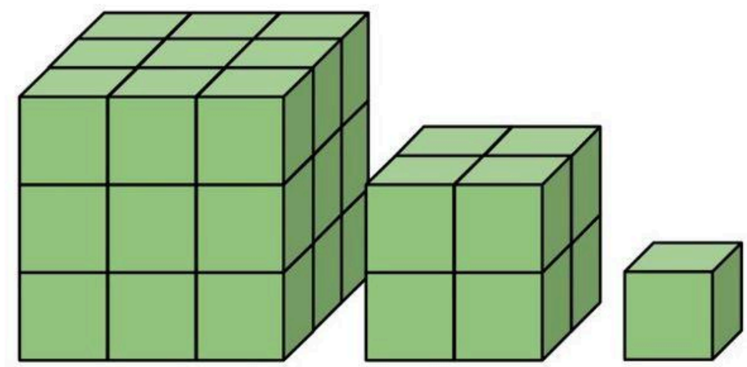
Surface-to-Volume Ratio in Nanotechnology

In nanotechnology, the surface-to-volume ratio (S/V ratio) plays a critical role because as particle size decreases to the nanoscale (1–100 nm), the proportion of atoms at the surface increases significantly compared to those inside the material. This leads to unique physical and chemical properties, making nanomaterials more reactive, efficient, and functional in various applications.

For example, in a bulk material, most atoms are inside the structure, while only a small percentage are at the surface. However, when the material is broken down into nanoparticles, a larger fraction of atoms is exposed at the surface, leading to enhanced interactions with the environment.



Formula for Surface-to-Volume Ratio

For a sphere of radius r the surface area and volume are:

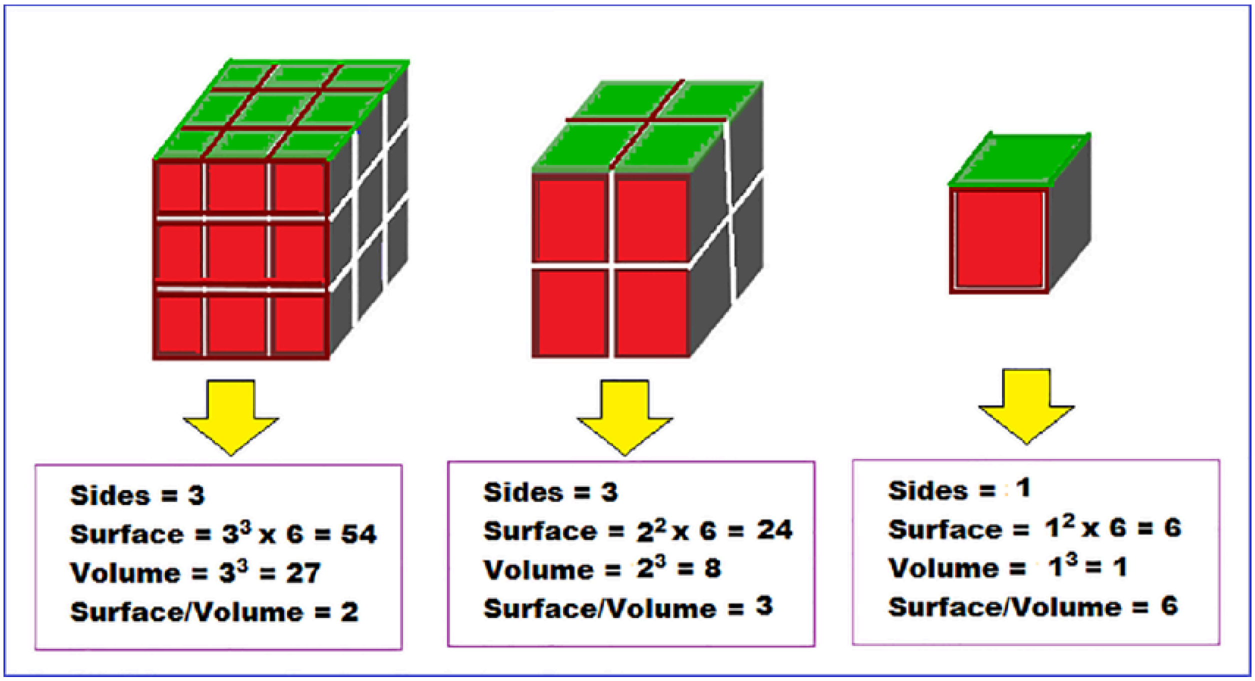
Surface Area: $\mathbf{A = 4\pi r^2}$

Volume : $\mathbf{V = 4/3\ \pi\ r^3}$

The surface-to-volume ratio is given by: $\frac{\text{Surface Area}}{\text{Volume}} = \frac{4\ \pi\ r^2}{4/3\ \pi\ r^3}$

Simplifying, we get: S/V = 3 / r

This equation shows that as the radius decreases, the surface-to-volume ratio increases. This is why nanoparticles (which have very small r) have a much higher surface area compared to their volume.



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Importance of Surface-to-Volume Ratio in Nanotechnology

The surface-to-volume ratio (SVR) increases significantly as the size of a material decreases to the nanoscale. This leads to unique properties that make nanomaterials highly useful in various applications.

