Chapter 14: Properties and Applications of Ceramics

ISSUES TO ADDRESS...

- In what ways are ceramic phase diagrams different from phase diagrams for metals?
- How are the mechanical properties of ceramics measured, and how do they differ from those for metals?
- How do we classify ceramics?
- What are some applications of ceramics?

Ceramic Phase Diagrams

MgO-Al_2O_3 diagram:

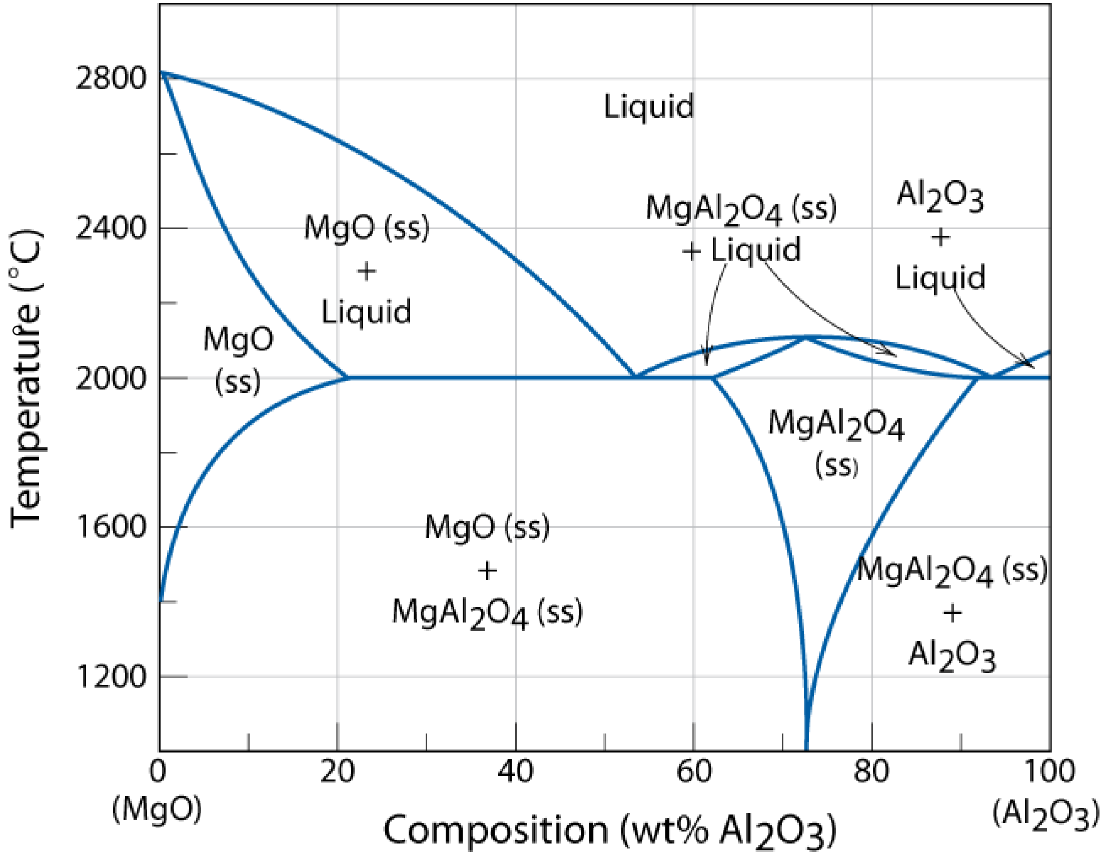


Fig. 14.2, Callister & Rethwisch 9e.
[Adapted from B. Hallstedt, "Thermodynamic Assessment of the System MgO–Al_2O_3," J. Am. Ceram. Soc., 75[6], 1502 (1992). Reprinted by permission of the American Ceramic Society.]

Mechanical Properties

Ceramic materials are more brittle than metals.

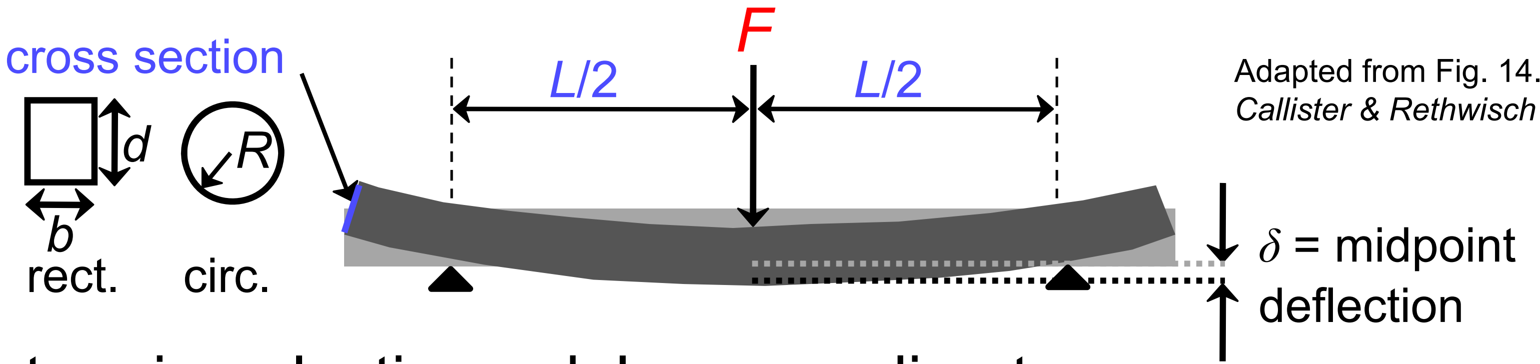
Why is this so?

- Consider mechanism of deformation
  - In crystalline, by dislocation motion
  - In highly ionic solids, dislocation motion is difficult
    - few slip systems
    - resistance to motion of ions of like charge (e.g., anions) past one another

Flexural Tests – Measurement of Elastic Modulus

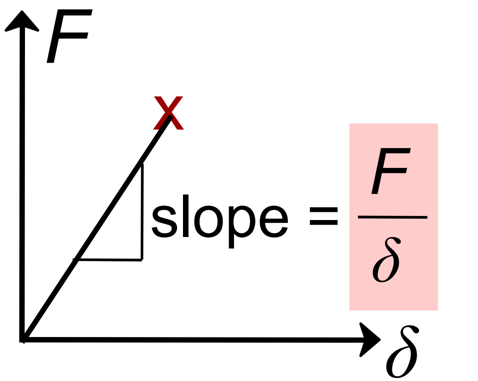
- Room *T* behavior is usually elastic, with brittle failure.
- 3-Point Bend Testing often used.

  -- tensile tests are difficult for brittle materials.



