微纳光电子材料与器件工艺原理

Materials: Structures and Synthesis

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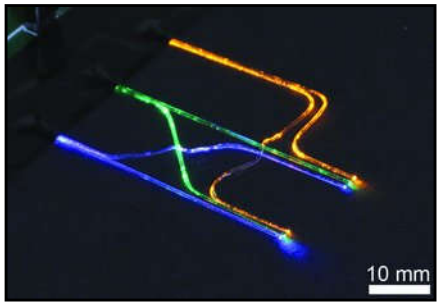
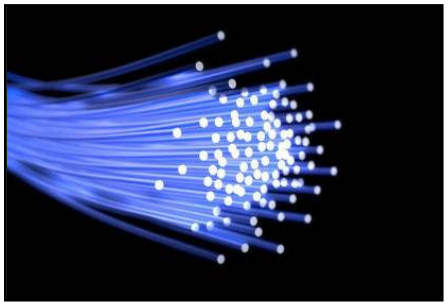
Optical and Electronic Devices

LEDs

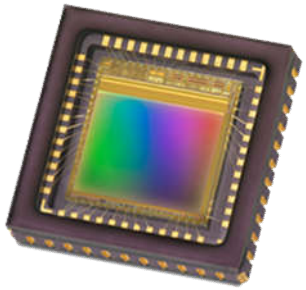
lasers



waveguides

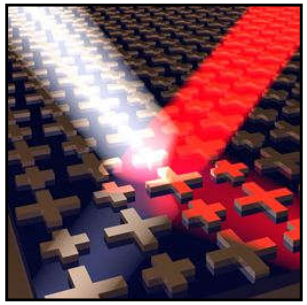


fibers

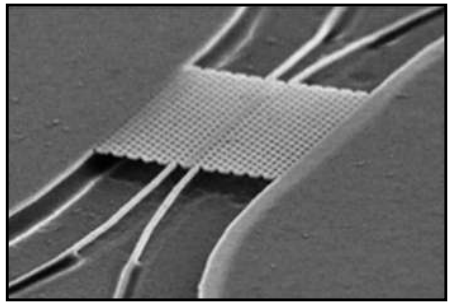


detectors

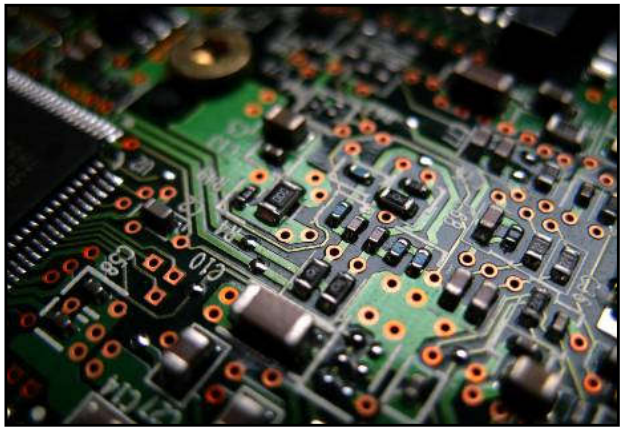
solar cells



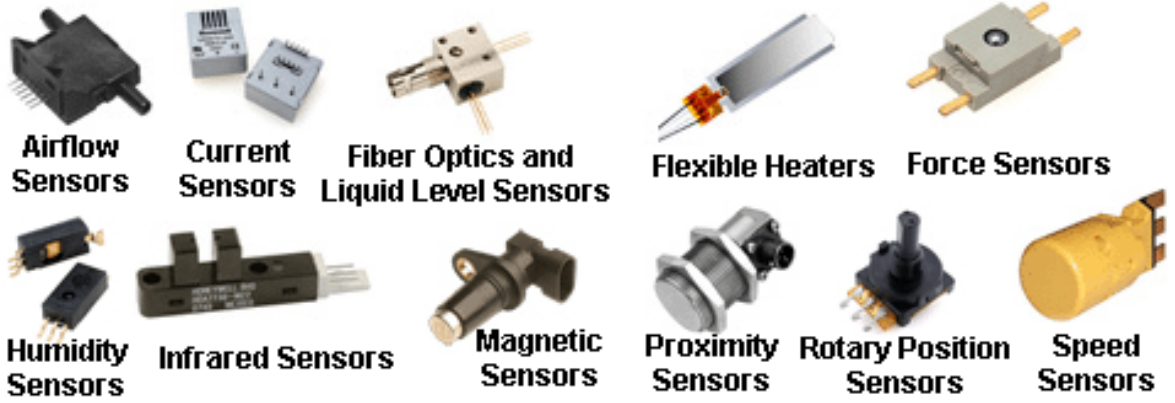
metamaterials



photonic crystals

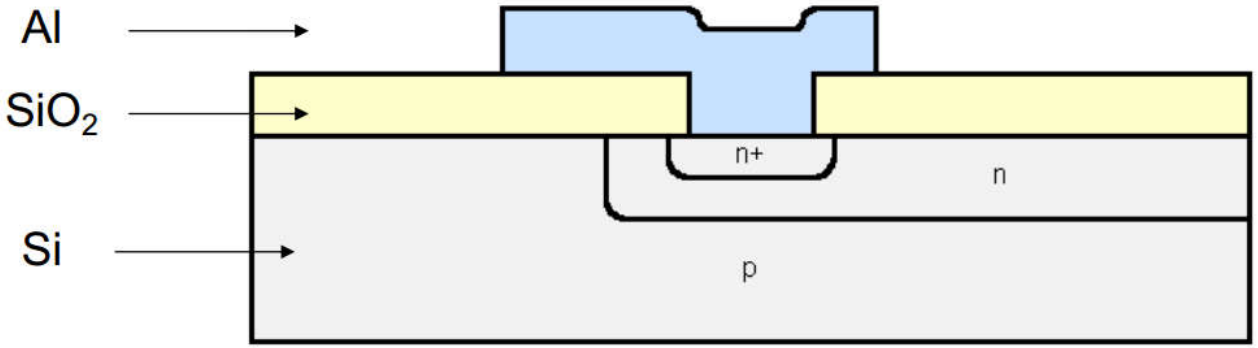


integrated circuits



Raw Materials