1. Increased Reactivity: Higher SVR means more surface atoms, leading to enhanced chemical reactivity. This is useful in catalysis and drug delivery.

2. Improved Catalytic Activity: More active sites on the surface speed up chemical reactions, making nanomaterials efficient catalysts.

3. Lower Melting Points: Due to weaker atomic bonds at the surface, nanoparticles have lower melting points than bulk materials.

4. Optical Properties: The high SVR affects electronic and optical properties, enabling applications in imaging and sensors.

5. Enhanced Mechanical Strength: Nanomaterials exhibit higher strength and hardness due to restricted dislocation movement.

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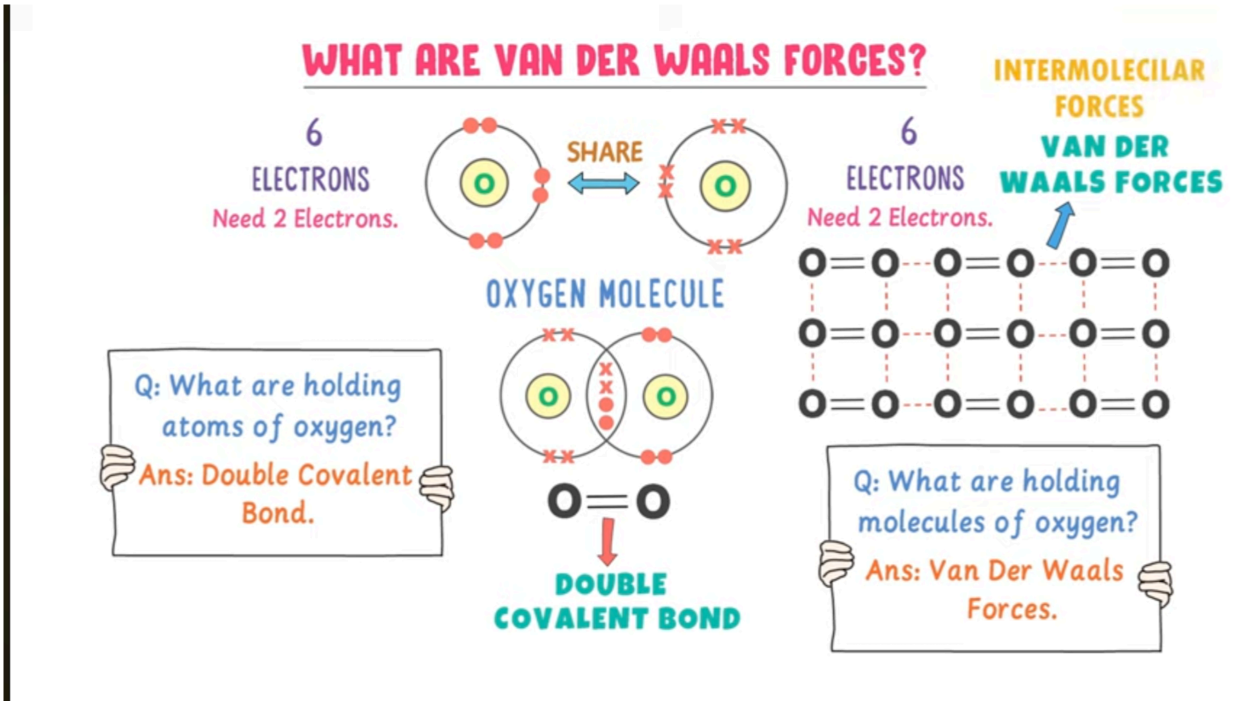
Bonding in solids van der Waals interactions in Nanotechnology :-
Van Der Waals forces are weak intermolecular attractions due to temporary dipoles in atoms or molecules.



2.Importance in Nanotechnology:
These forces dominate at the nanoscale where surface interactions are significant. They help in stabilizing nanoparticles and assembling nanostructures.

3.Examples in Nanotechnology:
- Carbon Nanotubes (CNTs): CNTs stick together due to Van der Waals forces, impacting their mechanical and electrical properties.
- Graphene Sheets: Layers of graphene are held by Van der Waals forces, allowing easy separation or stacking.
- Nanoparticle Dispersion: In colloidal solutions, Van der Waals forces influence how nanoparticles cluster or remain dispersed.

Applications:
- Used in nano-coatings, drug delivery, and adhesives.
- Plays a role in self-assembly of nanostructures like DNA nanotechnology.

