Introduction to Materials Science

Introduction

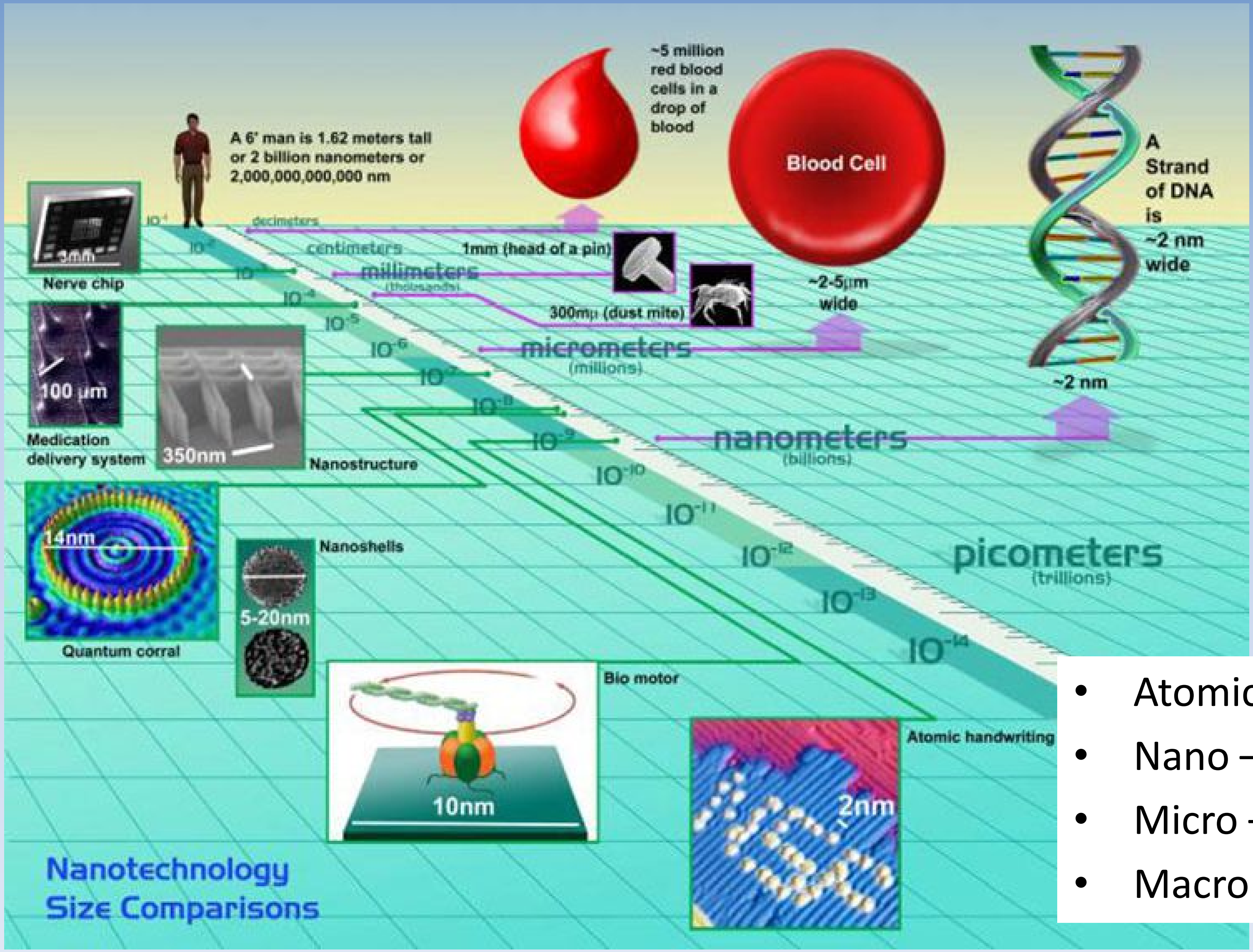
What is material science?

A branch of science that focuses on materials; interdisciplinary field composed of physics and chemistry.

What is a material scientist?

A person who uses his/her combined knowledge of physics, chemistry and metallurgy(studies the physical and chemical behavior of metallic elements) to exploit property-structure combinations for practical use.

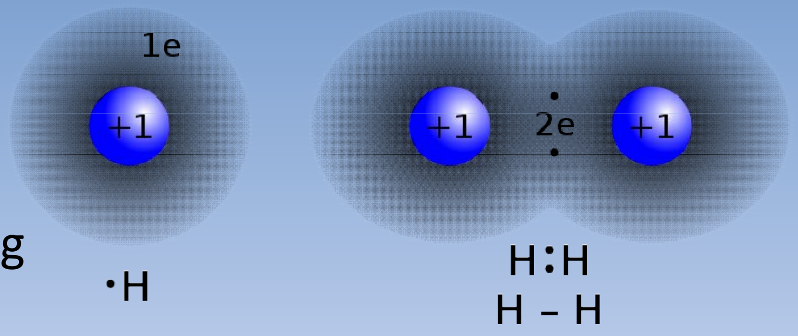
Length Scales of Material Science

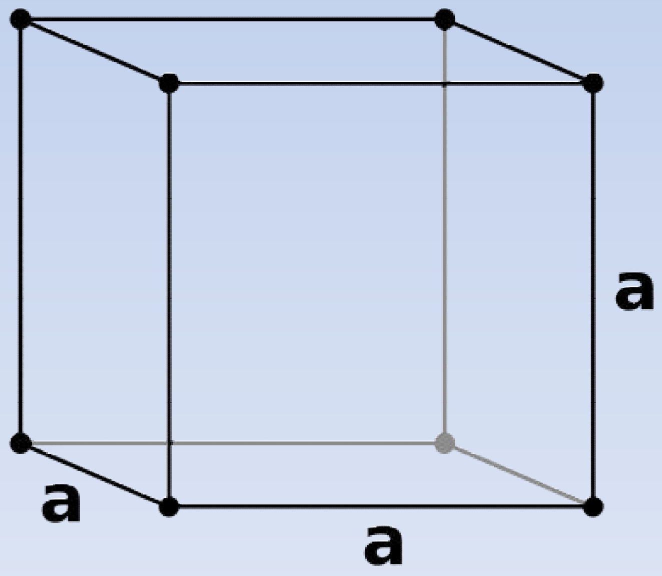


- Atomic – < 10^{-10} m
- Nano – 10^{-9} m
- Micro – 10^{-6} m
- Macro – > 10^{-3} m

Atomic Structure – 10^{-10} m

- Pertains to atom electron structure and atomic arrangement
- Atom length scale
  - Includes electron structure – atomic bonding
    - ionic
    - covalent
    - metallic
    - London dispersion forces (Van der Waals)
  - Atomic ordering – long range (metals), short range (glass)
    - 7 lattices
    - 14 different crystalline arrangements (Bravais Lattices).