MOS: **Metal-Oxide-Semiconductor**

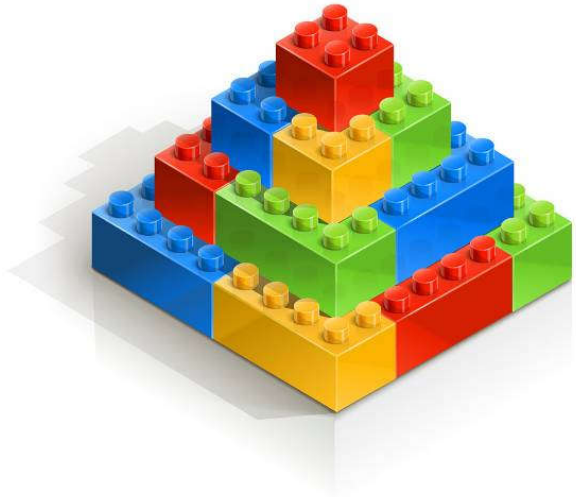


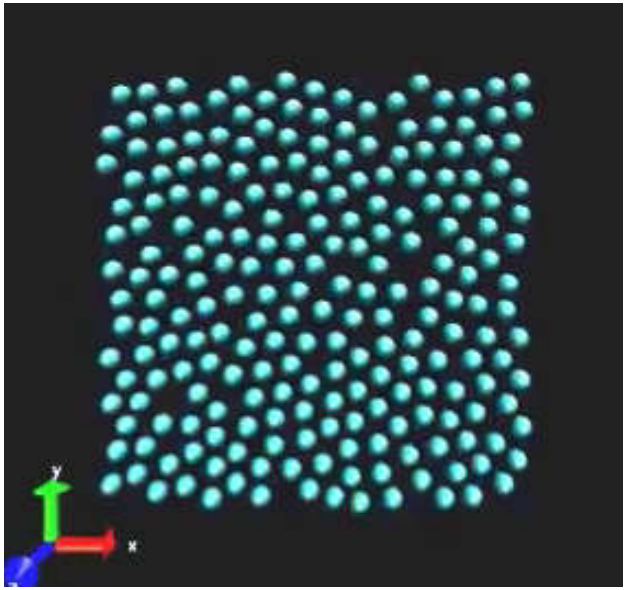
Silicon

SiO_2

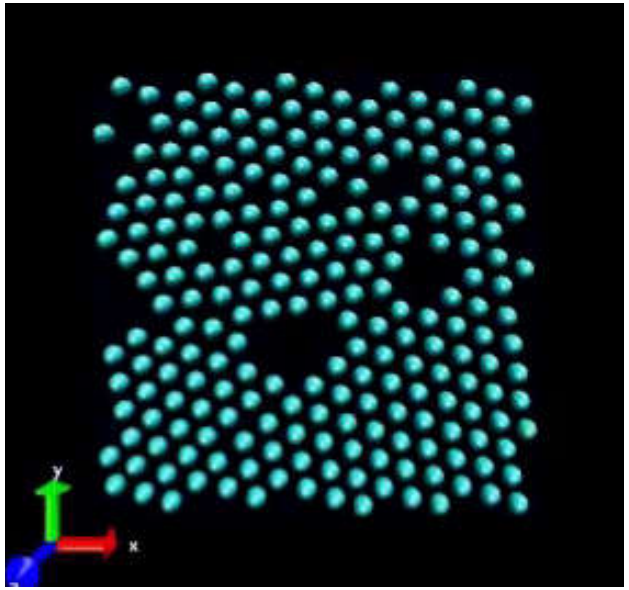
Metal

Crystal Structures

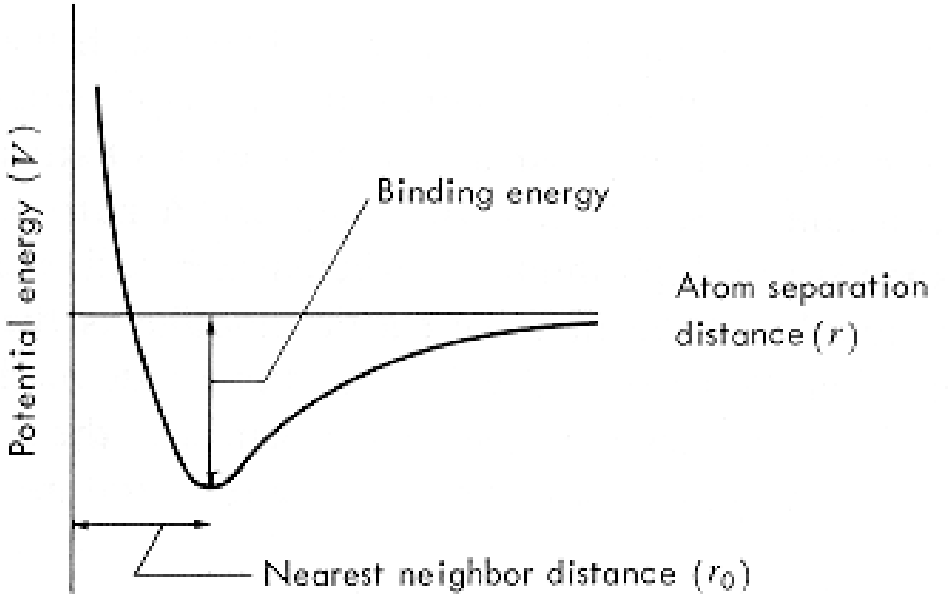




video

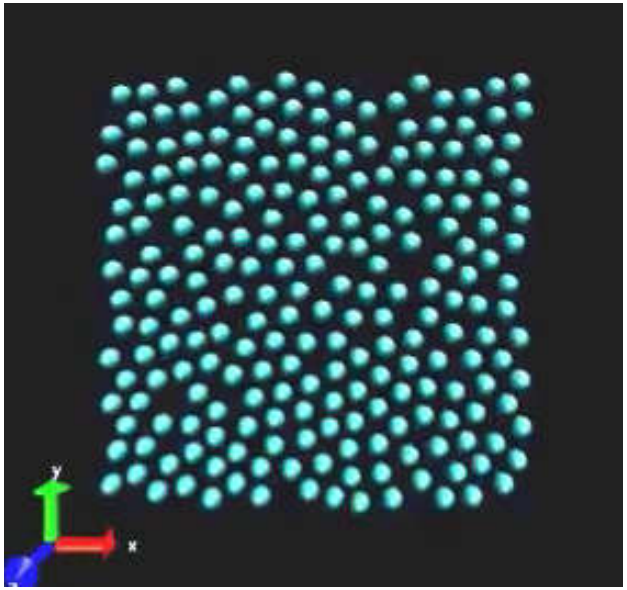


It is all about *energy*

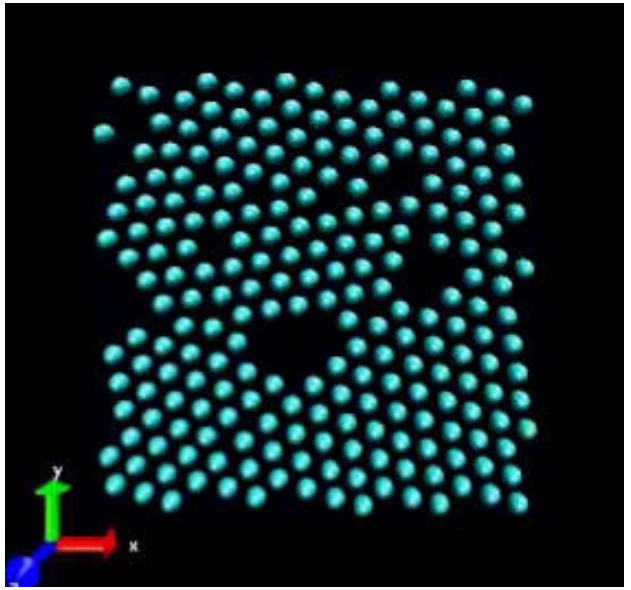


Lennard-Jones Potential

$$V(r) = \frac{A}{r^{12}} - \frac{B}{r^{6}}$$

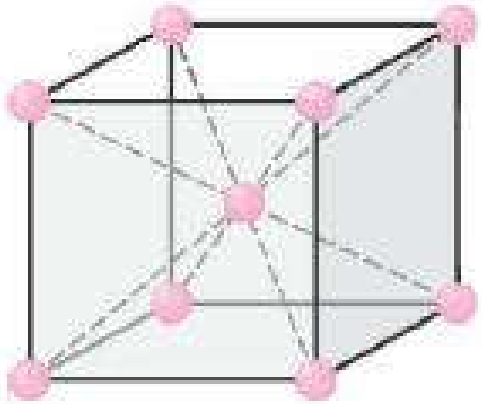


video



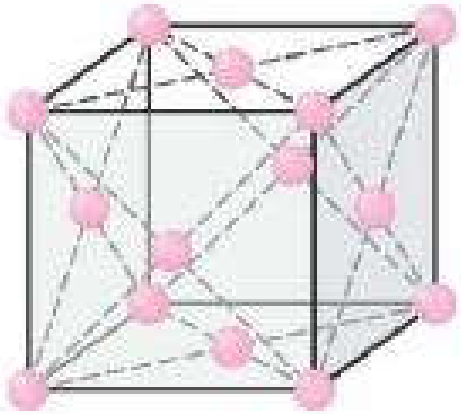
Crystal Structures

Li, Na, Cr,...



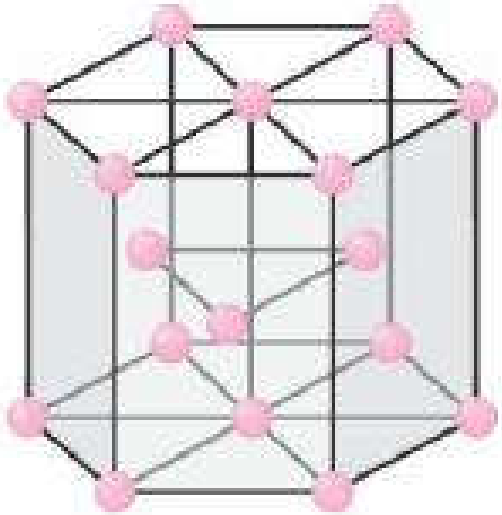
BCC

Al, Cu, Au,...