Adapted from Fig. 14.9, *Callister & Rethwisch 9e.*

- Determine elastic modulus according to:



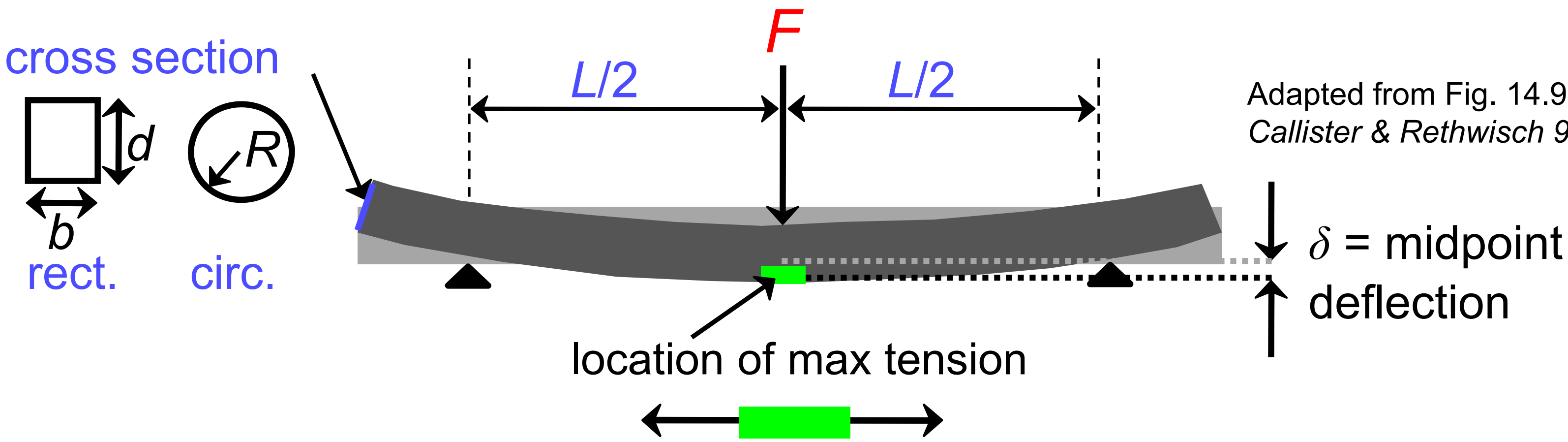
linear-elastic behavior

$$E = \frac{F}{\delta}\frac{L^3}{4bd^3} \quad \text{(rect. cross section)}$$

$$E = \frac{F}{\delta}\frac{L^3}{12\pi R^4} \quad \text{(circ. cross section)}$$

Flexural Tests – Measurement of Flexural Strength

- 3-point bend test to measure room-*T* flexural strength.



Adapted from Fig. 14.9, *Callister & Rethwisch 9e.*

- Flexural strength:

$$\sigma_{fs} = \frac{3F_f L}{2bd^2} \quad \text{(rect. cross section)}$$

$$\sigma_{fs} = \frac{F_f L}{\pi R^3} \quad \text{(circ. cross section)}$$

- Typical values:

Material	σ_{fs} (MPa)	E(GPa)
Si nitride	250-1000	304
Si carbide	100-820	345
Al oxide	275-700	393
glass (soda-lime)	69	69

Data from Table 14.1, *Callister & Rethwisch 9e.*

Classification of Ceramics

Ceramic Materials

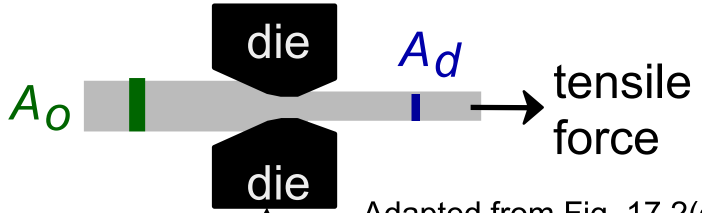
- **Glasses**
  - -optical
  - -composite reinforce
  - -containers/ household
- **Clay products**
  - -whiteware
  - -structural
- **Refractories**
  - -bricks for high *T* (furnaces)
- **Abrasives**
  - -sandpaper
  - -cutting
  - -polishing
- **Cements**
  - -composites
  - -structural
- **Advanced ceramics**
  - -engine rotors valves bearings
  - -sensors

Adapted from Fig. 14.14 and discussion in Section 14.10-16, *Callister & Rethwisch 9e.*

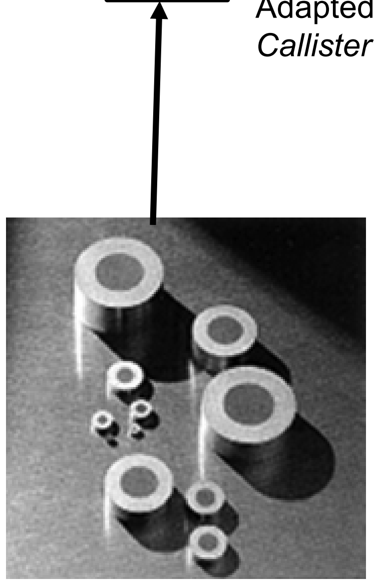
Ceramics Application: Die Blanks

- Die blanks:
  -- Need wear resistant properties!

- Die surface:
  -- 4 μm polycrystalline diamond particles that are sintered onto a cemented tungsten carbide substrate.
  -- polycrystalline diamond gives uniform hardness in all directions to reduce wear.



Adapted from Fig. 17.2(d), *Callister & Rethwisch 9e.*



Courtesy Martin Deakins, GE Superabrasives, Worthington, OH. Used with permission.

Ceramics Application: Cutting Tools

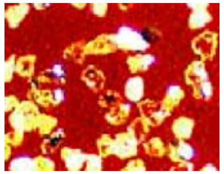
- Tools:
  -- for grinding glass, tungsten, carbide, ceramics
  -- for cutting Si wafers
  -- for oil drilling

- Materials:
  -- manufactured single crystal or polycrystalline diamonds in a metal or resin matrix.
  -- polycrystalline diamonds resharpen by microfracturing along cleavage planes.

oil drill bits

blades

Single crystal diamonds

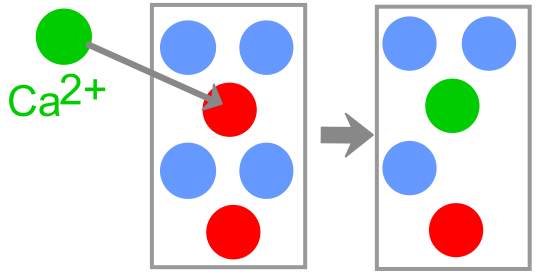


polycrystalline diamonds in a resin matrix.

Photos courtesy Martin Deakins, GE Superabrasives, Worthington, OH. Used with permission.

Ceramics Application: Sensors

- Example: ZrO_2 as an oxygen sensor
- Principle: Increase diffusion rate of oxygen to produce rapid response of sensor signal to change in oxygen concentration



A substituting Ca^{2+} ion removes a Zr^{4+} ion and an O^{2-} ion.

- Approach:

  Add Ca impurity to ZrO_2:

  -- increases O^{2-} vacancies

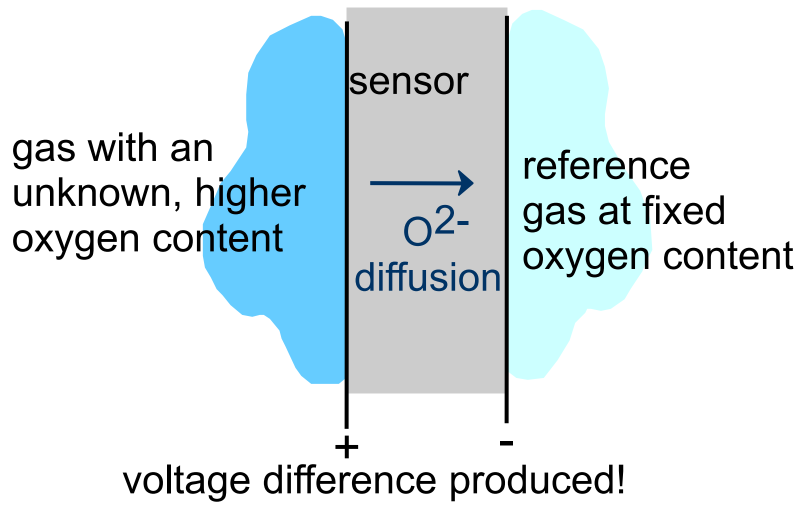
  -- increases O^{2-} diffusion rate

$$CaO \xrightarrow{ZrO_2} Ca_{Zr}'' + V_O^{\bullet\bullet} + \frac{1}{2} O_2$$

- Operation:

  -- voltage difference produced when O^{2-} ions diffuse from the external surface through the sensor to the reference gas surface.