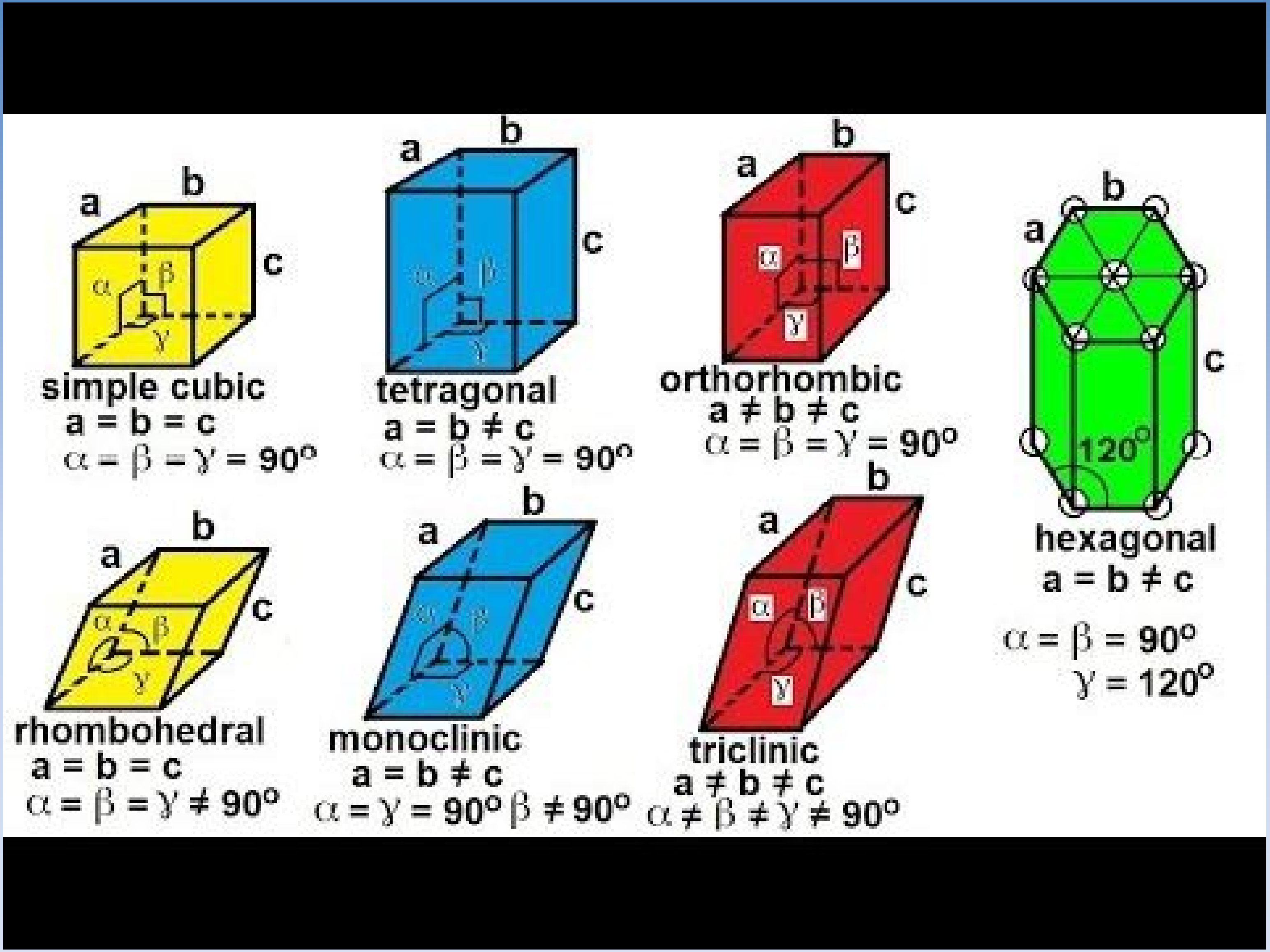


- Ionic bonding is a type of chemical bonding that involves the electrostatic attraction between oppositely charged ions, and is the primary interaction occurring in ionic compounds.
- The ions are atoms that have gained one or more electrons (known as anions, which are negatively charged) and atoms that have lost one or more electrons (known as cations, which are positively charged).