FCC

Mg, Zn, Ti,...



HCP

- 3D:
  - 14 Bravais lattices
  - 32 point groups
  - 230 space groups

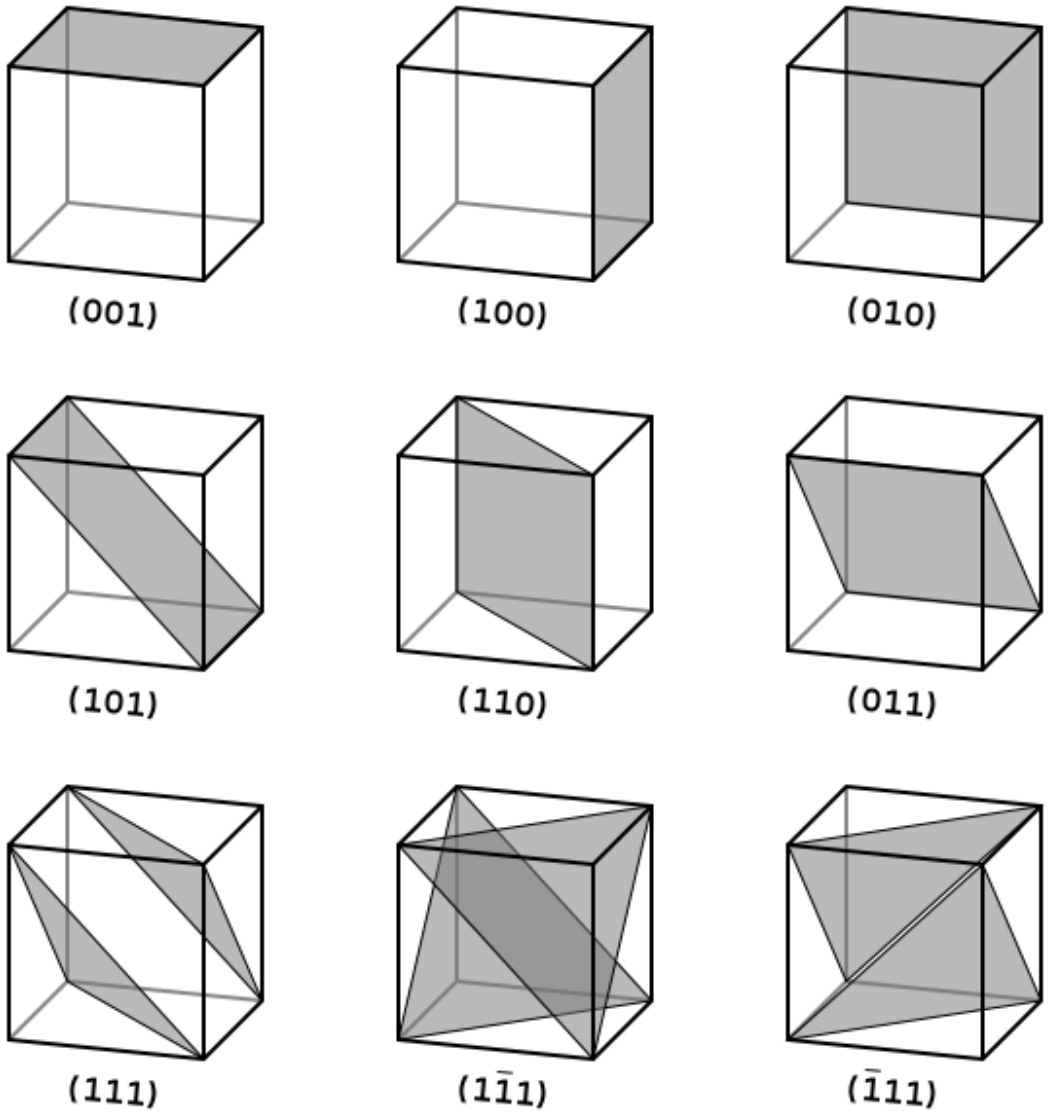
https://en.wikipedia.org/wiki/Crystal_structure

Miller Indices

(*lmn*) plane

intercepts at

a_1/l, a_2/m, a_3/n



https://en.wikipedia.org/wiki/Crystal_structure

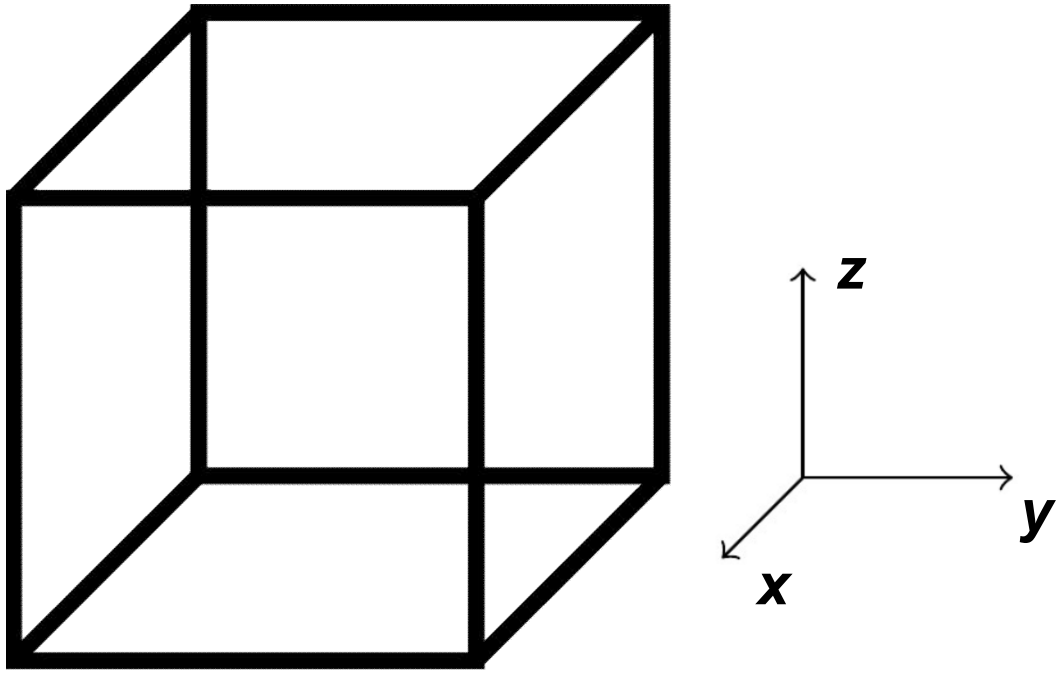
Exercise in class

- draw planes below
  - (120), (112), (131)