  -- magnitude of voltage difference $\propto$ partial pressure of oxygen at the external surface



$$\text{emf} = \frac{RT}{4F} \ln \left(\frac{P'_{O_2}}{P''_{O_2}} \right)$$

Refractories

- Materials to be used at high temperatures (e.g., in high temperature furnaces).
- Consider the Silica (SiO_2) - Alumina (Al_2O_3) system.
- Silica refractories - silica rich - small additions of alumina depress melting temperature (phase diagram):

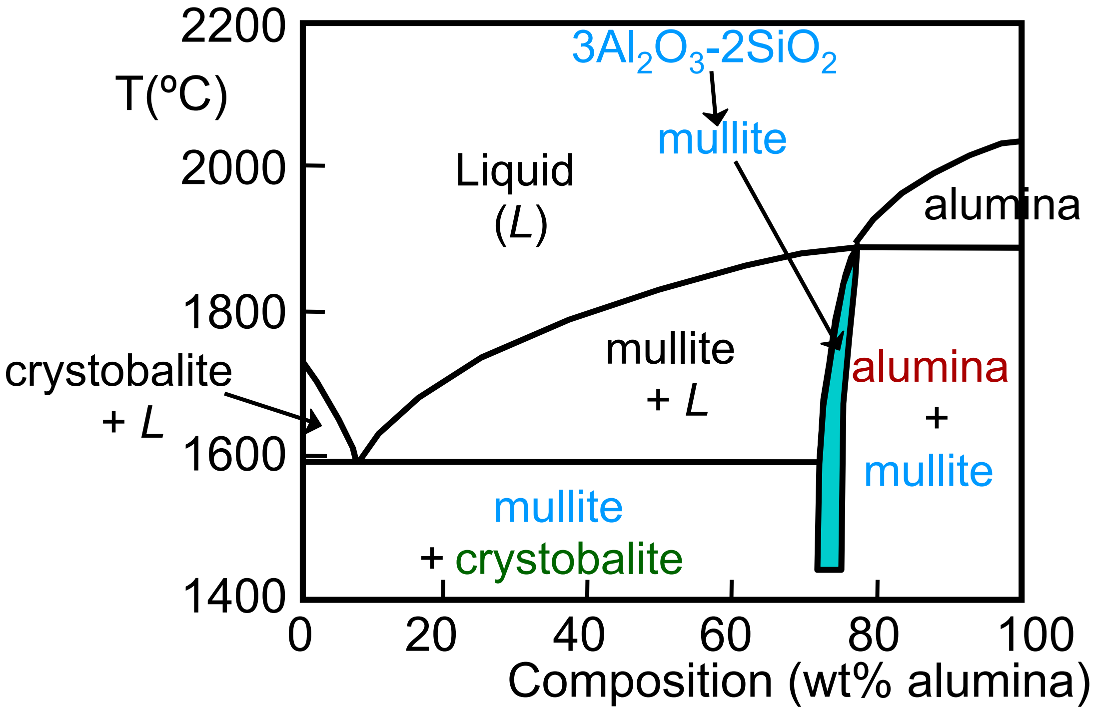


Fig. 14.4, *Callister & Rethwisch 9e.*
[Adapted from F. J. Klug, S. Prochazka, and R. H. Doremus, “Alumina–Silica Phase Diagram in the Mullite Region,” J. Am. Ceram. Soc., 70[10], 758 (1987). Reprinted by permission of the American Ceramic Society.]

Advanced Ceramics: Materials for Automobile Engines

- Advantages:
  - Operate at high temperatures – high efficiencies
  - Low frictional losses
  - Operate without a cooling system
  - Lower weights than current engines
- Disadvantages:
  - Ceramic materials are brittle
  - Difficult to remove internal voids (that weaken structures)
  - Ceramic parts are difficult to form and machine

- Potential candidate materials: Si_3N_4, SiC, & ZrO_2
- Possible engine parts: engine block & piston coatings

Advanced Ceramics: Materials for Ceramic Armor

Components:

-- Outer facing plates

-- Backing sheet

Properties/Materials:

-- Facing plates -- hard and brittle

— fracture high-velocity projectile

— Al_2O_3, B_4C, SiC, TiB_2

-- Backing sheets -- soft and ductile

— deform and absorb remaining energy

— aluminum, synthetic fiber laminates

Nanocarbons

- Fullerenes – spherical cluster of 60 carbon atoms, C_{60}
  - Like a soccer ball
- Carbon nanotubes – sheet of graphite rolled into a tube
  - Ends capped with fullerene hemispheres