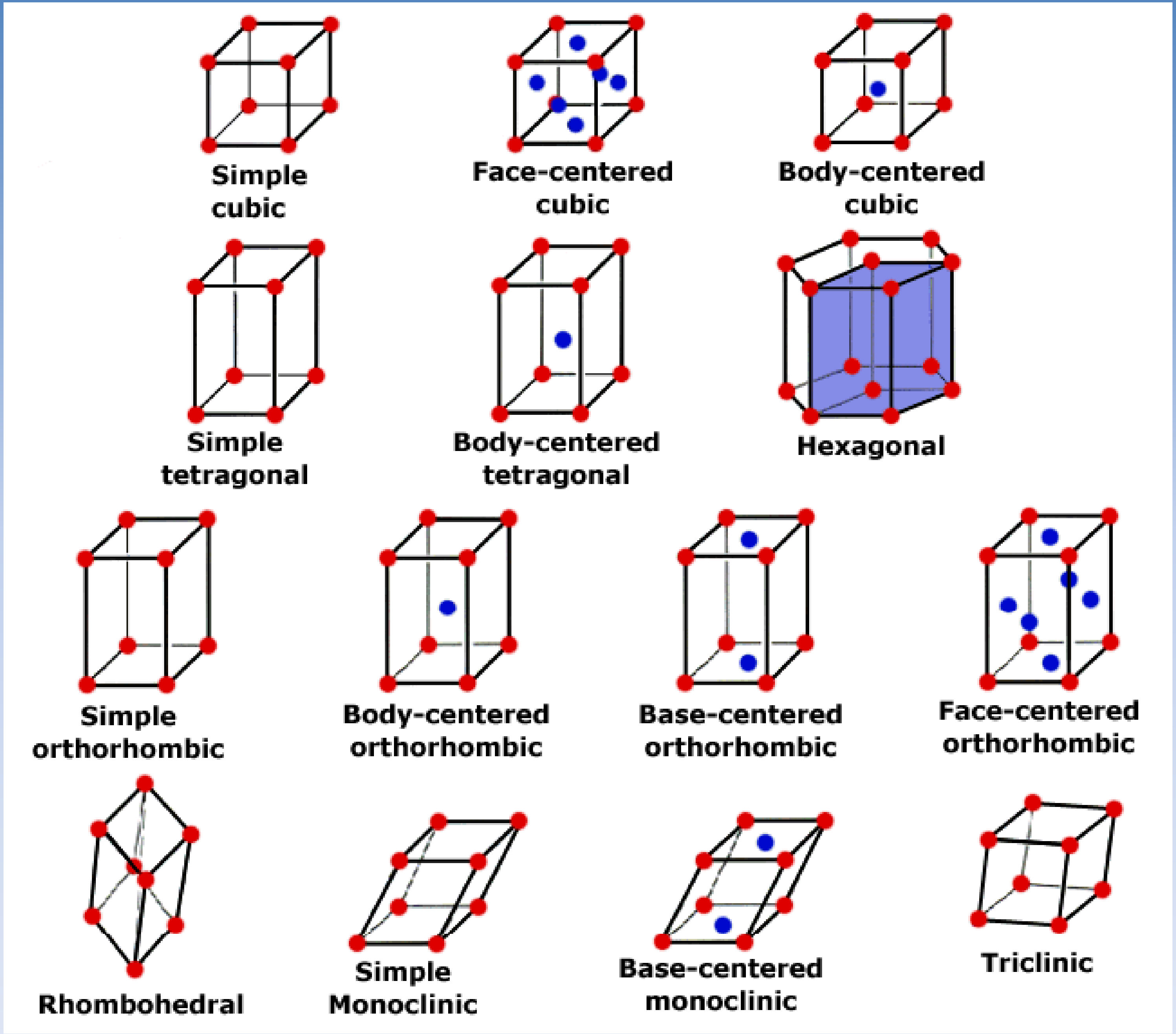
- an ionic bond is the transfer of electrons from a metal to a non-metal in order to obtain a full valence shell for both atoms.

- Ex : NaCl, NH4,SO4…

- A **covalent bond**, also called a **molecular bond**, is a chemical bond that involves the sharing of electron pairs between atoms.
- HCl, SO_2, CO_2, and CH_4

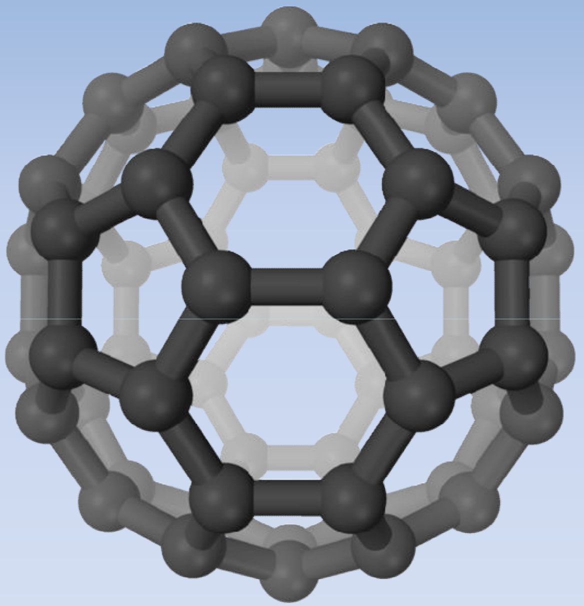


simple cubic
a = b = c
α = β = γ = 90°
tetragonal
a = b ≠ c
α = β = γ = 90°
orthorhombic
a ≠ b ≠ c
α = β = γ = 90°
hexagonal
a = b ≠ c
α = β = 90°
γ = 120°
rhombohedral
a = b = c
α = β = γ ≠ 90°
monoclinic
a = b ≠ c
α = γ = 90° β ≠ 90°
triclinic
a ≠ b ≠ c
α ≠ β ≠ γ ≠ 90°


Simple cubic
Face-centered cubic
Body-centered cubic
Simple tetragonal
Body-centered tetragonal
Hexagonal
Simple orthorhombic
Body-centered orthorhombic
Base-centered orthorhombic
Face-centered orthorhombic
Rhombohedral
Simple Monoclinic
Base-centered monoclinic
Triclinic