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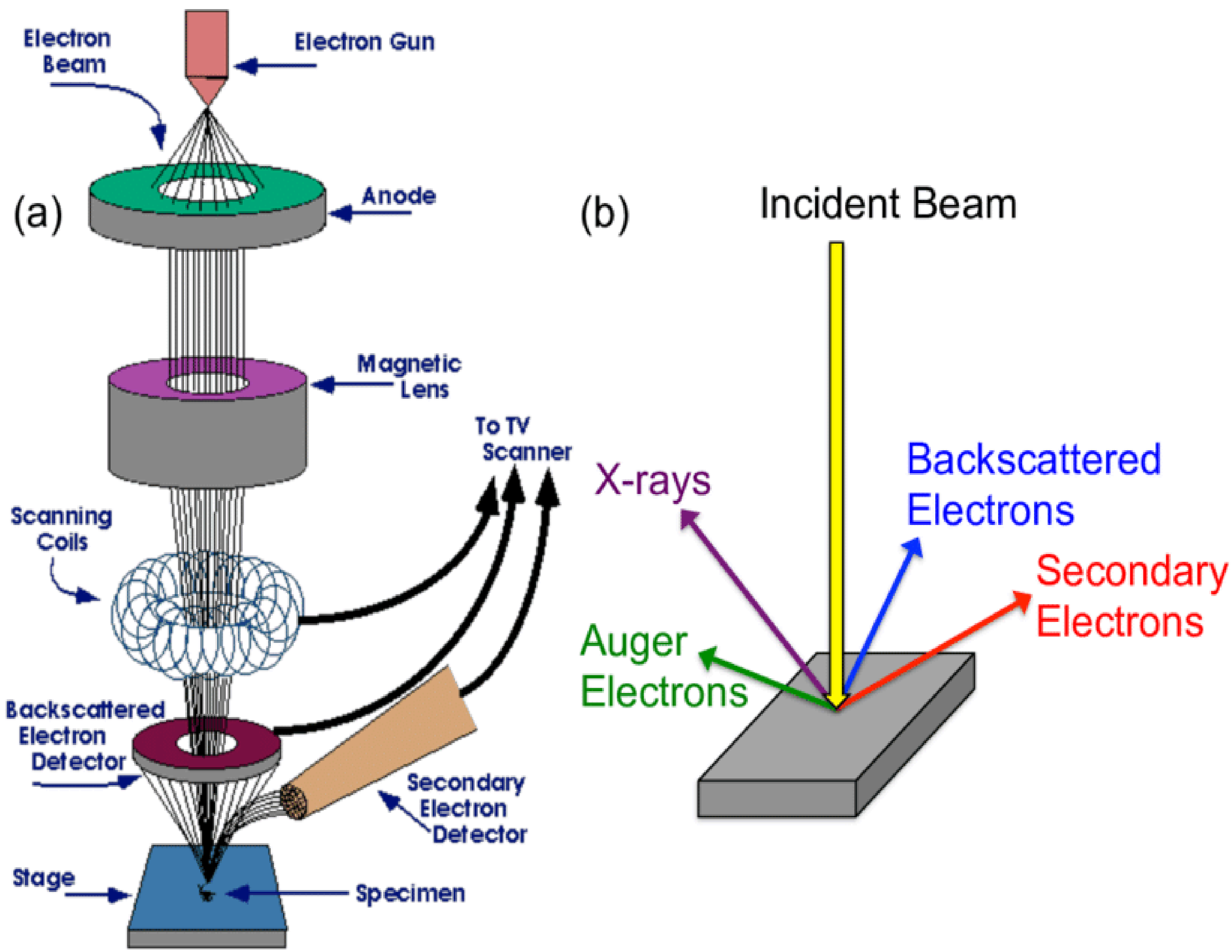
Scanning electron microscope (SEM):

Scanning electron microscope is a microscope that produces three dimensional image by using
an electron beam that scans the surface of a specimen inside a vacuum chamber.

Principle: When the accelerated primary electrons strikes the sample. It produces secondary electrons or backscattered electrons. These secondary electrons are collected by a positive charged electron detector and convert them into signal and an image is formed on screen.



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Construction:
It consists of an electron gun to produce high energy electron beam. A magnetic condensing lens is used to condense (narrow) the electron beam. When narrow electrons beam strike the sample, then contacting spot size is small. A scanning coil is arranged in-between magnetic condensing lens and the sample. The scanning coil deflects the electrons beam in the X and Y axes so that it can scans the surface in rectangular form. The objective lens is used to focus electrons beam onto sample. The electron detector (Scintillator) is used to collect the secondary electrons and can be converted into electrical signal.

Working:
A beam of electrons is produced by electron gun and these primary electrons are accelerated by
the grid and anode. These accelerated primary electrons hit on sample through condensing lenses
and scanning coil. These primary electrons produces secondary electrons or backscattered
electrons. The collection of secondary electrons are very difficult and hence a high voltage is
applied to the collector. These collected electrons produce scintillations on to the photo multiplier tube are converted into electrical signals. These signals are amplified by the video
amplifier and is fed to the CRO which produce an image.

Uses:
(1) study of topography and morphology.
(2) Study of crystallography.
(3) Chemistry.
(4) Study of orientation of grains.
(5) It provides detailed images of the surfaces of cells and whole organisms that are not possible by TEM.