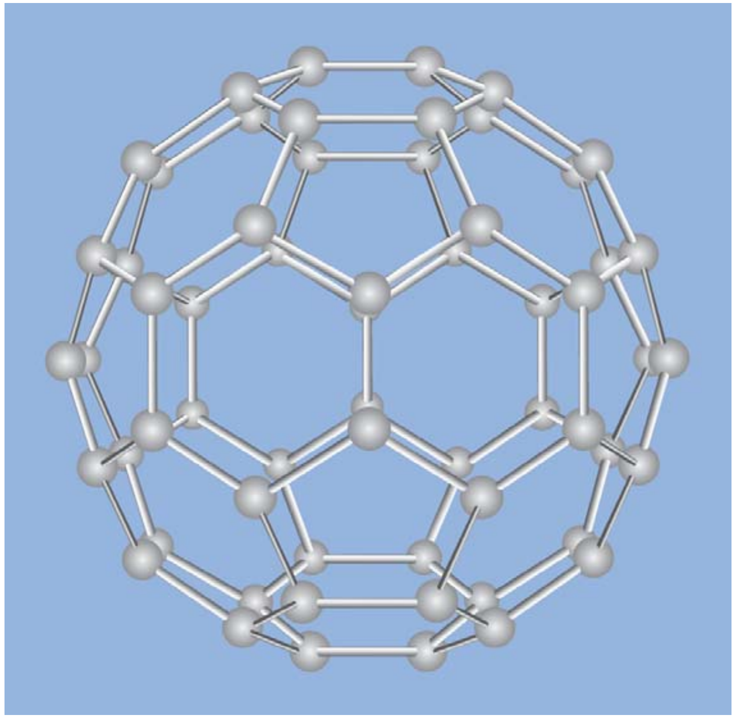


Fig. 14.20, *Callister & Rethwisch 9e.*

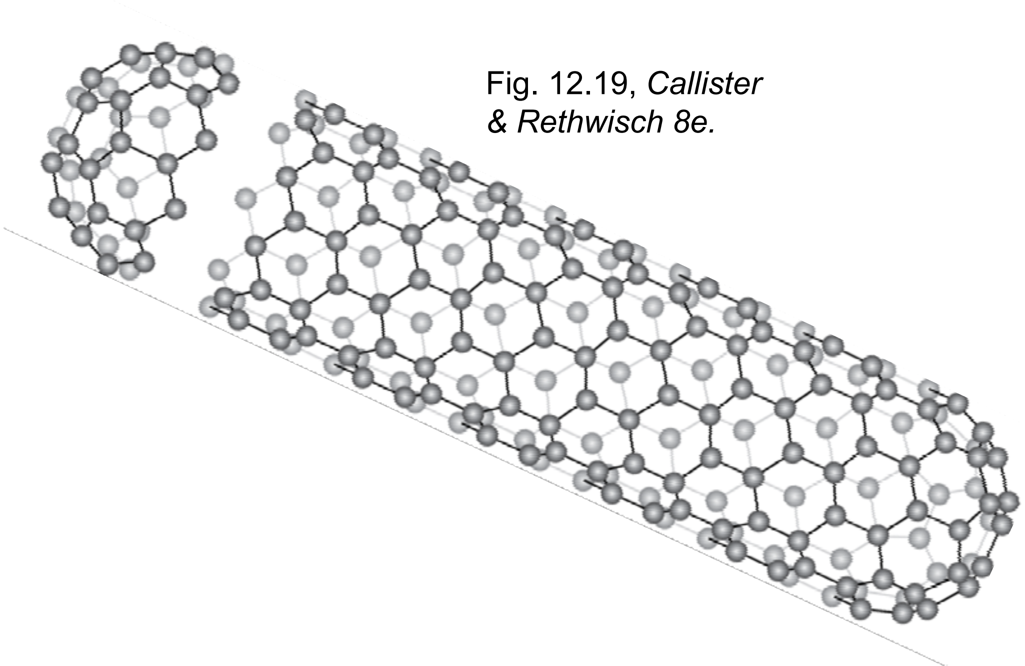


Fig. 12.19, *Callister & Rethwisch 8e.*

Nanocarbons (cont.)

- Graphene – single-atomic-layer of graphite
  - composed of hexagonally sp^2 bonded carbon atoms

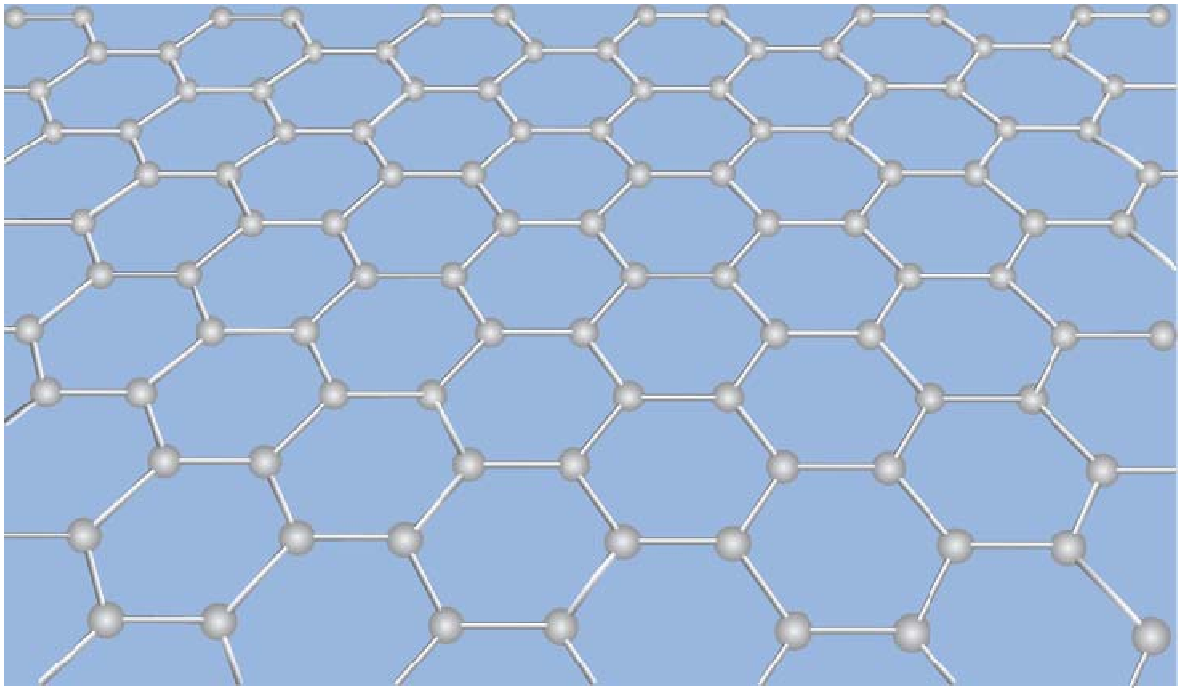
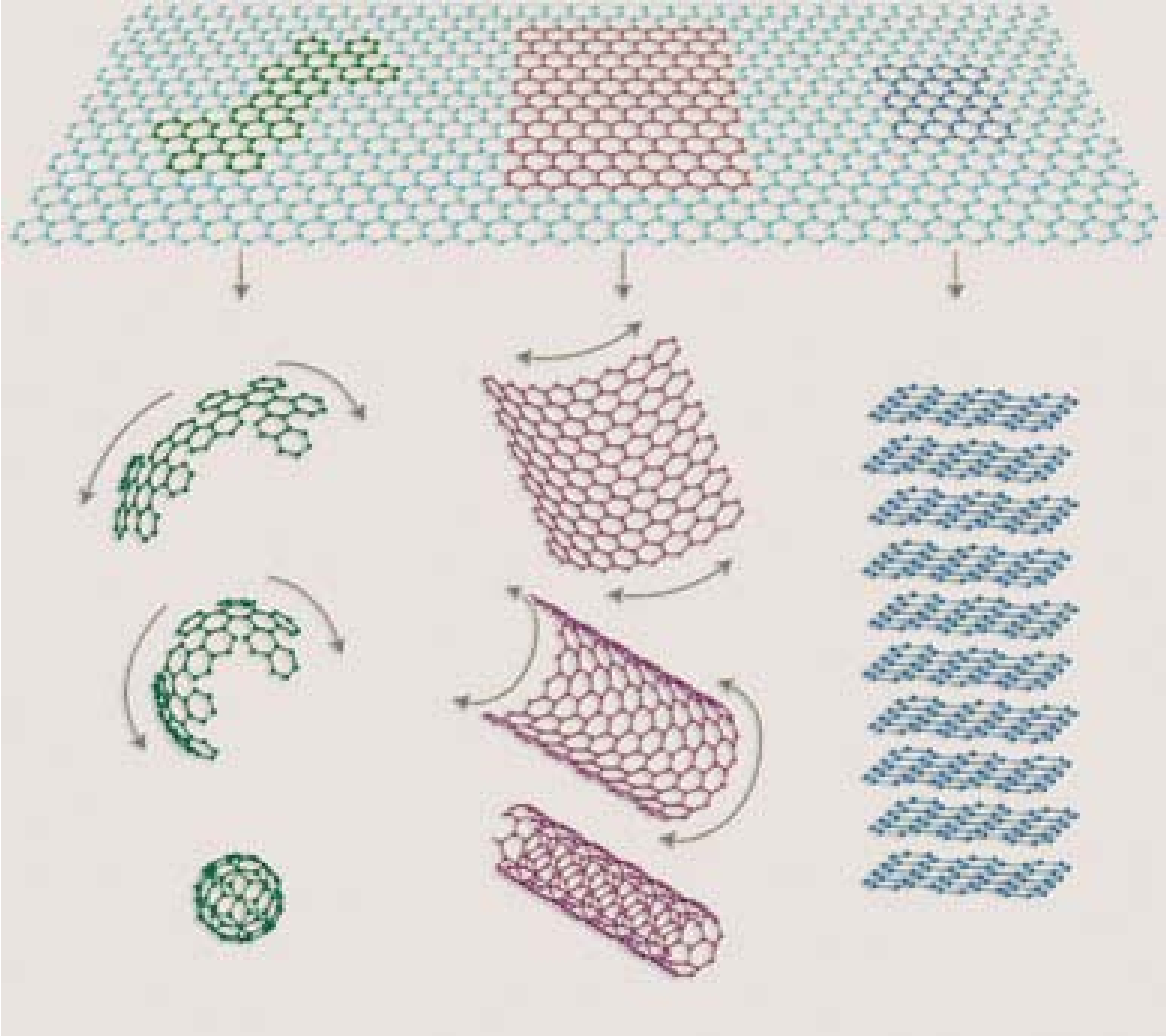
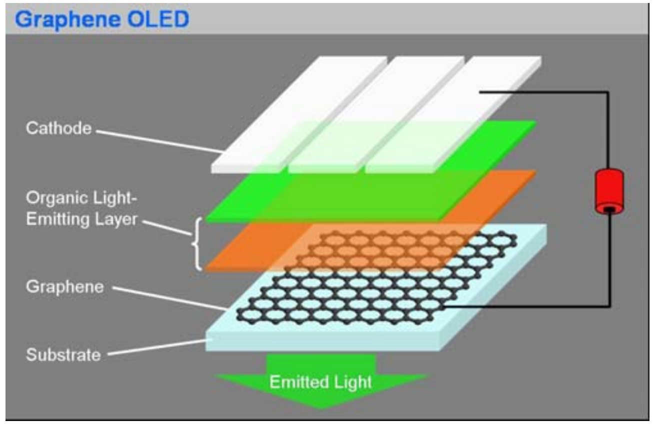
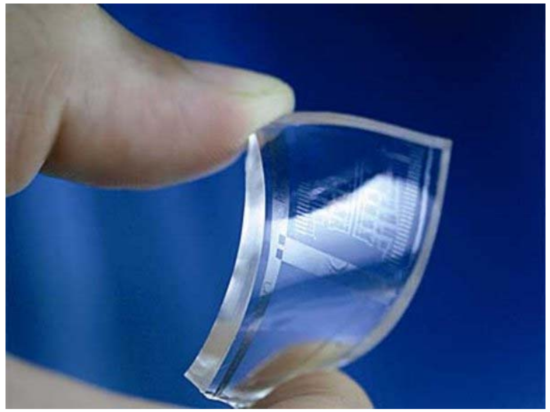