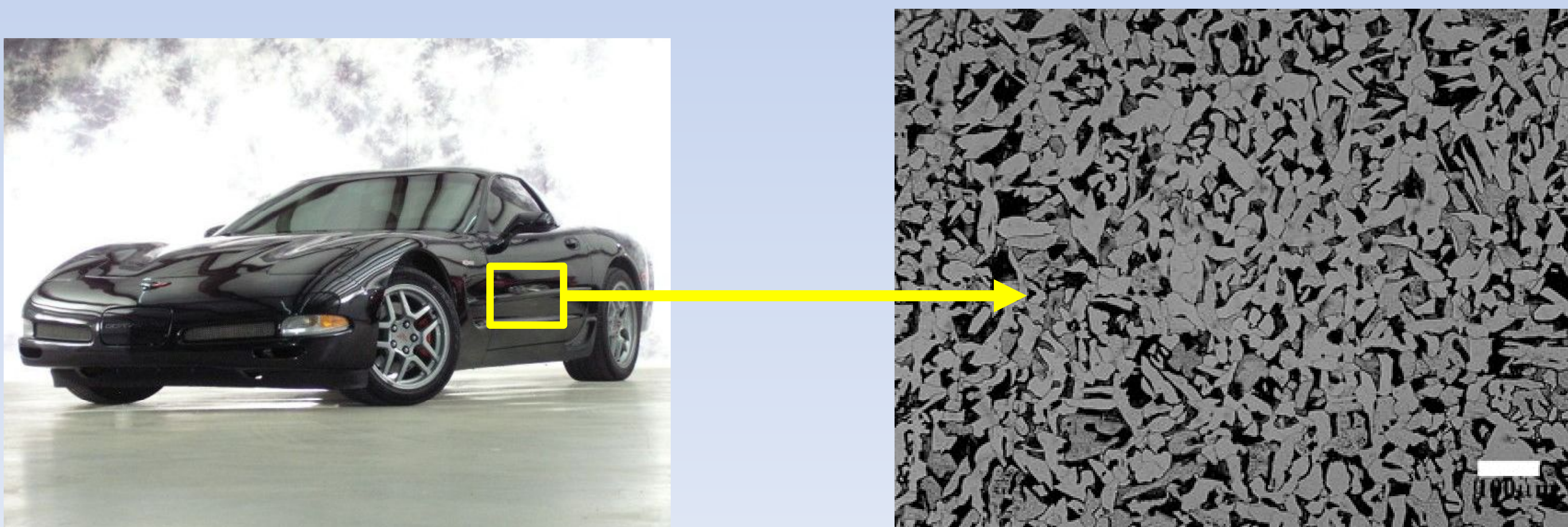
Nano Structure – 10^{-9} m

- Length scale that pertains to clusters of atoms that make up small particles or material features
- Show interesting properties because increase surface area to volume ratio
  - More atoms on surface compared to bulk atoms
  - Optical, magnetic, mechanical and electrical properties change



Microstructure – 10^{-6}

- Features are visible with high magnification in light microscope.
  - These features are traditionally altered to improve material performance



Macrostructure – 10^{-3} m

- Macrostructure pertains to collective features on microstructure level
- Grain flow, cracks, porosity
  are all examples of macrostructure features

Classes of Materials

- metals
- polymers
- ceramics
- composites

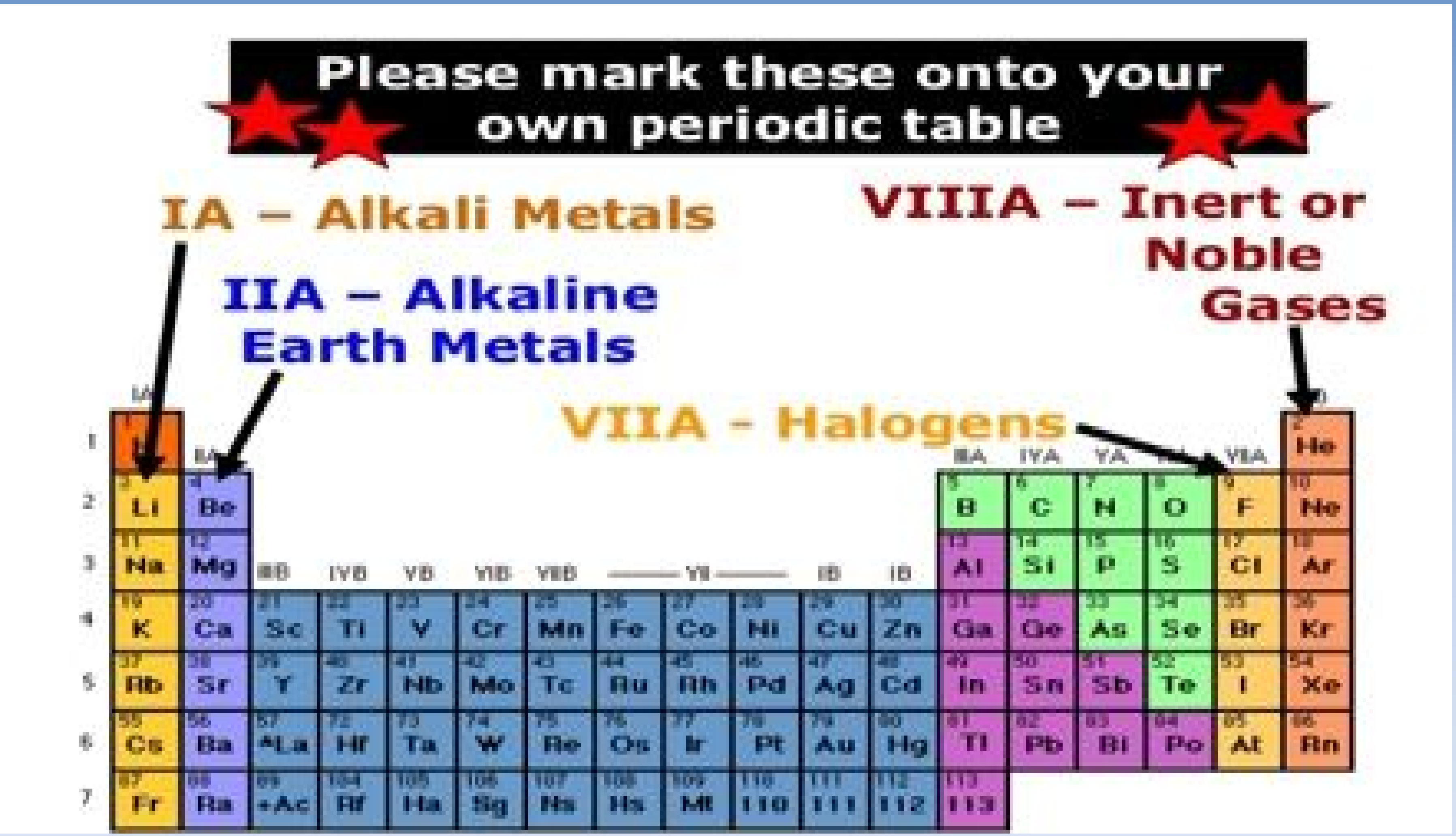
What are materials?

