Nanomaterials

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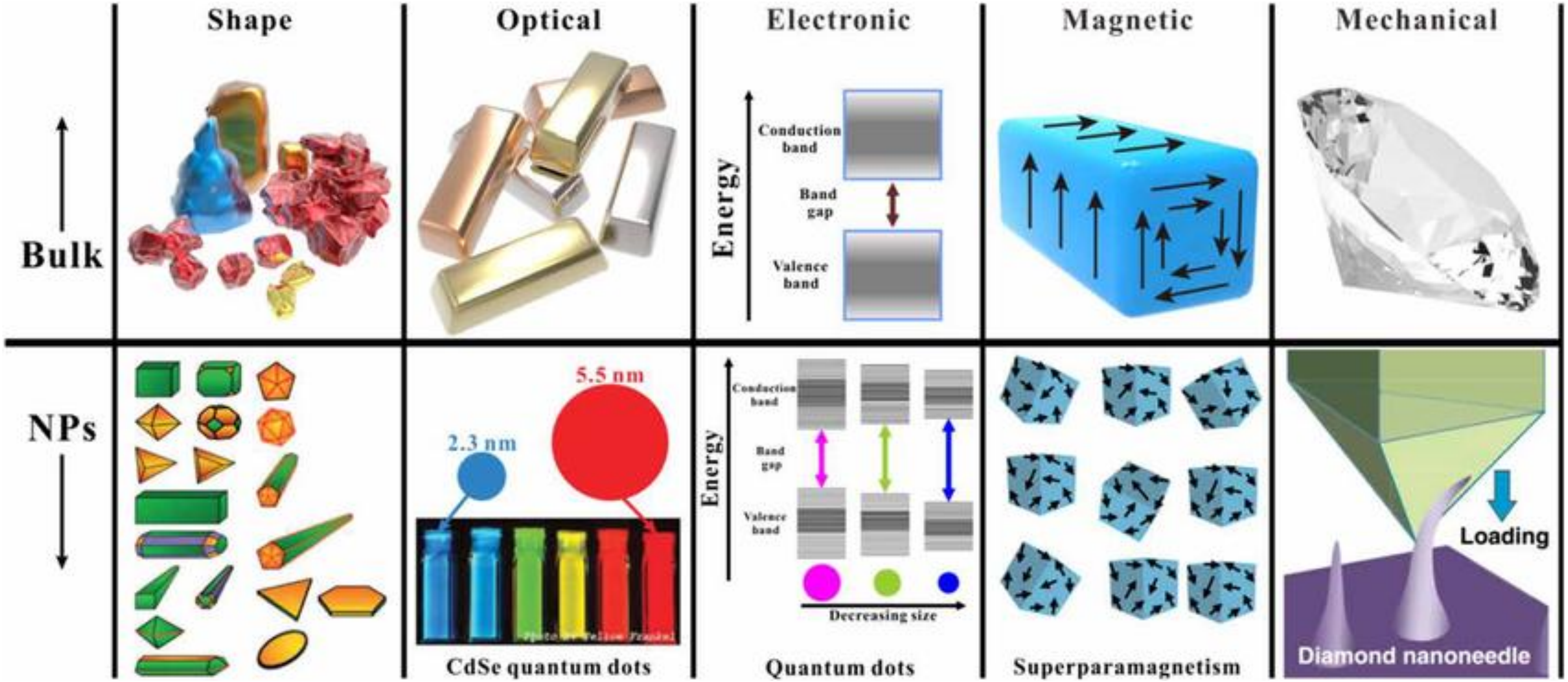
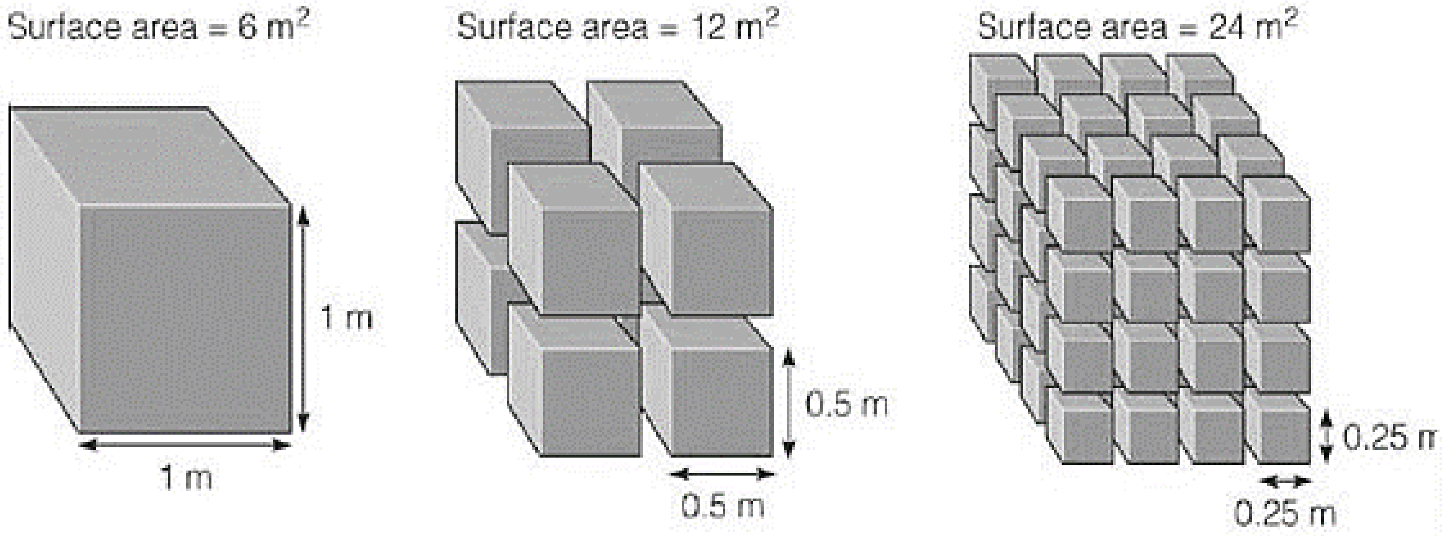
Definition of Nanomaterials