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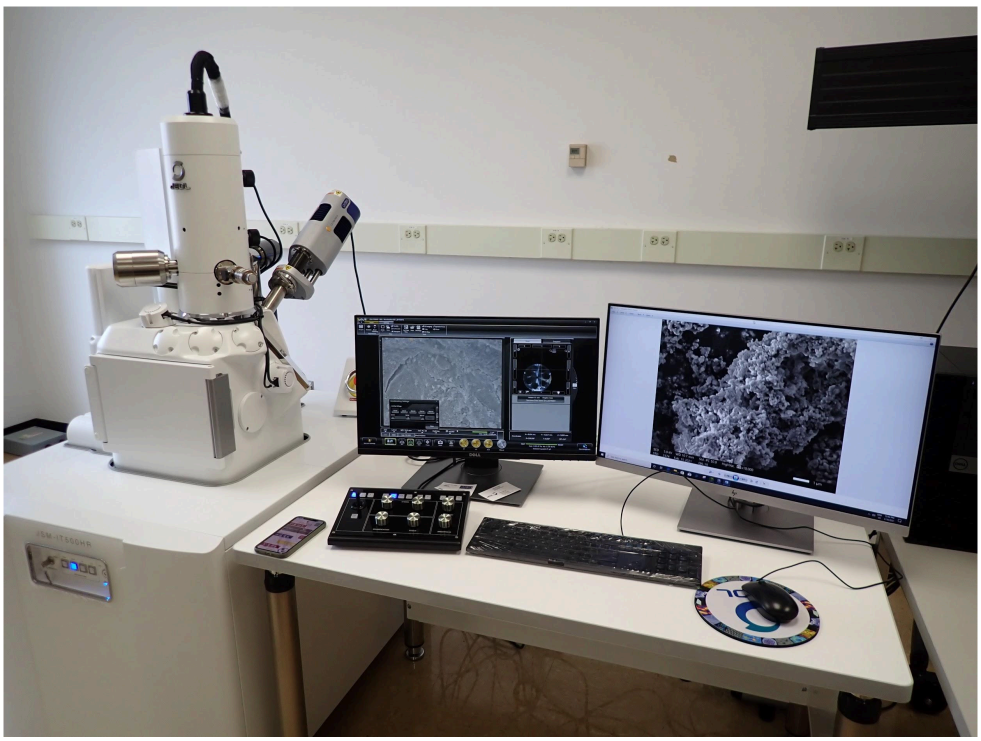
Advantages:
(1) Produces detailed three-dimensional and topographical images.
(2) Samples require a small amount of preparation.
(3) It perform fast scanning
(4) Easy to operate with training

Disadvantages:
(1) It typically has a lower resolution (>1 nm) than the TEM.
(2) Expensive to buy and run.
(3) Large (takes up lots of space)
(4) Needs to be in an environment where there is no electric, magnetic or vibration interference.



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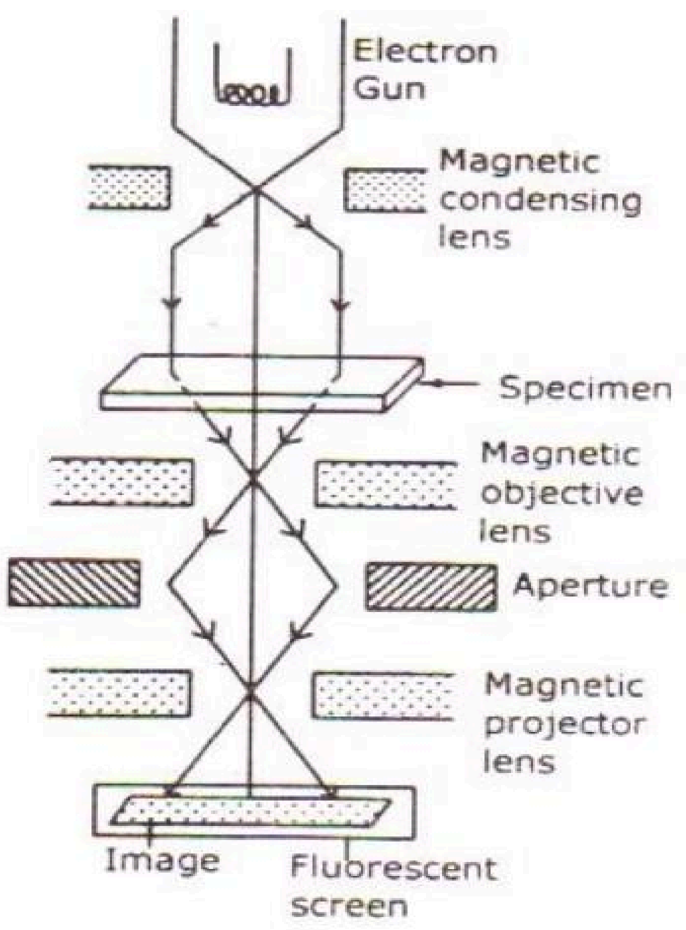
Transmission electron microscope (TEM):

Principle:
A Transmission Electron Microscope (TEM) works on the principle that a beam of high-energy electrons, when transmitted through an ultra-thin specimen, interacts with it to form an image. Since electrons have a much smaller wavelength than visible light, TEM provides extremely high-resolution images, allowing the visualization of atomic structures.