What do we mean when we say "materials"?

1. **Metals**
   - aluminum
   - copper
   - steel (iron alloy)
   - nickel
   - titanium
2. **Ceramics**
   - clay
   - silica glass
   - alumina
   - quartz
3. **Polymers**
   - polyvinyl chloride (PVC)
   - Teflon
   - various plastics
   - glue (adhesives)
   - Kevlar
4. **Composites**
   - wood
   - carbon fiber resins
   - concrete

Metals

- Metals consist of alkaline, alkaline earth, metalloids and transition metals
- Metal alloys are mixtures of two or more metal and nonmetal elements
- Properties:
  - Electrically conductive (free electrons)
  - Thermally conductive
  - High strength – large capacity to carry load over x-section area (stress)
  - Ductile – endure large amounts of deformation before breaking.
  - Magnetic – ferromagnetism, paramagnetic
  - Medium melting point



Please mark these onto your own periodic table
IA – Alkali Metals
IIA – Alkaline Earth Metals
VIIIA – Inert or Noble Gases
VIIA - Halogens

- **Diamagnetism** refers to materials that are not affected by a magnetic field.
- **Paramagnetism** refers to materials like aluminum or platinum which become magnetized in a magnetic field but their magnetism disappears when the field is removed.
- **Ferromagnetism** refers to materials (such as iron and nickel) that can retain their magnetic properties when the magnetic field is removed.

Metal Applications

- Electrical wire: aluminum, copper, silver
- Heat transfer fins: aluminum, silver
- Construction beams (bridges,):
- steel (Fe-C alloys)
- Consumer goods: …

Polymers

- Polymers consist of various hydro-carbon (organic elements) with select additives to elucidate specific properties
- Polymers are typically disordered (amorphous) strands of hydrocarbon molecules.
- Bonding: Covalent-London Dispersion Forces
- Properties:
  - ductile: can be stretched up to 1000% of original length
  - lightweight: Low densities
  - medium strength: Depending on additives
  - chemical stability: inert to corrosive environments
  - low melting point

Polymer Applications

- Car tires: vulcanized polymer (added sulfur)
- Ziploc bags
- Food storage containers
- Plumbing: polyvinyl chloride (PVC)
- Kevlar
- Aerospace and energy applications: Teflon
- Consumer goods:
  - calculator casings
  - TV consuls
  - shoe soles
  - cell phone casings
  - Elmer's Glue (adhesives)
  - contact lenses
  - Many, many. many more…

Ceramics

- Consist of metal and non metal elements
- Typically a mixture of elements in the form of a chemical compound , for example Al_2O_3 or glass
- Three types: composites, monolithic and amorphous ceramics
- Bonding covalent – ionic
  - Typically covalent. In some cases highly direction covalent bonding
  - Ionic in case of SiO_2 glasses and slags
- Properties:
  - wear resistant (hard)
  - chemical stability: corrosion resistant
  - high temperature strength: strength retention at very high temperatures
  - high melting points
  - good insulators (dielectrics)
  - good optical properties

Ceramic Applications

- Window glass: $Al_2O_3 – SiO_2 – MgO – CaO$
- Aerospace, energy and automotive industry
  - heat shield tiles
  - engine components
  - reactor vessel and furnace linings
- Consumer products:
  - pottery
  - dishes (fine china, plates, bowls)
  - glassware (cups, mugs, etc.)
  - eye glass lenses

Composites

- A mixture of two different materials to create a new material with combined properties
- Bonding: depends on type of composite (strong-covalent, medium-)
- Properties: Depends on composites
  - High melting points with improved high temperature strength: ceramic-ceramic
  - High strength and ductile with improved wear resistance: metal-ceramic
  - High strength and ductile: polymer-polymer

Composites: Applications

- Plywood: laminated wood for buildings
- Concrete: basements, bridges,
- Fiberglass: boats
- Carbon fiber resins: bicycle frames

Advanced Applications Ceramics & Composites

- Aerospace and Defense Applications
  - Structural materials used for missiles, aircraft, space vehicles
- Ultrahigh Temperature Ceramic-Composites (UHTCs)
  - Metal-nonmetal, Covalent bonded compounds (ZrB_2 – SiC)
  - High melting point materials;
  - strong materials at temperature;
  - excellent oxidation resistance
- Why these materials?
  - Service temperatures are in excess of 2000°C
  - Materials have high melting points (>3000°C)
  - Light weight

Advanced Applications Polymers

- Self-decontaminating polymers
  - medical, military, security and environmental applications
  - current applications: look for attachment to textiles for self toxin cleaning fabrics