- Nanomaterials are materials in which at least one dimension lies in the nanometer range (1–100 nm).
  - 1 nanometer (nm) = 10^{-9} meter
- At the nanoscale, materials show new physical, chemical, optical, and electrical properties that are different from their bulk counterparts.



Shape
Optical
Electronic
Magnetic
Mechanical
Bulk
Energy
Conduction band
Band gap
Valence band
NPs
5.5 nm
2.3 nm
Conduction band
Band gap
Valence band
Decreasing size
Loading
Diamond nanoneedle
CdSe quantum dots
Quantum dots
Superparamagnetism

BULK vs NANO



Surface area increases as we move

from Macro to nanolevel

At the nanoscale, classical physics becomes inadequate and quantum effects become significant.

Why is nanoscale special?

- The nanoscale (1–100 nm) is special because materials at this size behave **very differently** from their bulk form.

1. **Large surface area to volume ratio**

   At the nanoscale, a huge fraction of atoms lie on the surface. This makes materials **more reactive, stronger catalysts, and better at adsorption**.

2. **Quantum effects become dominant**

   Electrons are confined in very small spaces, leading to **quantum size effects**. As a result, materials show **new optical, electrical, and magnetic properties** that do not exist at larger scales.

3. **Size-dependent properties**

   Changing the particle size can change the **color, conductivity, melting point, hardness, and chemical reactivity** of a material.

4. Enhanced mechanical properties

Nanomaterials can be **stronger, lighter, and more flexible** than bulk materials due to fewer defects and better atomic packing.

5. Unique optical behavior

Nanoparticles interact with light differently, leading to phenomena like **surface plasmon resonance**, used in sensors and medical diagnostics.

6. Interdisciplinary impact

At the nanoscale, physics, chemistry, biology, and engineering overlap, enabling **innovations in medicine, electronics, energy, and environmental science**.

Surface Effects at the Nanoscale

1. **High fraction of surface atoms**

   At the nanoscale, a large number of atoms lie **at or near the surface** rather than in the bulk. This leads to **high surface energy**, making nanomaterials more **reactive and unstable** compared to bulk materials.

2. **Surface tension**

   Liquid surfaces behave like **elastic films** due to unbalanced cohesive forces acting on surface molecules. At the nanoscale, surface tension becomes more significant and strongly influences **shape, stability, and growth** of nanoparticles.

3. **Kelvin effect**

   Smaller particles or droplets exhibit **higher vapor pressure** than larger ones. As a result, nanosized droplets **evaporate faster**, affecting processes such as condensation, nanoparticle growth, and stability.

4.Ostwald ripening

Due to differences in surface energy, **smaller particles dissolve** and redeposit onto **larger particles**, causing the growth of large particles at the expense of smaller ones. This process reduces total surface energy but leads to **particle size increase over time**.