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Construction:

A TEM consists of the following main components:

- Electron Gun – Generates and accelerates electrons using a heated tungsten filament (cathode) and an anode.
- Condenser Lenses – Focus the electron beam onto the specimen.
- Specimen Holder – Holds the ultra-thin sample (typically 50–100 nm thick).
- Objective Lens – Forms the primary magnified image of the specimen.
- Intermediate & Projector Lenses – Further magnify and focus the image onto the screen or detector.
- Fluorescent Screen/Detector – Captures and displays the final image.

Working:

1. The electron gun emits a high-energy beam of electrons (typically 100-300 keV).
2. The condenser lenses focus the beam onto the thin specimen.
3. Some electrons pass through the specimen, while others are absorbed or scattered.
4. The transmitted electrons create an image, which is magnified by objective and projector lenses.
5. The final image is displayed on a fluorescent screen or recorded by a detector.

Uses:

(1) To view tissue section, molecules.

(2) The structure of protein molecules (contrasted by metal shadowing)

(3) The organization of molecules in viruses and cytoskeletal filaments (prepared by the negative staining technique),

(4) The arrangement of protein molecules in cell membranes (by freeze-fracture).

Advantages:

(1) It can provide information about surface features, shape, size and structure.

(2) High-quality image.

Disadvantages:

(1) The instruments are very large and expensive.

(2) Sample preparations from bulk materials are normally very time-consuming.

(3) Electron beam must penetrate the sample, making it impossible to examine structures on solid substrates.

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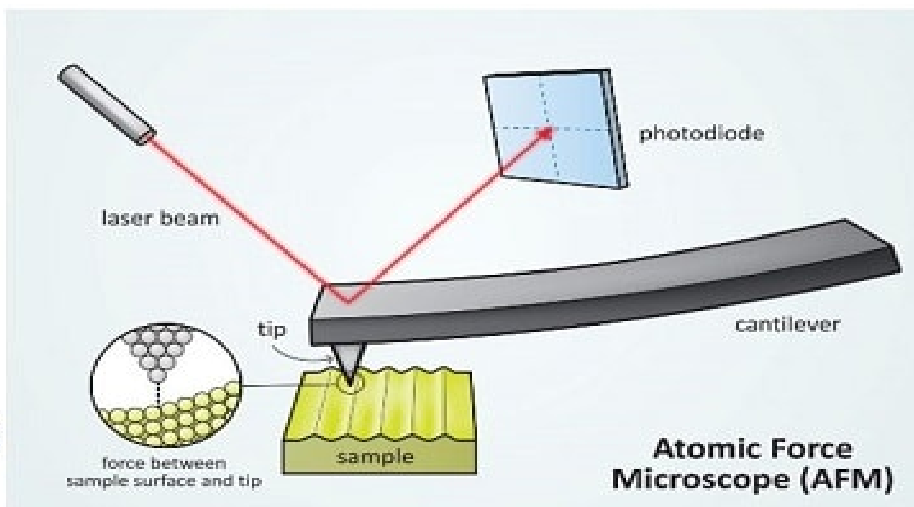
Atomic force microscope (AFM):

Atomic Force Microscopy (AFM) is a scanning probe microscopy technique that uses a sharp tip to "feel" a surface and create high-resolution images, measuring and visualizing materials at the atomic and nanoscale.

An Atomic Force Microscope (AFM) consists of following components:

1. LASER
2. Photodiode
3. Cantilever with a sharp tip: A rigid body fixed at one end and free end is exposed to vertical loads.
4. Detector and feedback circuit
5. Piezoelectric scanner: It is a scanner made from piezoelectric material, which expands and contracts proportionally to an applied voltage.



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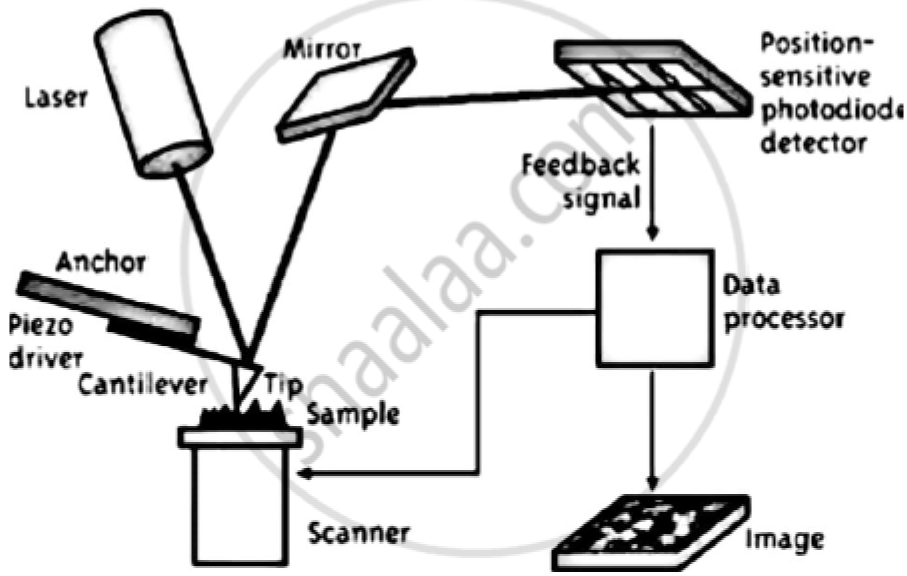

Working of Atomic Force Microscope:

(1) It is operated by a small tip (probe) to scan very closely across a surface.