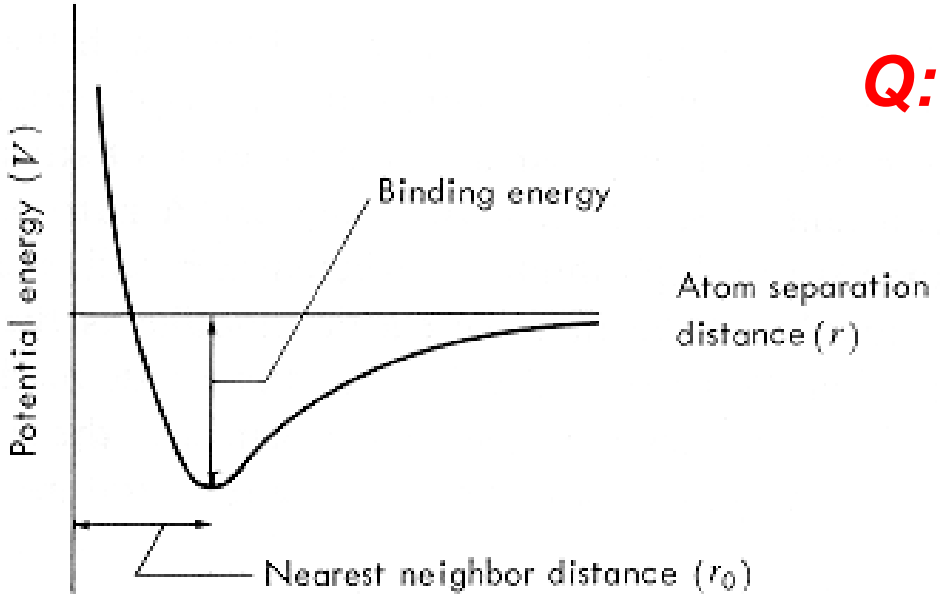
(*lmn*) plane

intercepts at

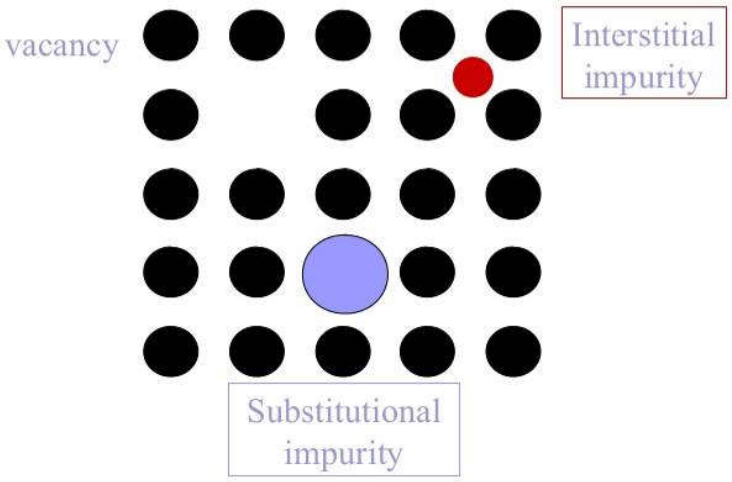
a_1/l, a_2/m, a_3/n



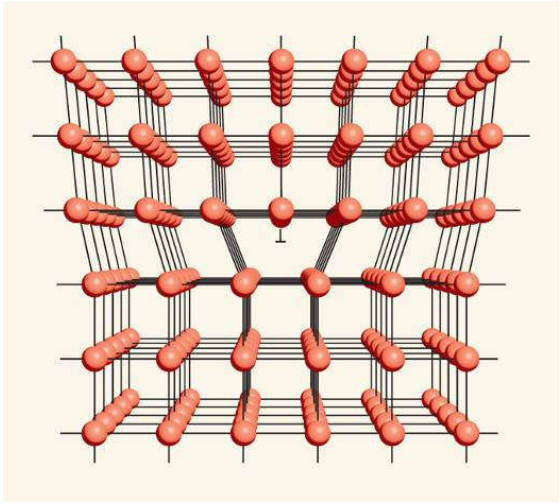
Defects in Crystals



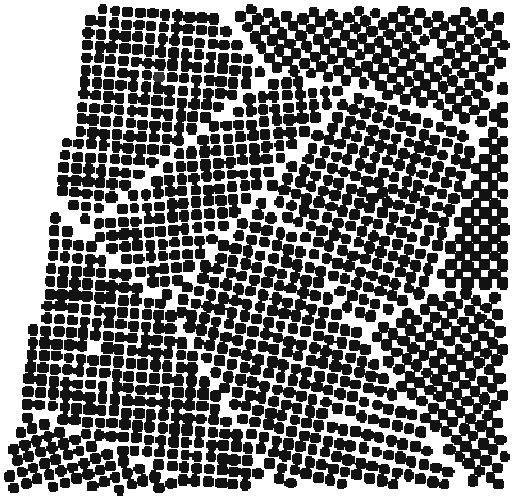
Q: why?



0D
point defect

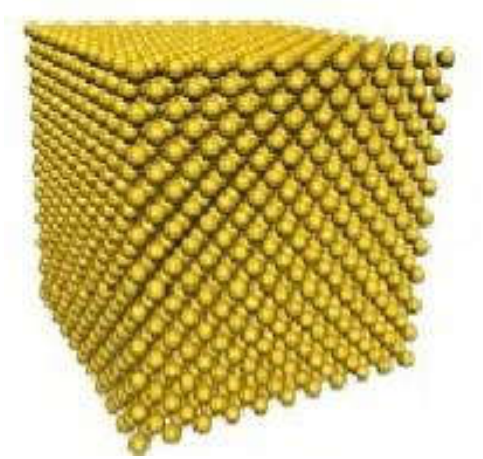


1D
dislocation



2D
grain boundary

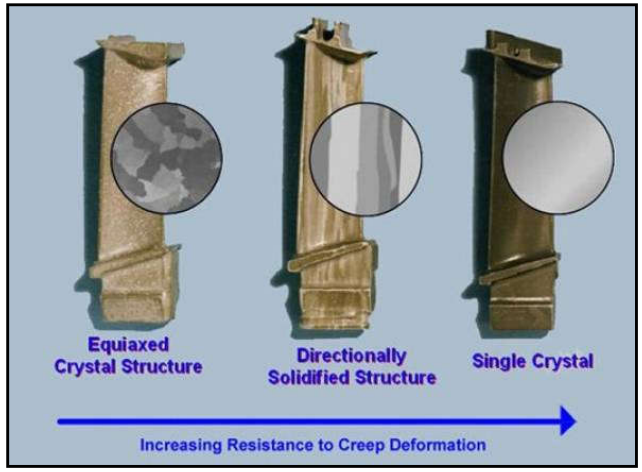
Single Crystal (Mono Crystal)



Quartz

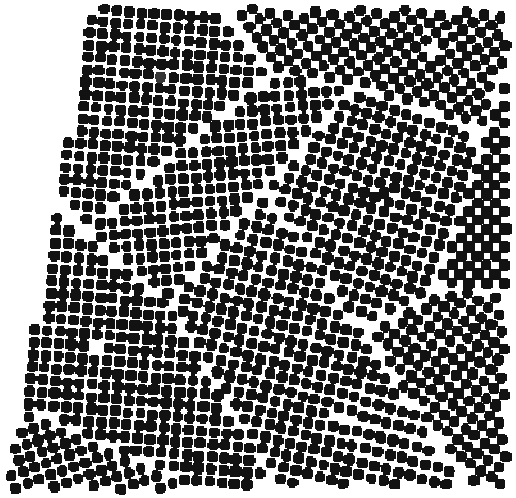
Sugar

Silicon wafers,
GaAs, GaN, sapphire, ...

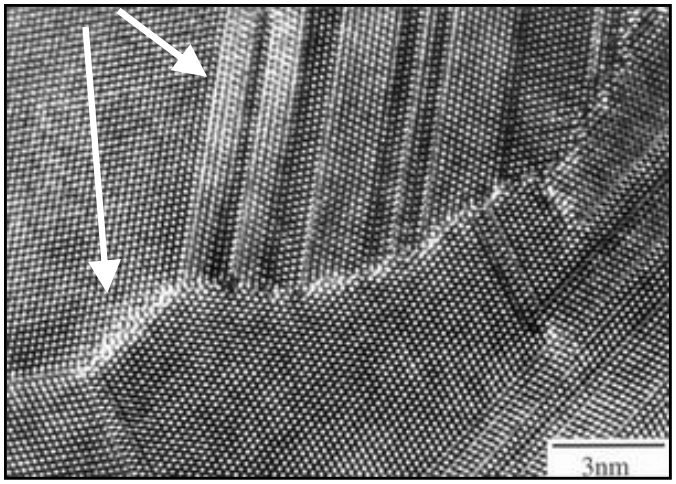


turbine blade

Polycrystal

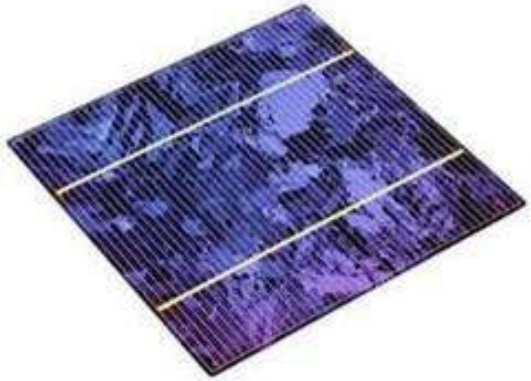


grain boundary



polycrystalline silicon

Q: why blue?