5. Adsorption

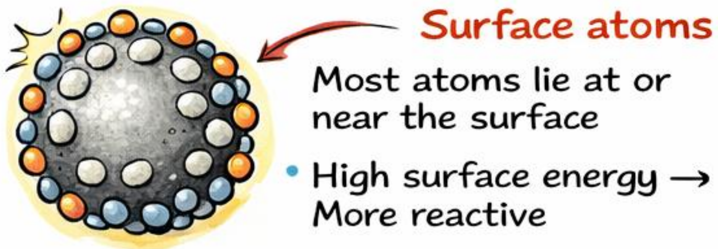
The high surface area of nanoparticles allows **impurities, gases, or molecules** to readily stick to the surface. Adsorption plays a crucial role in **catalysis, sensing, and surface modification**.

6. Surface charge

Adsorption of ions from the surrounding medium can leave nanoparticles **electrically charged**. This surface charge affects **colloidal stability, interaction with other particles, and dispersion behavior**.

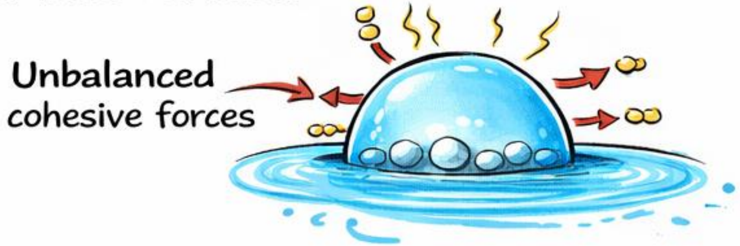
Surface Effects at the Nanoscale

High fraction of Surface Atoms



- ✓ Most atoms lie at or near the surface
- ✓ High surface energy → More reactive

Surface Tension



- ✓ Surface behaves like **elastic film**
- ✓ Strongly influences nanoparticle shape & stability

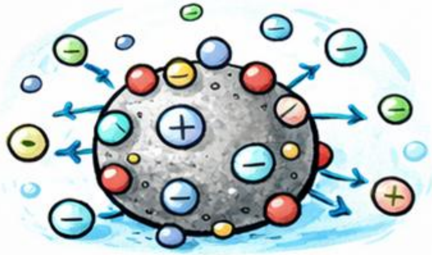
Kelvin Effect

- ✓ Smaller particles evaporate faster
- ✓ Higher vapor pressure for smaller size

Ostwald Ripening

- ✓ Smaller particles dissolve
- ✓ Larger particles grow over time

Surface Charge



- ✓ Adsorbed ions create surface charge
- ✓ Affects colloidal stability & dispersion

Effects of approaching Nanoscale:

1. Increase in Surface-to-Volume Ratio: As the size of a material decreases to the nanoscale, its surface-to-volume ratio increases sharply. A large fraction of atoms lie on the surface, making surface effects dominant. This results in higher surface energy, enhanced chemical reactivity, and greater influence of adsorption and surface forces.

2. Reduction in Dimensions Affects Material Properties: Reducing the dimensions of a material to the nanoscale significantly alters its physical, chemical, optical, electrical, and mechanical properties. These changes arise due to quantum confinement effects and increased surface contribution, leading to size-dependent behavior that is absent in bulk materials.

Macro vs Nano: The Size Effect

MACRO LEVEL	NANO LEVEL
• Large dimensions (micrometer to meter scale) • Very small surface-to-volume ratio • Properties are size-independent • Classical physics dominates • Lower surface energy and reactivity • Mechanical, optical, and electrical properties remain constant	• Dimensions between 1–100 nm • Extremely high surface-to-volume ratio • Properties become size-dependent • Quantum effects dominate • High surface energy and enhanced reactivity • Unique optical, electrical, and mechanical properties

Macro vs Nano: The Size Effect

Macro Scale (Bulk Materials)

- ✓ Large size, small surface-to-volume ratio
- ✓ Properties are size-independent
- ✓ Classical physics dominate

<- 1 μm to meter

Reduction in Size

Nano Scale (Nanomaterials)

- ✓ EXtremely high surface-to-volume ratio
- ✓ Properties are size-dependent
- Quantum effects dominate
- ✓ High surface energy and reactivity
- ✓ Unique properties emerging at nanoscale

- ✓ Large size, small surface-to-volume ratio
- ✓ Properties are size-independent
- ✓ Classical physics dominate
- ✓ Low surface energy and reactivity
- ✓ Properties remain constant with size

Key Size Effects Observed

- Increased surface activity
- Quantum confinement of electrons
- Changes in color, conductivity, melting point
- Enhanced catalytic & mechanical performance

Reducing material size from macro to nano introduces unique properties: high surface activity and quantum effects.