Other well known materials

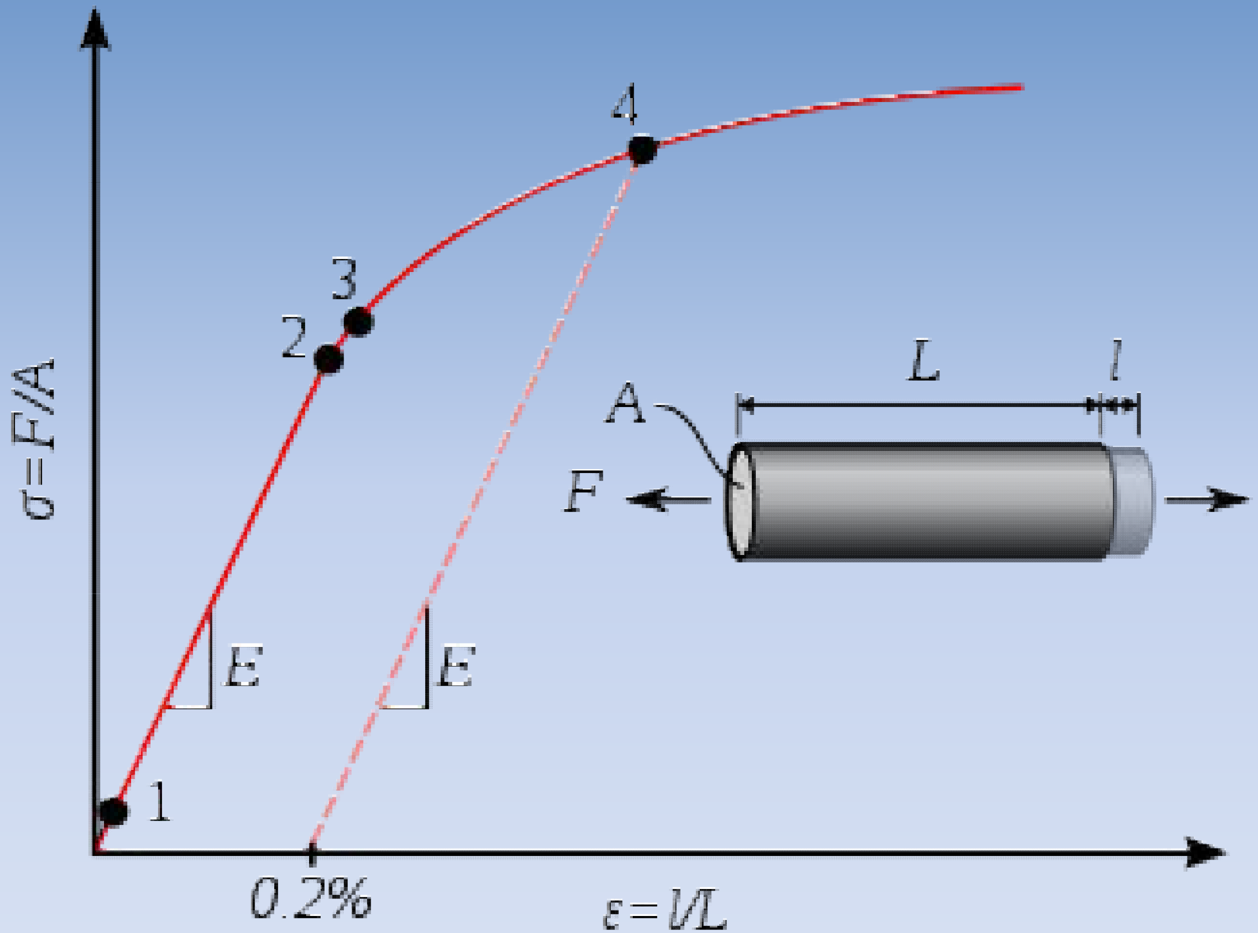
- Semiconductors – ceramics
  - computer chips
  - memory storage devices
  - solar cells
  - image screens
- Nanomaterials – ceramics, metals, polymers
  - gold nanoshells
  - quantum dots
  - medical devices

How do we test materials?

We use mechanical, chemical and optical methods

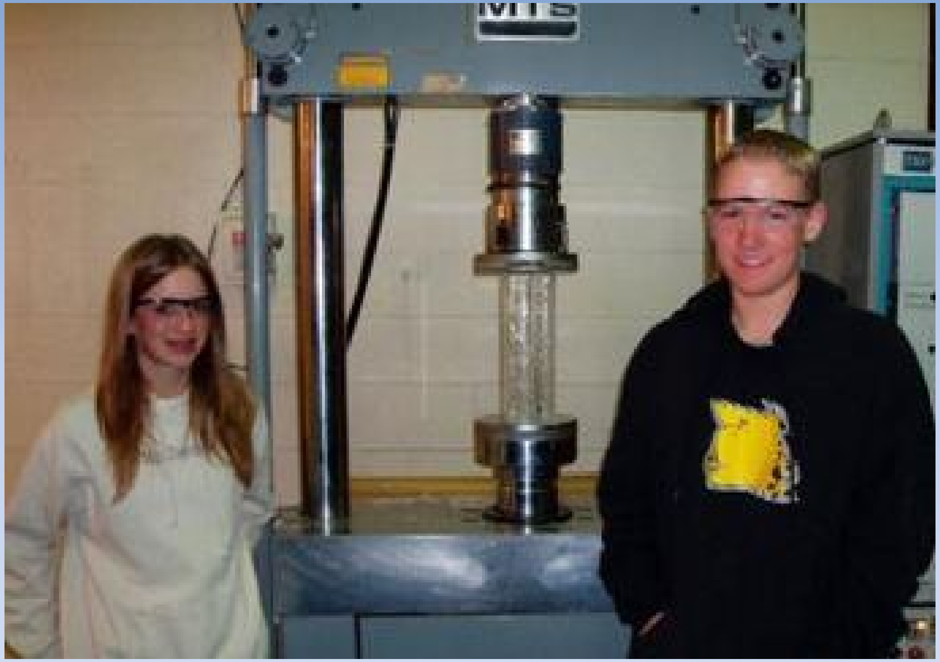
- Mechanical testing gives strength, ductility and toughness material information
  - tensile tests
  - bend tests
  - compressive tests
  - fracture testing
- Chemical testing tells us about composition and chemical stability
  - x-ray diffraction and fluorescence – composition testing
  - corrosion testing
- Optical testing is more of a way to view atomic, nano and microstructures, and gives us insight to structure property relationships
  - light optical microscope – microstructure
  - scanning electron microscope – microstructure and nano structure
  - transmission electron microscope – nanostucture and atomic structure
  - scanning tunneling electron microscope – atomic structures

Mechanical Testing



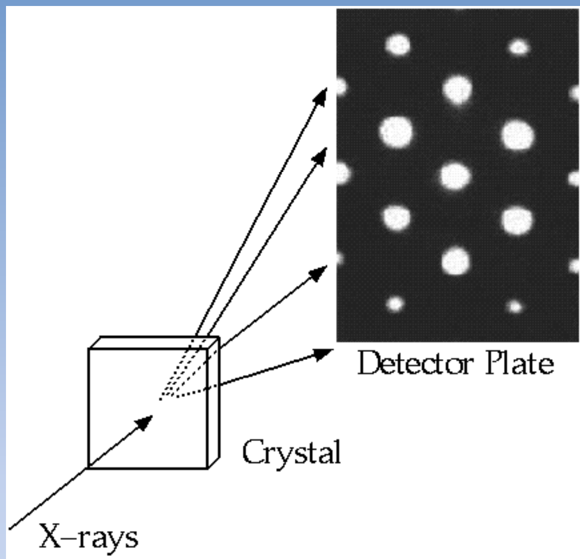
Schematic stress-strain curve created from experiments using universal test frame