(2) An AFM measures the force between the tip and the sample. A sharp tip is mounted on the end of a millimeter-sized cantilever, a force F exerted on the tip by the sample deflects the cantilever by x,

$$F = C\,x$$ where C is the force constant of the cantilever.

(3) The displacement of the cantilever is measured as a function of tip position, often by using the back of the cantilever as a reflector for a laser beam.

(4) Motion of the reflector changes the path of the laser beam, which is detected using a photodiode array, Pico meter-scale displacements can easily be measured.

(5) The force present in the tip is kept constant and the scanning is done. As the scanning Continues, the tip will have vertical movement depending upon the topography of the Sample.

(6) The tip has a mirror on the top of it, a laser beam is used to have the record of vertical Movements of needle.

(7) The Information is later converted to visible one.

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Advantages:

(1) Three-dimensional topography is measured with the AFM, directly revealing surface textures.
(2) AFM provides nanoscale resolution in surface imaging.
(3) AFM requires only minimal sample preparation.
(4) AFM is the only imaging technique to provide mechanical information on the surface.

Disadvantages:

(1) It gives a single scan image size.
(2) An AFM cannot scan images as fast as a SEM.
(3) The relatively slow rate of scanning during AFM imaging.
(4) AFM microscope less suited for measuring accurate distances between topographical features on the image.

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Applications of Nanotechnology in Sensing Toxic Gases

1. What is Toxic Gas Sensing?

Toxic gas sensors detect harmful gases by measuring changes in electrical, optical, or chemical properties when gas molecules interact with the sensor.

2. Types of Gas Sensors

- Metal Oxide Sensors (MOS) – Detect CO, NO_2, NH_3 using resistance changes.
- Electrochemical Sensors – Measure CO, H_2S, SO_2 via redox reactions.
- Infrared (IR) Sensors – Identify CO_2, CH_4 by absorption of IR light.
- Photoionization Detectors (PID) – Detect VOCs using UV ionization.
- Nanotechnology-based Sensors – Use graphene, CNTs, and metal nanoparticles for high sensitivity.

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3. Applications

- Industrial Safety – Prevent gas leaks (CO, NH_3, H_2S) in factories, mines, and oil refineries.

- Environmental Monitoring – Measure air pollution (NO_2, SO_2, CO) and greenhouse gases (CO_2, CH_4).

- Healthcare – Detect VOCs in breath for disease diagnosis, monitor oxygen & CO_2 in hospitals.

- Smart Cities & Homes – Air quality monitoring, gas leak detection in IoT-based systems.

- Defense – Detect chemical warfare agents and toxic fumes in military operations.

- Agriculture & Food Safety – Monitor ammonia in farms, detect ethylene gas in food storage.

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Gas Sensing Capacitors

Gas sensing capacitors detect gases by measuring changes in capacitance caused by interactions between gas molecules and a dielectric material. These changes occur due to adsorption, diffusion, or chemical reactions, altering the dielectric constant (εr) or dielectric thickness (d).

1. Working Principle

A gas sensing capacitor consists of:

Two electrodes (conducting plates)

A dielectric material (sensitive to gas molecules)

When a gas interacts with the dielectric, it changes the dielectric constant (ε_r) or thickness (d), leading to a change in capacitance.
The capacitance is given by:

$$C = \varepsilon_0 \varepsilon_r A/d$$

ε_0 = Permittivity of free space
ε_r = Relative permittivity (dielectric constant)
A = Electrode area
d = Distance between electrodes

Any variation is due to gas adsorption alters , which is detected as a signal.

2. Types of Gas Sensing Capacitors

- Polymer-based Capacitive Sensors – Polymers like polyaniline or polyimide absorb gas molecules, changing the dielectric constant.
- Metal Oxide-based Capacitive Sensors – Metal oxides (ZnO, TiO_2) interact with gases like NO_2, CO_2, and NH_3, modifying capacitance.
- Nanomaterial-enhanced Capacitive Sensors – Graphene, CNTs, and nanoparticles improve sensitivity and selectivity.

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3. Applications

- Air Quality Monitoring – Detects CO_2, VOCs, and toxic gases in smart cities.
- Industrial Safety – Monitors gas leaks in factories and chemical plants.
- Medical Diagnostics – Breath analysis for diseases using VOC detection.
- Agriculture & Food Storage – Detects ethylene for fruit ripening control.