Fig. 14.22, *Callister & Rethwisch 9e.*

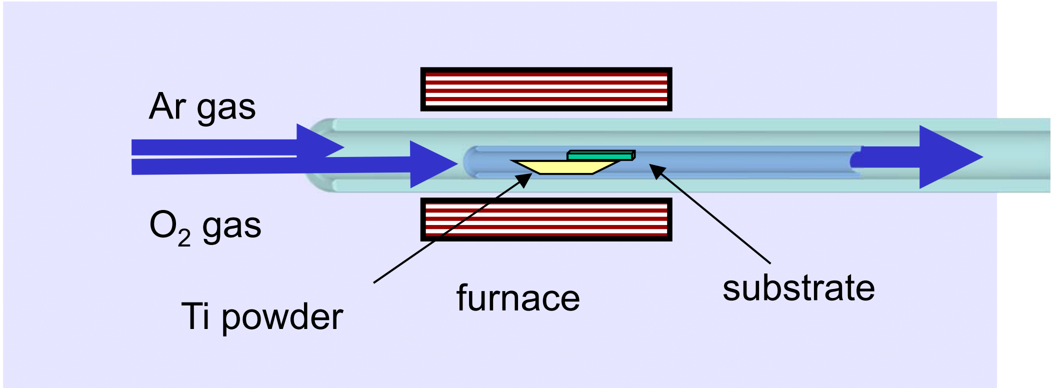
- Graphenes – Sheet of graphite

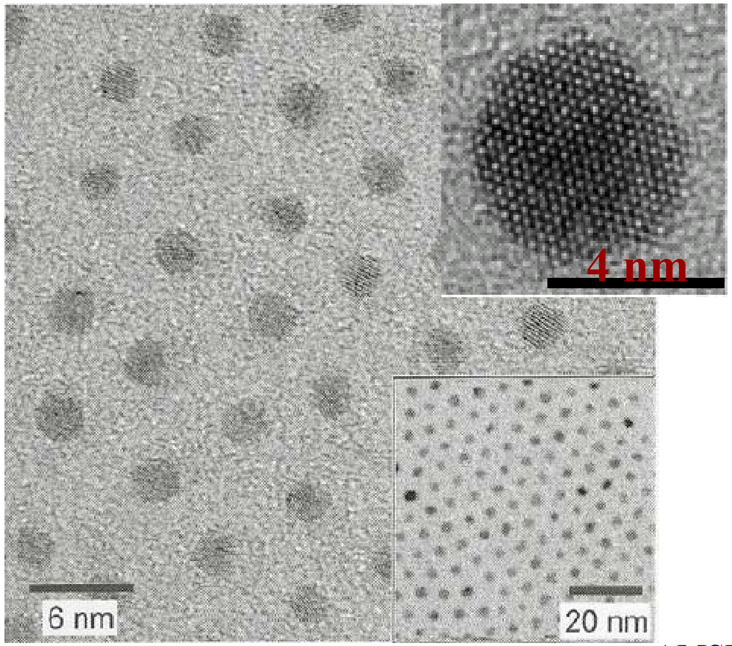


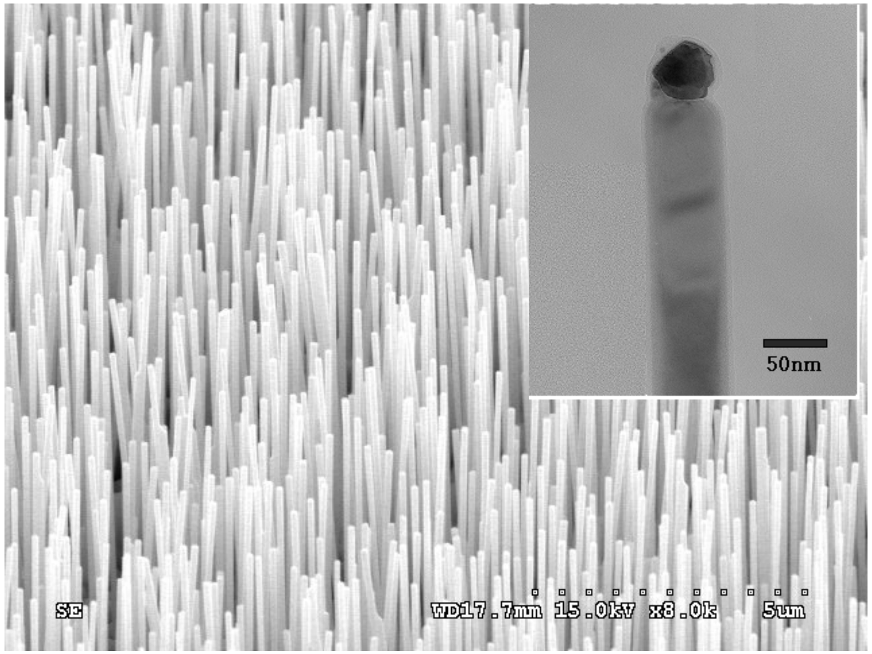




• Synthesis of Nanomaterials

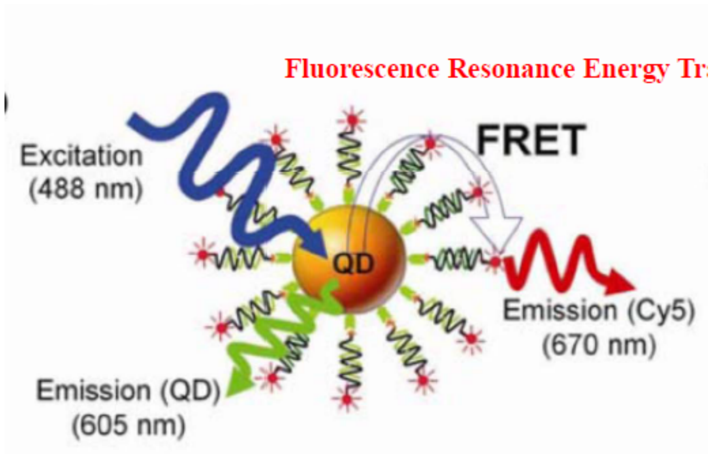




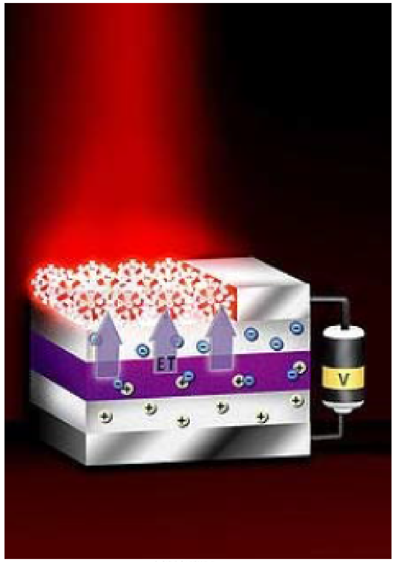


Applications of Nanomaterials (0-D)