Mechanical Testing

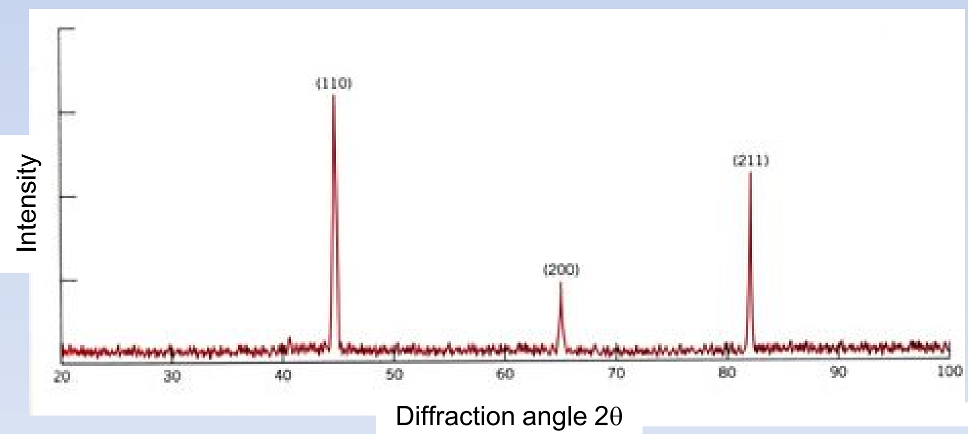


universal testing machines

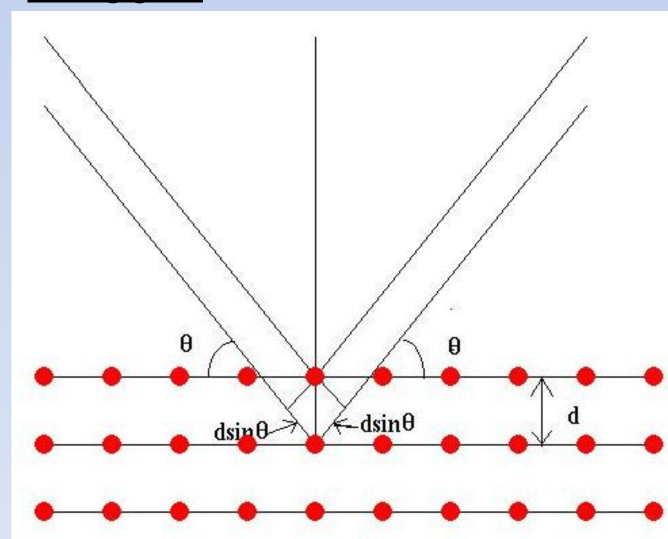
X-ray Diffraction



- x-rays are a form of light that has high energy and short wavelength
- when x-rays strike a material a portion of them are scattered in all directions
- if the atoms in the material is crystalline or well-ordered constructive interference can order