Poly-Crystalline
Solar Cell

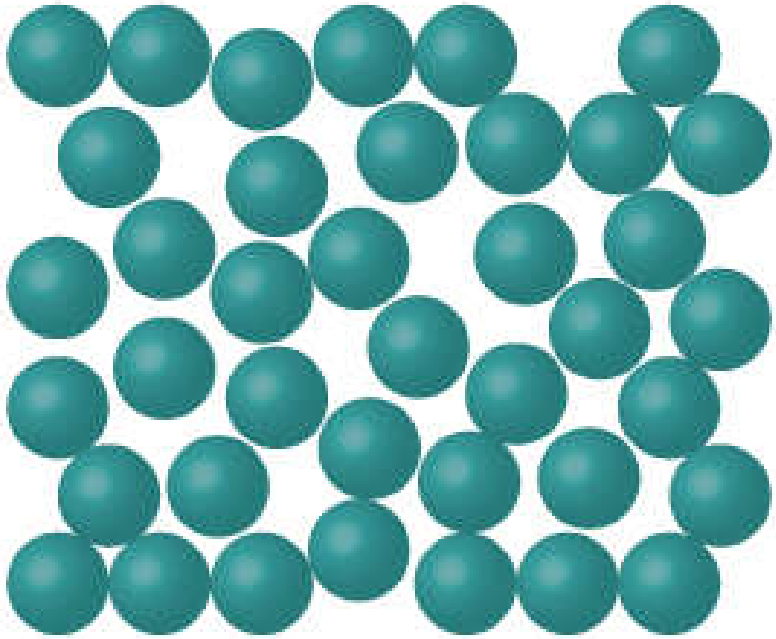
Mono-Crystalline
Solar Cell

metal

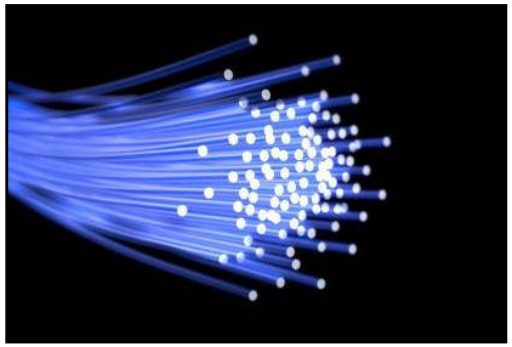
ceramic

Amorphous Materials

- **Defects are everywhere ...**



Amorphous



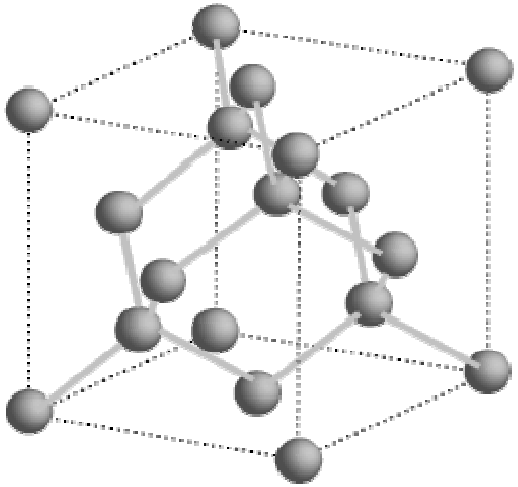
silica fiber

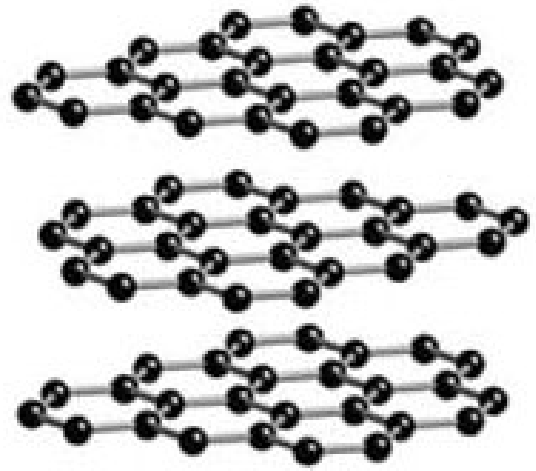
glass

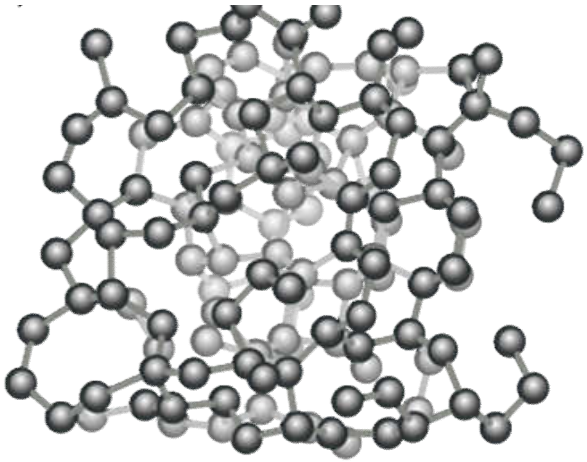
plastics

Q: why is glass transparent?

Carbon



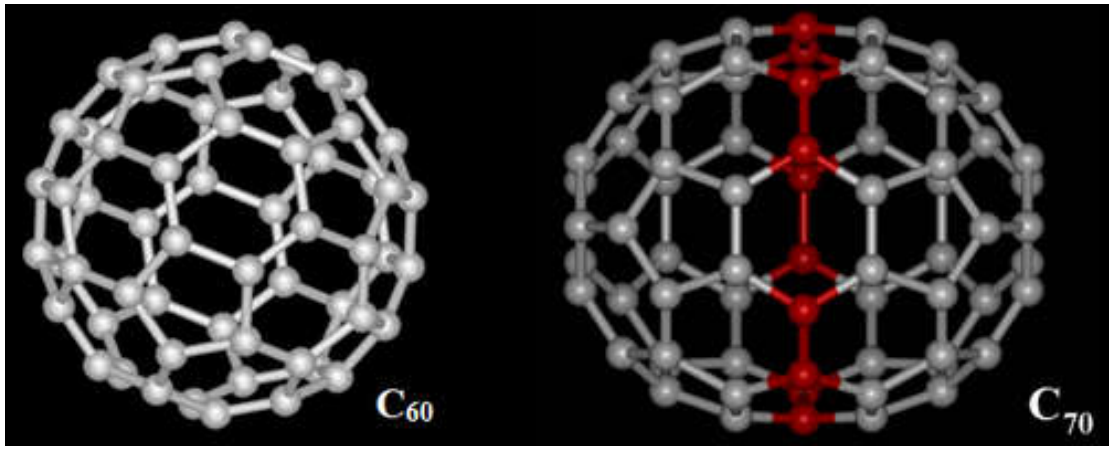




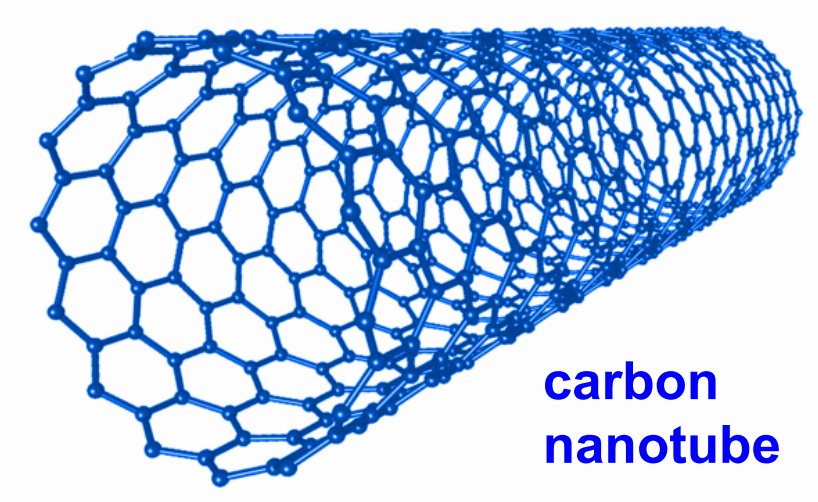
diamond **graphite** **amorphous carbon**

Q: which one is electrically conductive, diamond or graphite?