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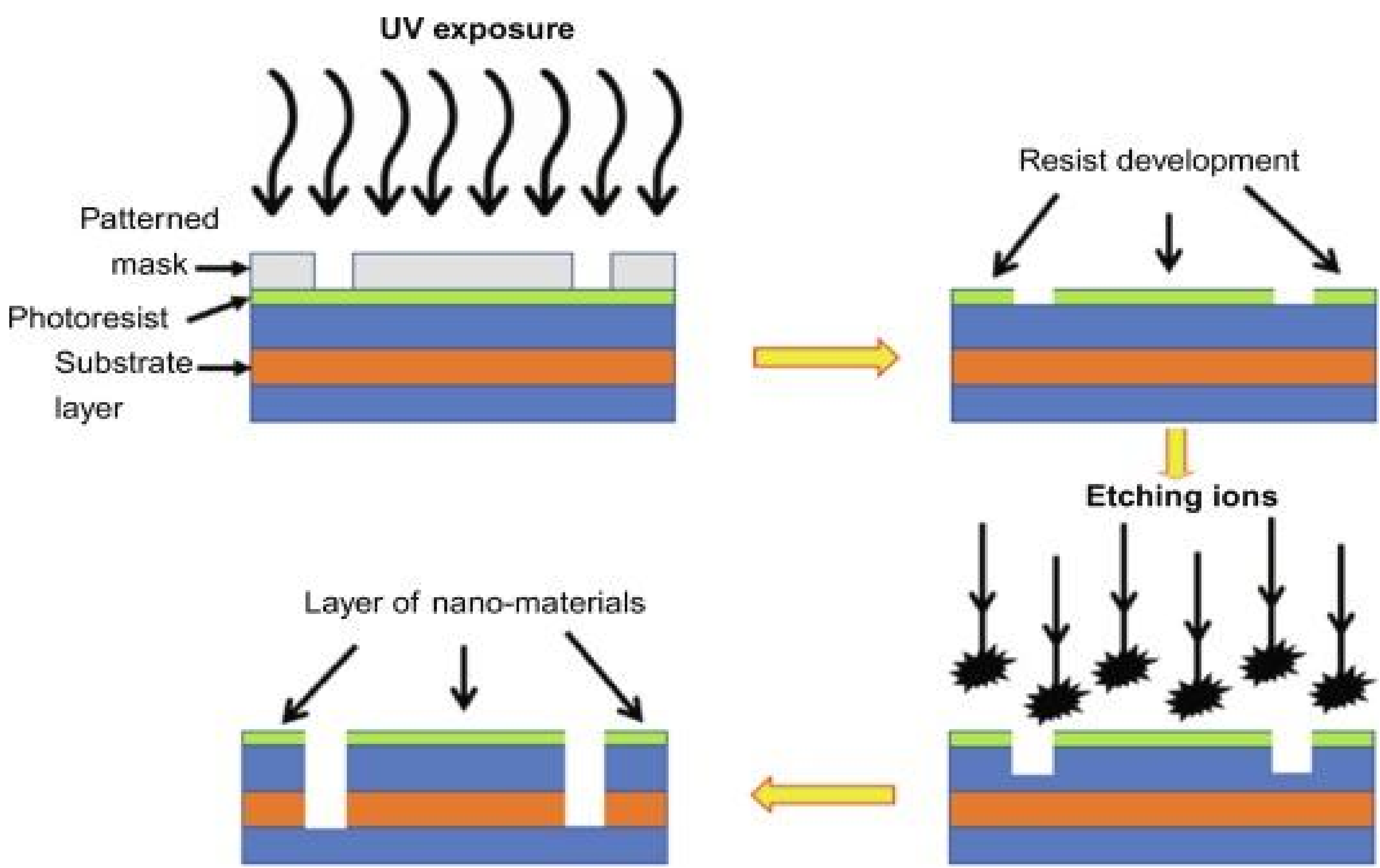
Lithography

Lithography, derived from the Greek words for "stone" and "to write," is a technique for transferring patterns onto a surface, typically a semiconductor wafer, using a mask and radiation.
Lithography is a process that uses a mask and radiation (like light) to transfer patterns onto a substrate, commonly used in microfabrication for creating integrated circuits and other microstructures.



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Steps of Lithography

1. UV Exposure

A patterned mask is placed over a photoresist-coated substrate.
The substrate consists of multiple layers, including the substrate material (like silicon) and photoresist, a light-sensitive material.
Ultraviolet (UV) light is exposed through the mask. The exposed regions of the photoresist undergo a chemical change.

2. Resist Development
After exposure, the substrate is developed using a chemical solution.
The photoresist dissolves in certain regions, creating a pattern that matches the mask.
This pattern defines the areas to be processed in the next step.

3. Etching
Etching removes material from the exposed areas of the substrate using etching ions (dry etching or wet etching).
The unprotected parts of the substrate are etched away, while the remaining photoresist protects the desired areas.

4. Formation of Nano-Structures
After etching, the remaining photoresist is removed, leaving behind a structured layer of nano-materials.
This pattern can be used for further processing, such as depositing metals, semiconductors, or other functional layers.

Applications

- Semiconductors – ICs, microprocessors, memory chips.
- MEMS – Sensors, actuators, biomedical devices.
- Nanoelectronics – Quantum dots, nanoscale transistors.
- Photonic Devices – Optical waveguides, laser components.
- Biomedical – Lab-on-a-chip, biosensors, DNA sequencing.
- Displays – OLED, LCD, MicroLED screens.
- Solar Cells – Thin-film solar panels, nanostructured surfaces.
- Data Storage – SSDs, magnetic memories, hard disks.