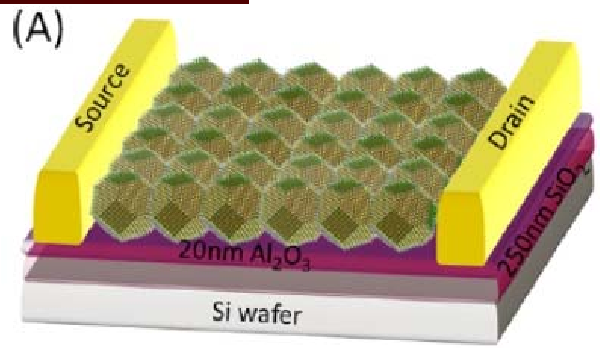
QD Biosensing



QD LED



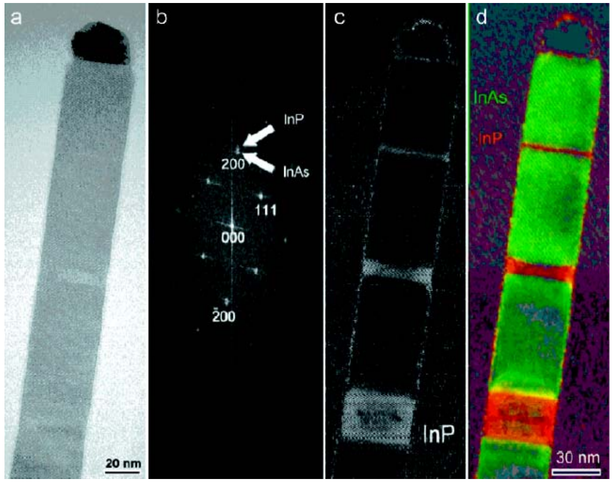
QD solar cells

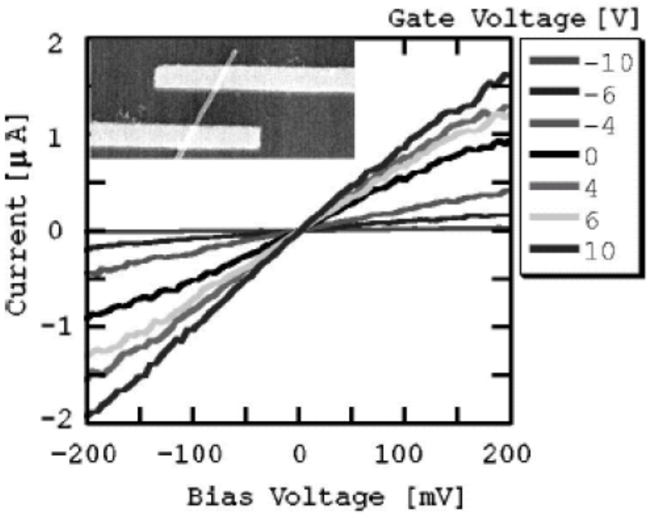


QD Transistor

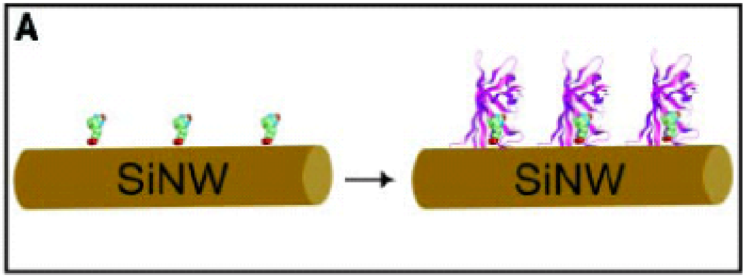
Applications of Nanomaterials (1-D)