Carbon

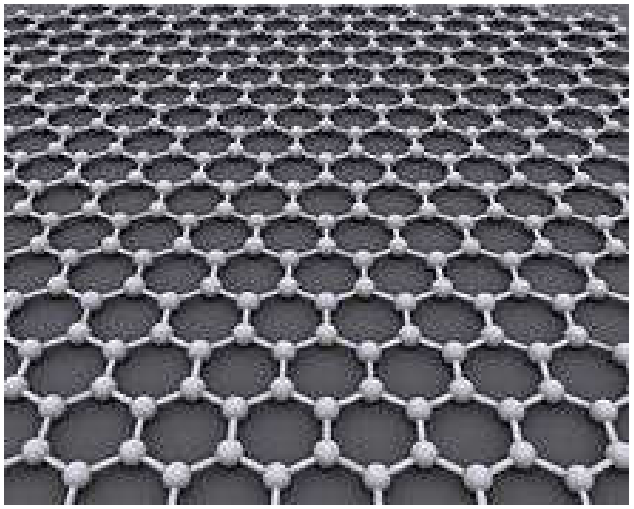


H. Kroto, R. Curl, R. Smalley
1996 Nobel Prize in Chemistry



carbon nanotube

S. Iijima, *Nature* **354,** 56 (1991)

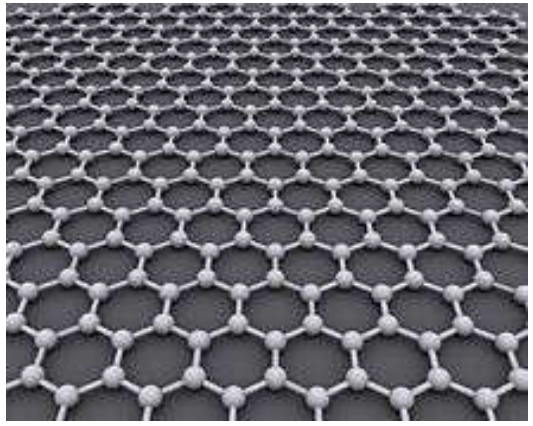


graphene

A. Geim, K. Novoselov
2010 Nobel Prize in Physics

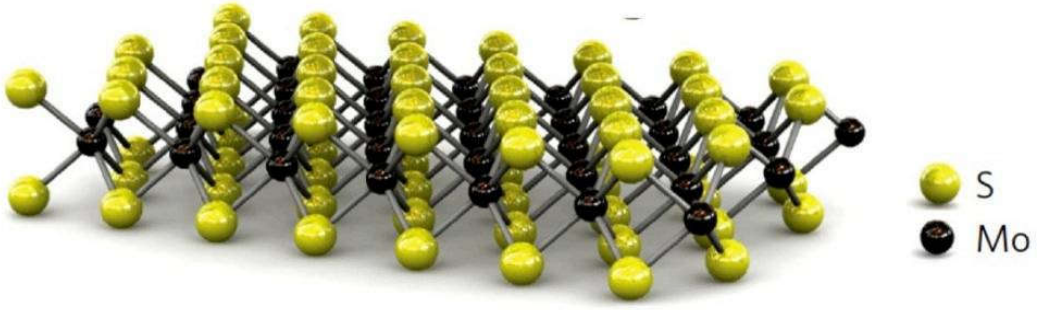
2D Materials

- **Single atomic layer crystal**

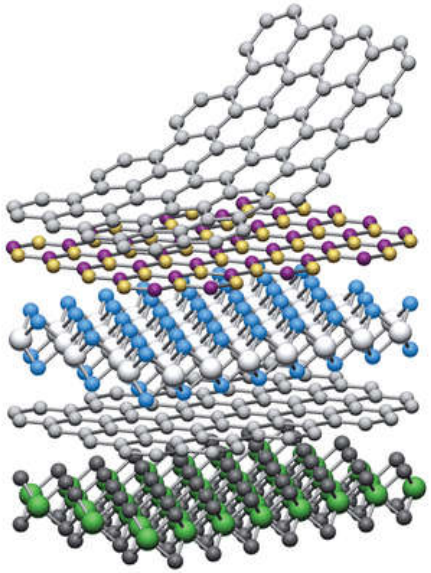


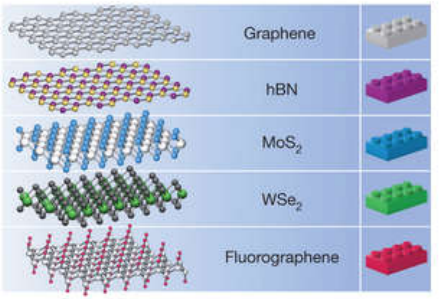
graphene

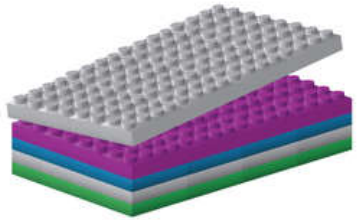
A. Geim, K. Novoselov
2010 Nobel Prize in Physics



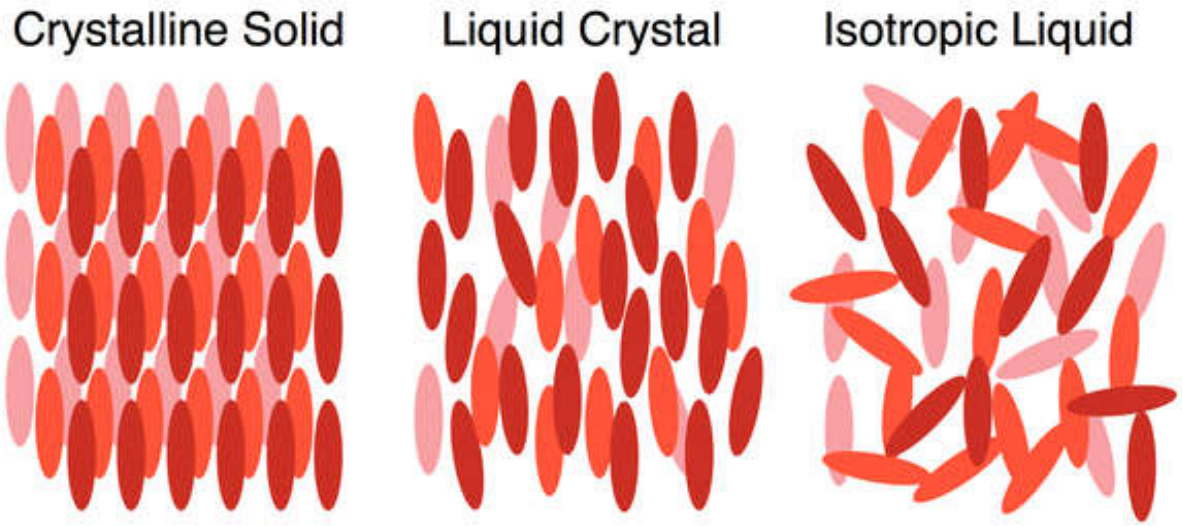
Transition metal dichalcogenide (TMDC)
MoS_2, WSe_2, ...