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Water Purification

Water purification is the process of removing undesirable chemicals, biological contaminants, suspended solids, and gases from water to produce water suitable for specific purposes, primarily human consumption. Various techniques are employed to achieve this, broadly categorized into physical, chemical, and membrane-based methods.

Physical Techniques:

- Sedimentation: Allows heavy particles to settle at the bottom of a container over time, separating them from the water.
- Filtration: Involves passing water through filters (sand, gravel, charcoal) to remove suspended particles and some microorganisms.
- Distillation: Involves boiling water to produce steam, which is then condensed back into liquid form, leaving impurities behind.

Chemical Techniques:

- Chlorination: Adding chlorine or chlorine compounds to water to kill bacteria, viruses, and other pathogens.
- Ozonation: Utilizing ozone gas to disinfect water by destroying bacteria and viruses.
- Coagulation and Flocculation: Adding chemicals (coagulants) to water, causing particles to clump together into larger particles (flocs) that can be easily removed.

Membrane Technologies:

- Microfiltration (MF): Removes particles larger than 0.1 microns, including bacteria and suspended solids.
- Ultrafiltration (UF): Filters out particles larger than 0.01 microns, including viruses and some proteins.

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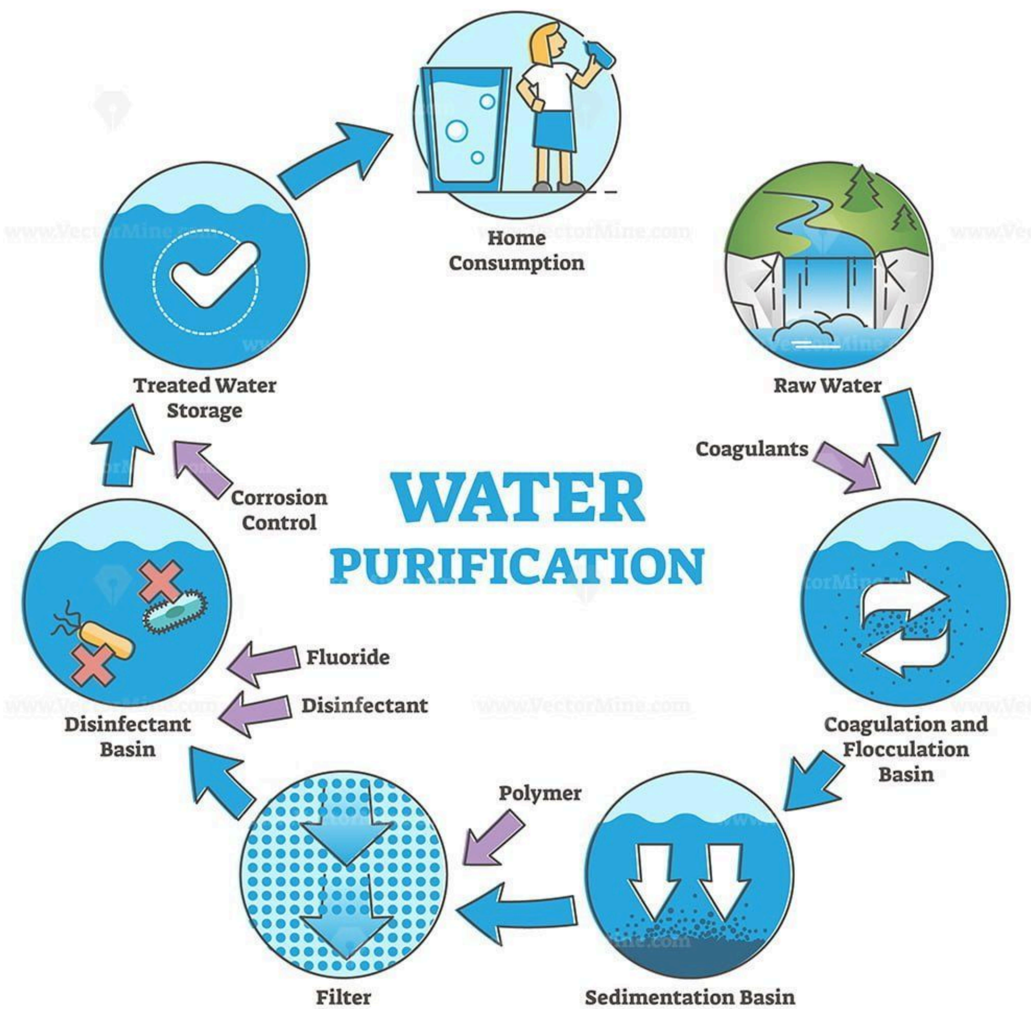
- Nanofiltration (NF): Targets particles larger than 0.001 microns, effectively removing multivalent ions and small organic molecules.

- Reverse Osmosis (RO): Employs a semipermeable membrane to remove ions, molecules, and larger particles, producing highly purified water.



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Applications:

1. Drinking Water Treatment: Ensures safe and clean water for human consumption.
2. Wastewater Treatment: Purifies industrial and municipal wastewater before releasing it into the environment.
3. Desalination: Removes salts and minerals from seawater to produce freshwater.
4. Industrial Processes: Provides purified water for manufacturing, pharmaceuticals, and food processing.