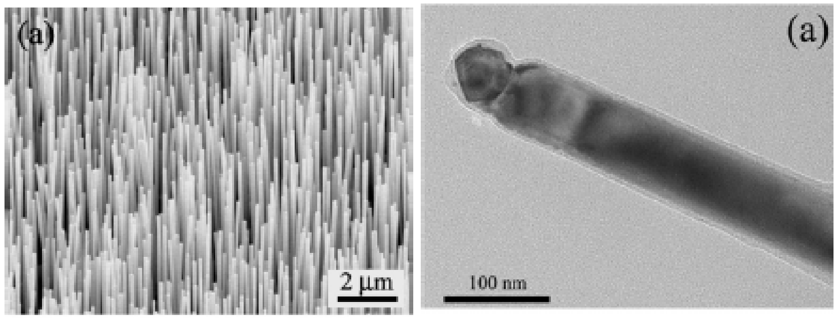
NW Transistor

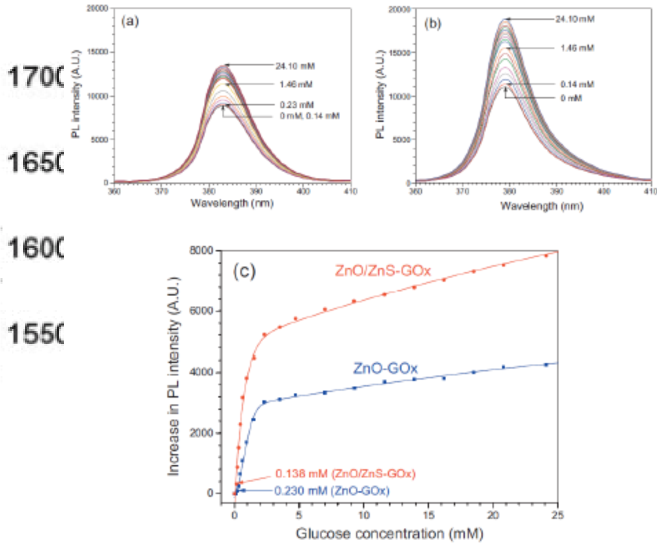




NW Biosensor

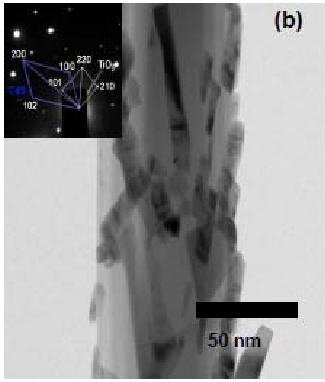


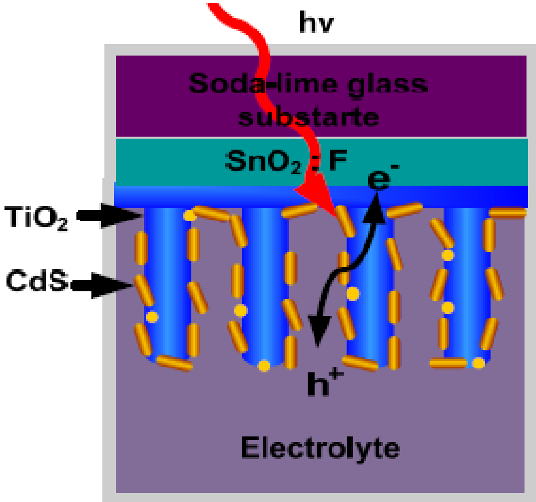


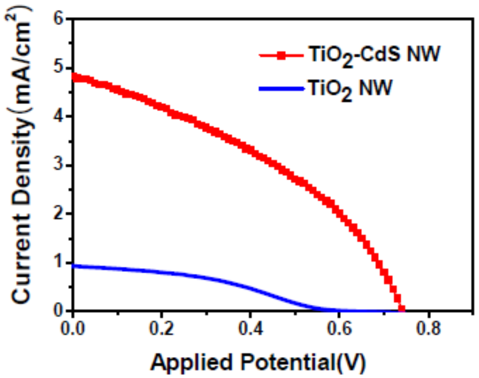


Applications of Nanomaterials (1-D)

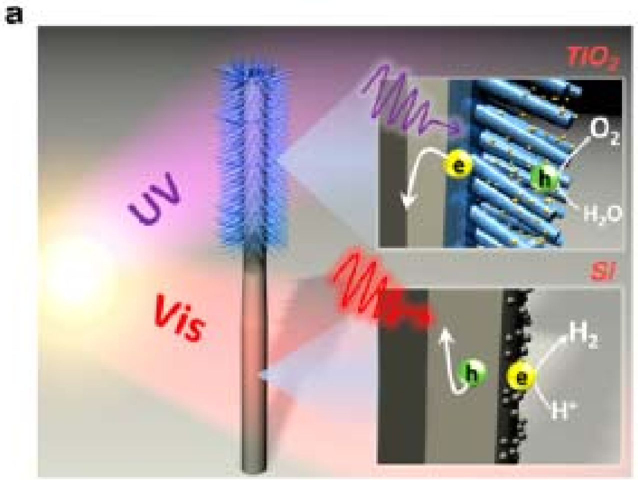
NW solar cells

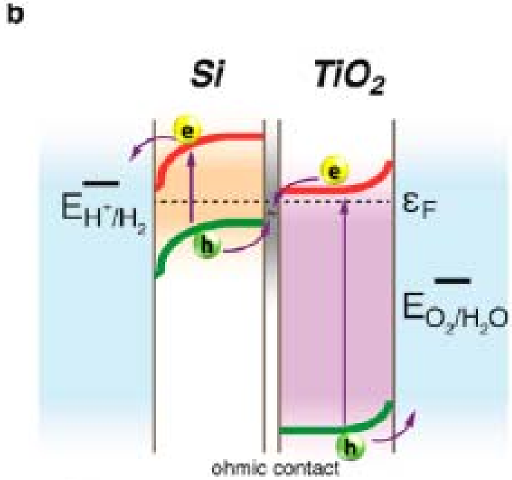


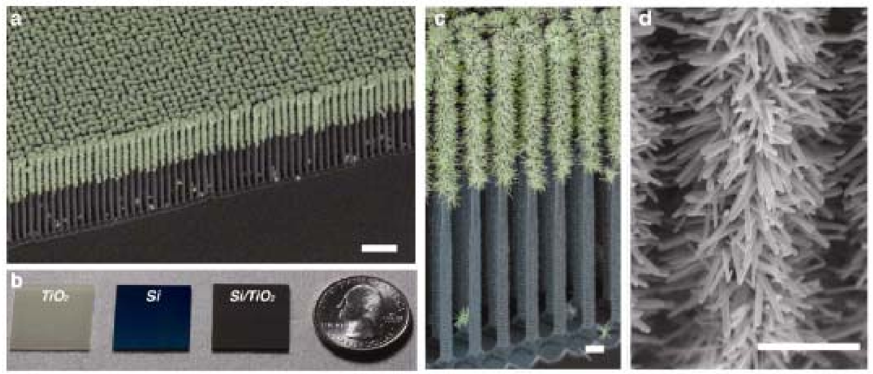




NW Water Splitting for H_2 gas







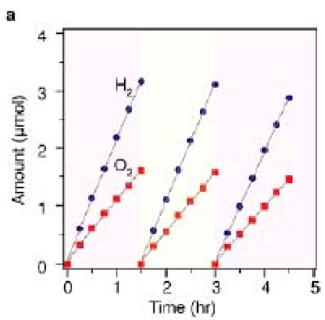
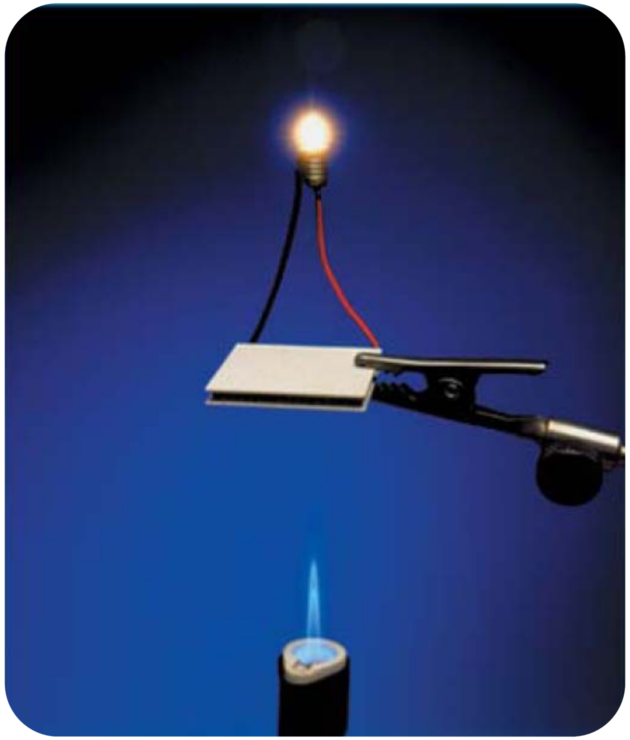
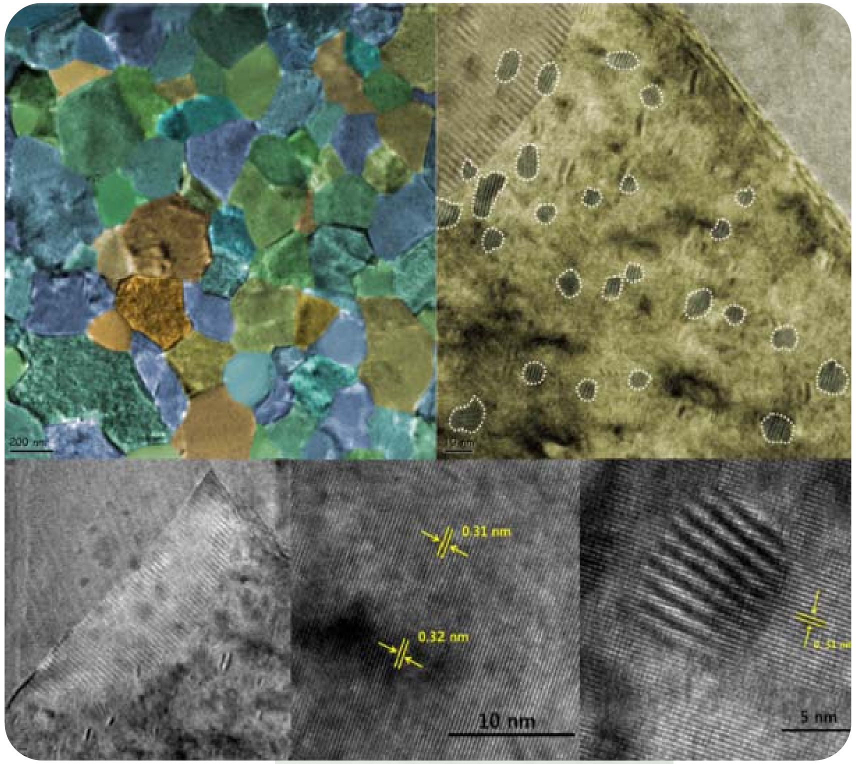