Liquid Crystals



Liquid crystal display (LCD)

P. de Gennes
1991 Nobel Prize in Physics

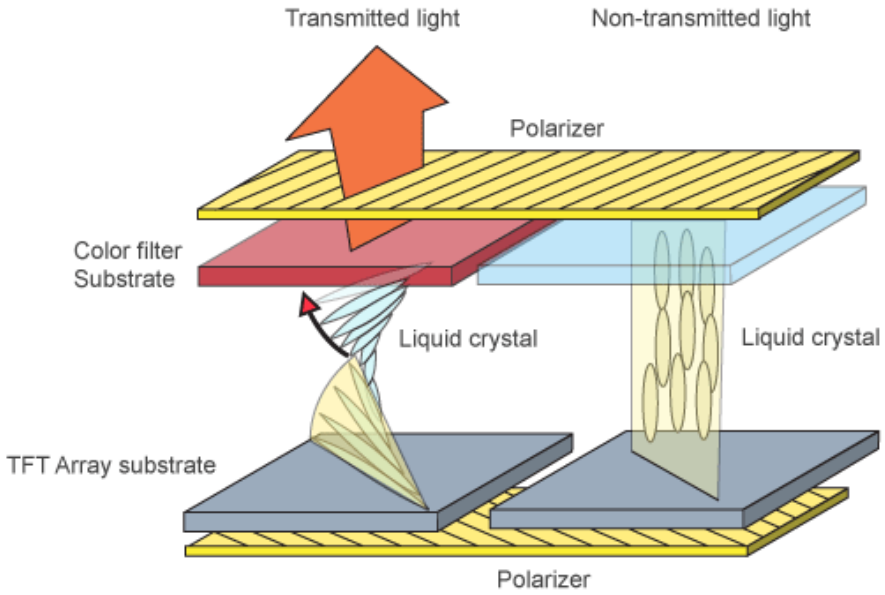
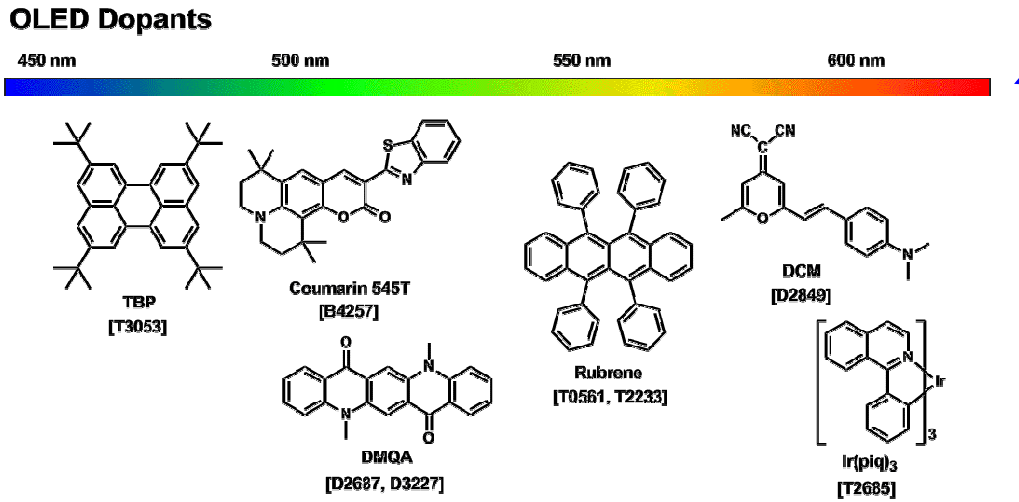
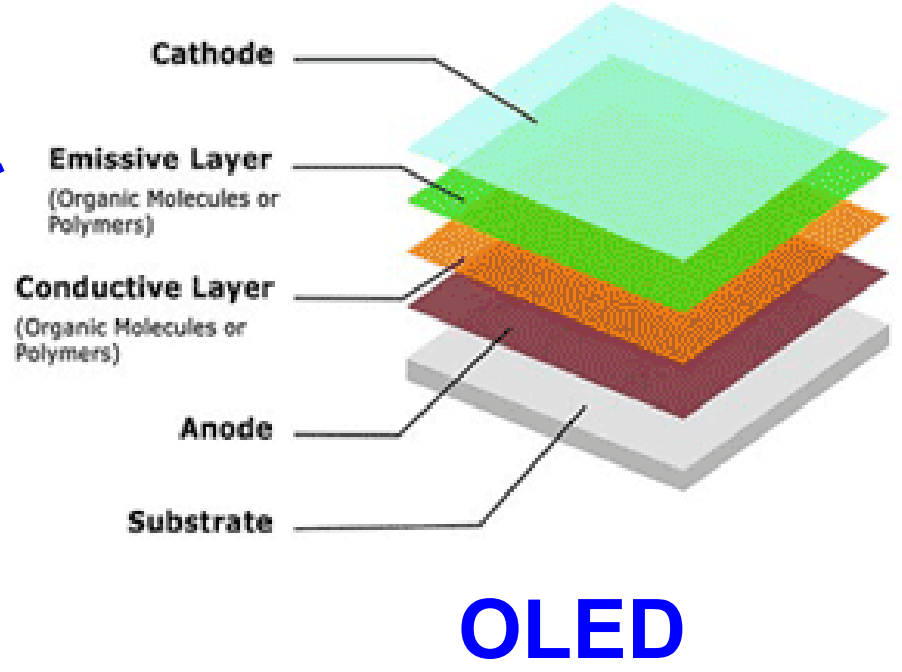


Diagram 2: The Fundamental Photonics of Liquid Crystal (Twisted Nematics)