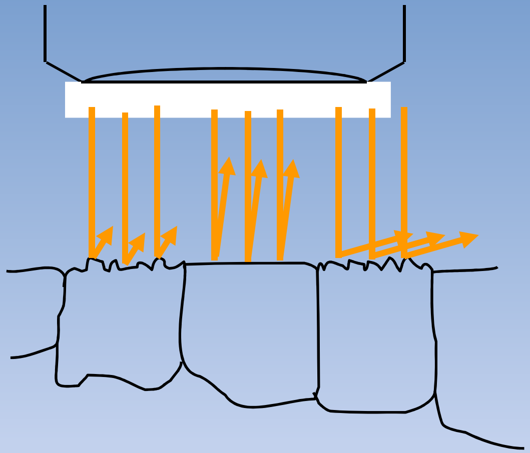


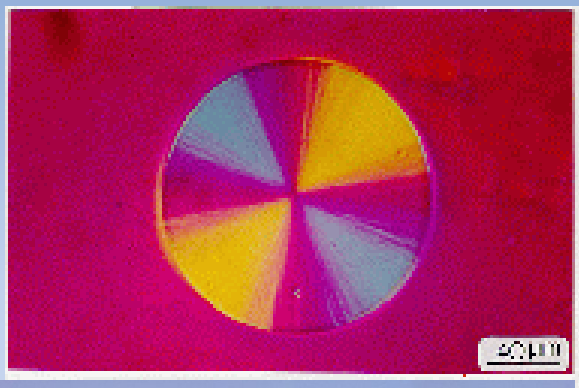
Bragg's Law: 2d sin $\theta = n\lambda$

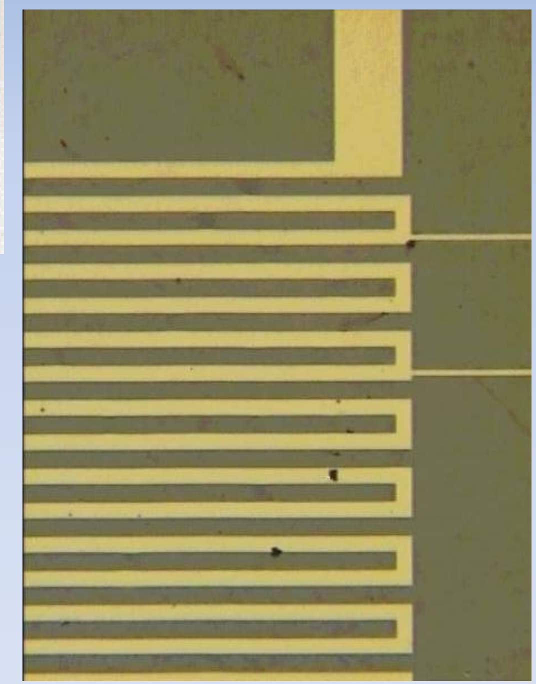


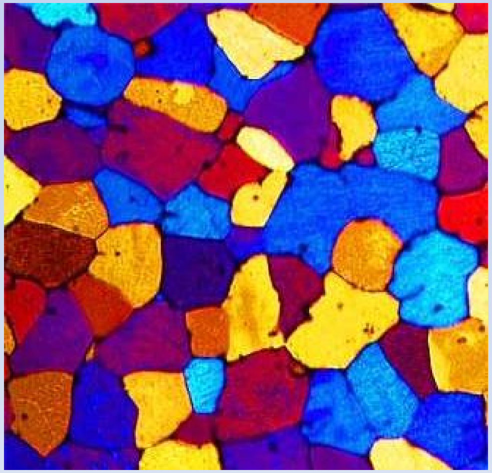
Optical Microscopy

- light is used to study the microstructure
- opaque materials use reflected light, where as transparent materials can use reflected or transmitted light







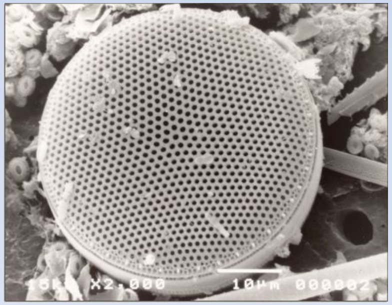


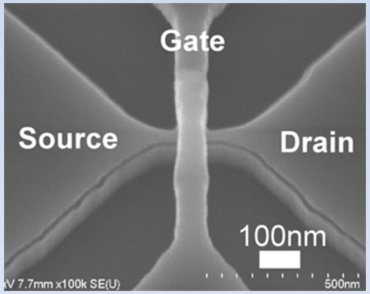
Electron Microscopy

- beams of electrons are used for imaging
- electrons are accelerated across large voltages
- a high velocity electron has a wavelength of about 0.003 nm
- the electron beam is focused and images are formed using magnetic lenses
- reflection and transmission imaging are both possible

Scanning Electron Microscopy (SEM)

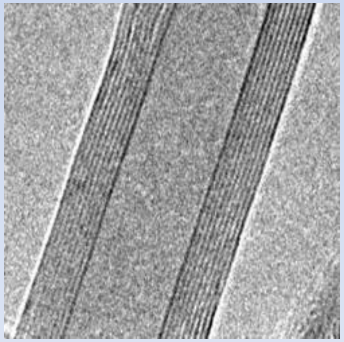
- an electron beam scans the surface and the reflected (backscattered) electrons are collected
- sample must be electrically conductive
- material surface is observed
- 200,000x magnification possible

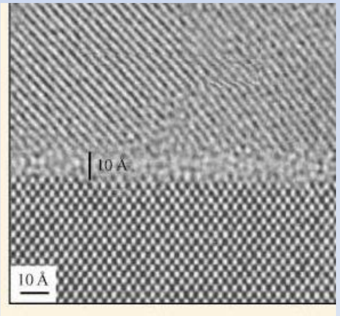




Transmission Electron Microscopy (TEM)

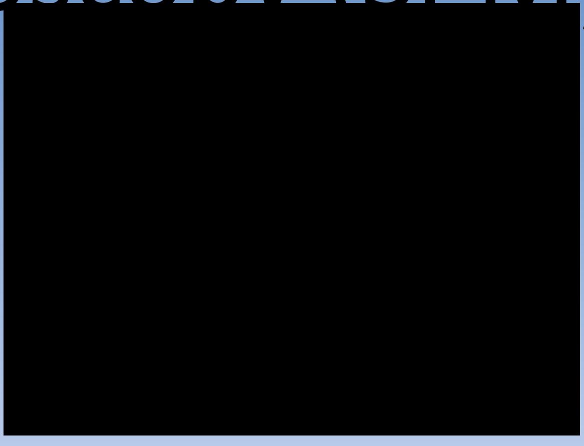
- an electron beam passes through the material
- thin samples
- details of internal microstructure observed
- 1,000,000x magnification possible



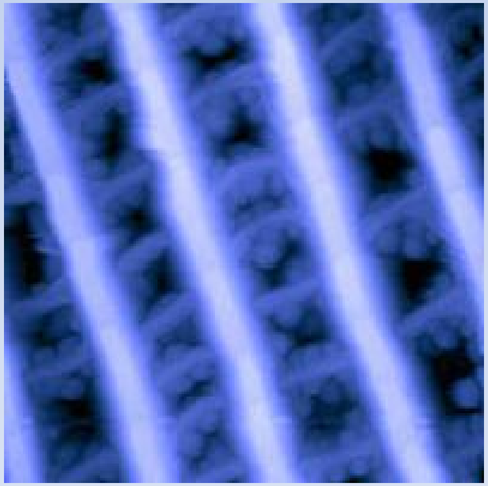


Scanning Probe Microscopy (SPM)

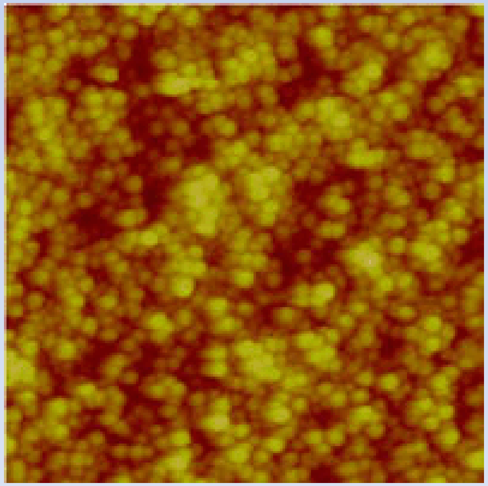
- 3D topographical map of material surface
- probe brought into close proximity of material surface
- probe rastered across the surface experiencing deflection in response to interactions with the material surface
- useful with many different types of materials



Animation of SPM on epitaxial silicon.



SPM image of a butterfly wing.



SPM image of silica coated gold nanoparticles.

SPM image of 70 nm photoresist lines.