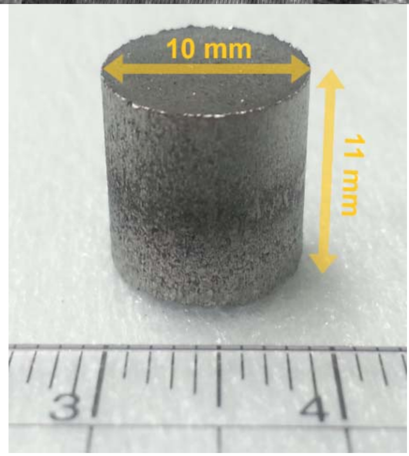
Figure 3. Structural characterization of the nanotree heterostructures. a, False-colored, large-scale SEM image of a Si/TiO_2 nanotree array. b, Comparison of the optical images of a TiO_2 nanowire substrate, a Si nanowire substrate, and a Si/TiO_2 nanotree substrate. c, SEM image of the details of a nanotree heterostructure. d, Magnified SEM image showing the large surface area of the TiO_2 segment used for water oxidation. The scale bars are 10 μm (a) and 1 μm (c, d).

Peidong Yan

Applications of Nanomaterials (3-D)







Today's TE Applications

Cassini - Saturn - NASA

40 years of NASA Investment in High Temperature TE Power Generation Technology for Deep Space Science Exploration

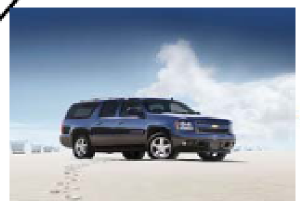

MRS BULLETIN

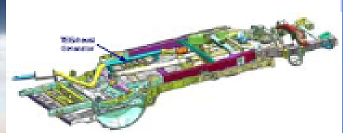
Harvesting Energy through Thermoelectrics: Power Generation and Cooling

IR Sensing

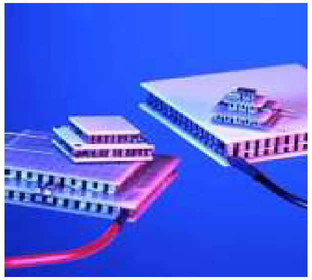
All-Solid-State Refrigeration

TE Powered Watch





Waste Heat Recovery

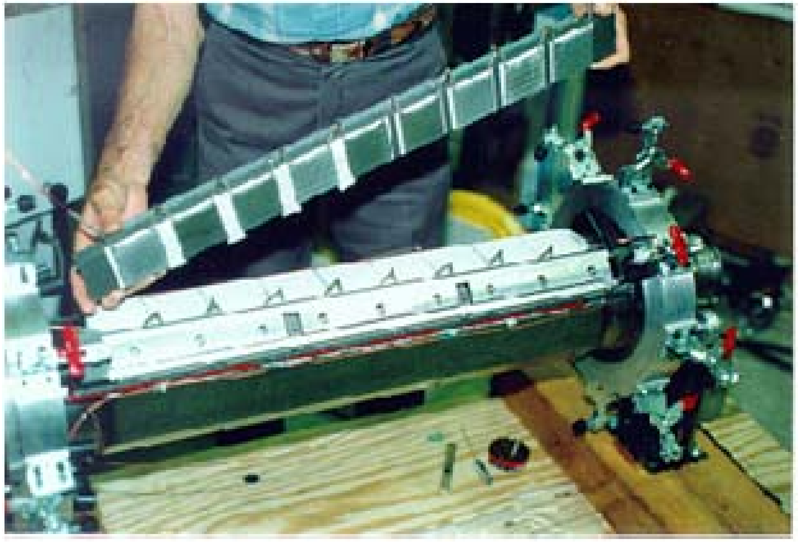


TE Module
A Key Enabling Technology Component

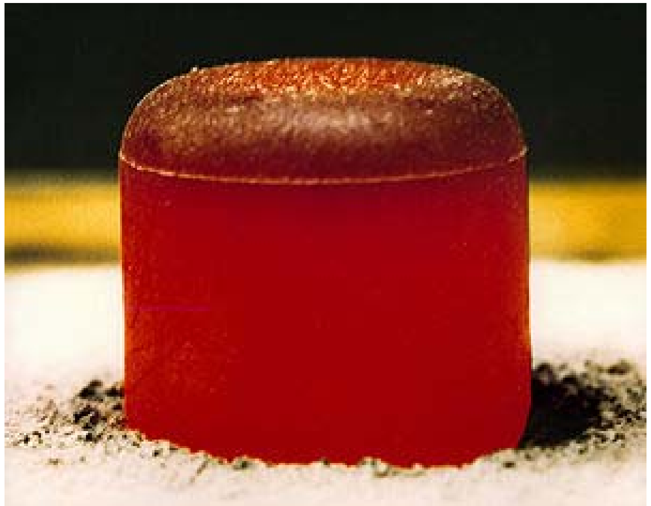
Autonomous Remote Power Generator

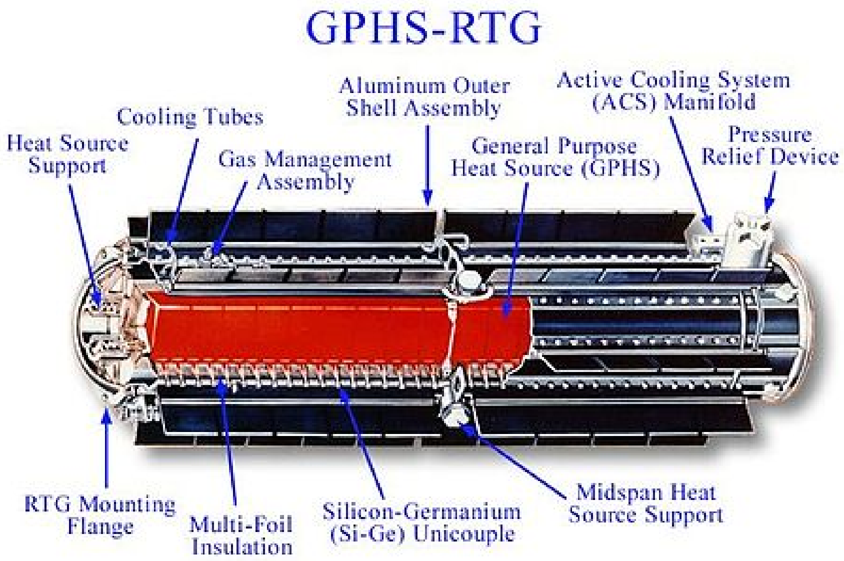
Active heated and cooled seating system

TE Power Generation (TEG) for Hybrid Cars



Radioisotope thermoelectric generator





Summary

- Room-temperature mechanical behavior – flexural tests
  -- linear-elastic; measurement of elastic modulus
  -- brittle fracture; measurement of flexural modulus

- Categories of ceramics:
  -- glasses
  -- clay products
  -- refractories
  -- cements
  -- advanced ceramics