Organic Materials

- **Small Molecules**

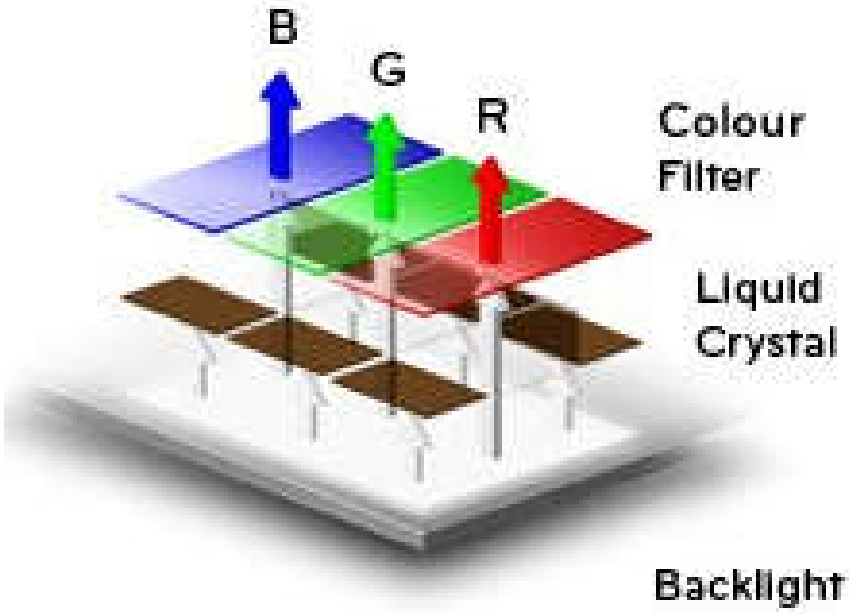


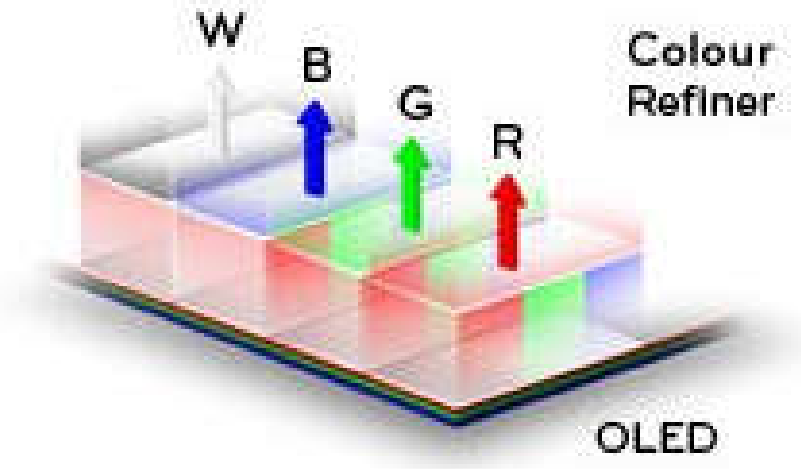


OLED

Organic Materials

LCD vs. OLED



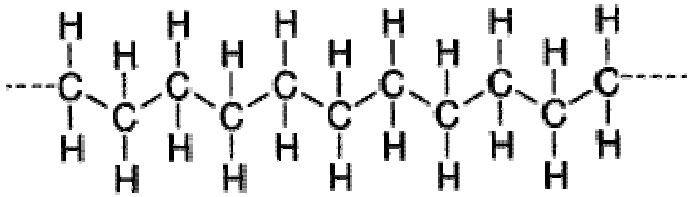


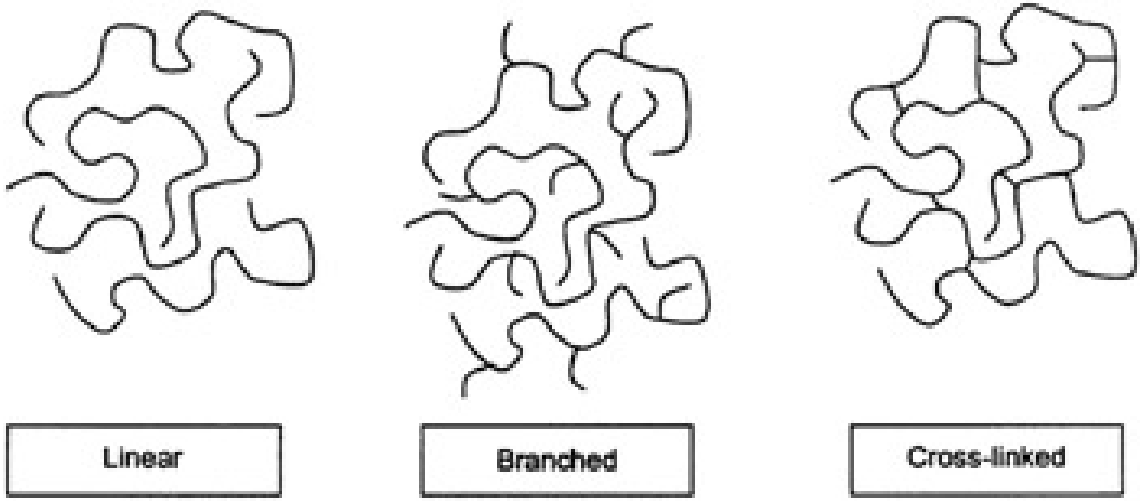
- Complex Structure
- BLU (Backlight Unit) CCFL, LED
- Lighting Unit = Pixel Unit

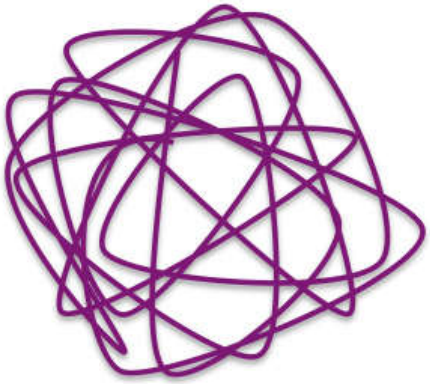
- Simple Structure
- Self-emissive
- Lighting Unit = Pixel Unit

Organic Materials

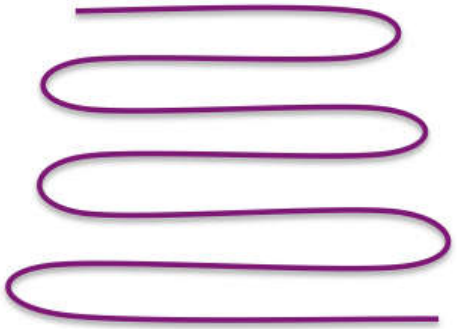
- **Polymers**



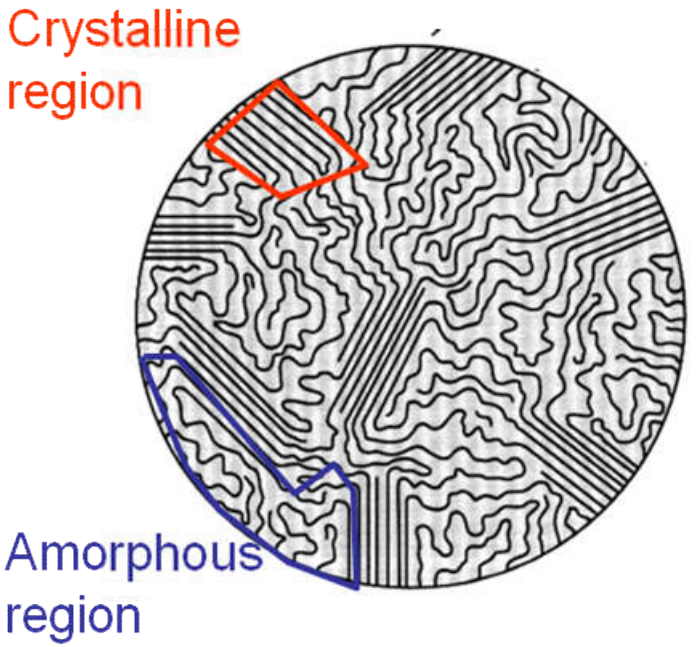




Amorphous

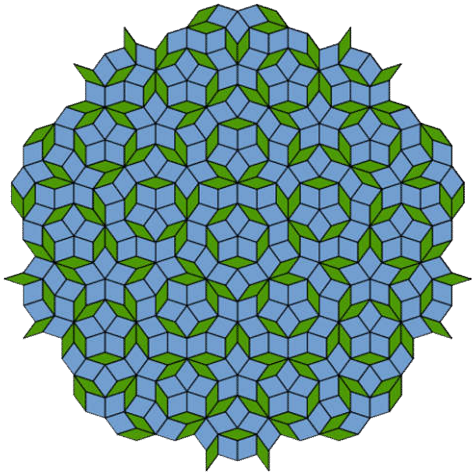


Crystalline

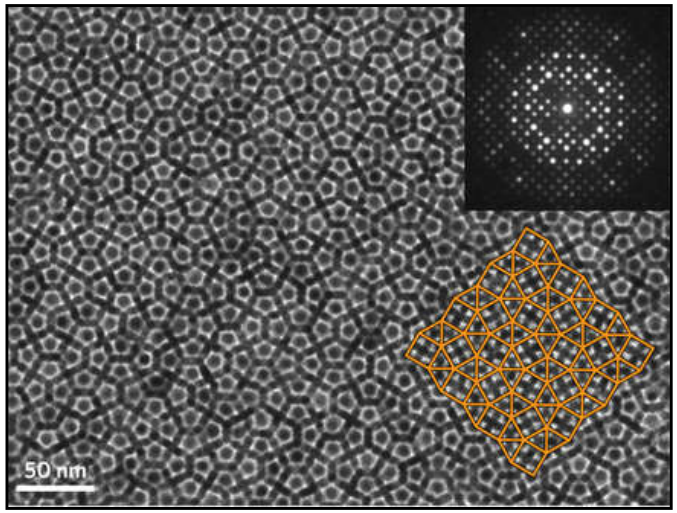


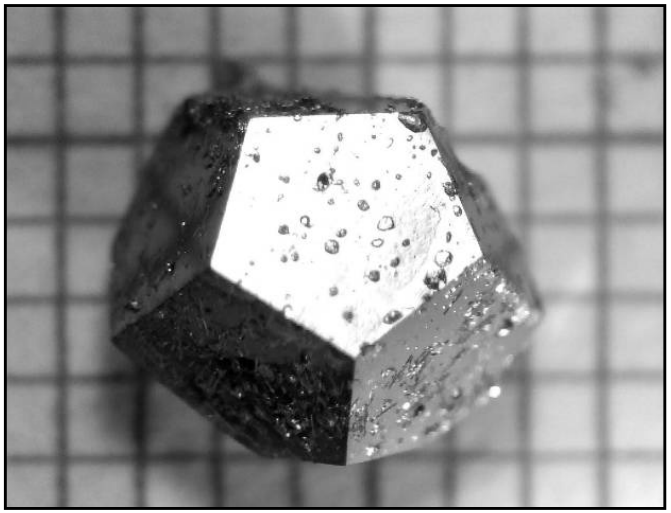
Quasi-Crystal

- Neither crystalline nor amorphous
  - 5, 8, 10, or 12-fold symmetry



Penrose tiling



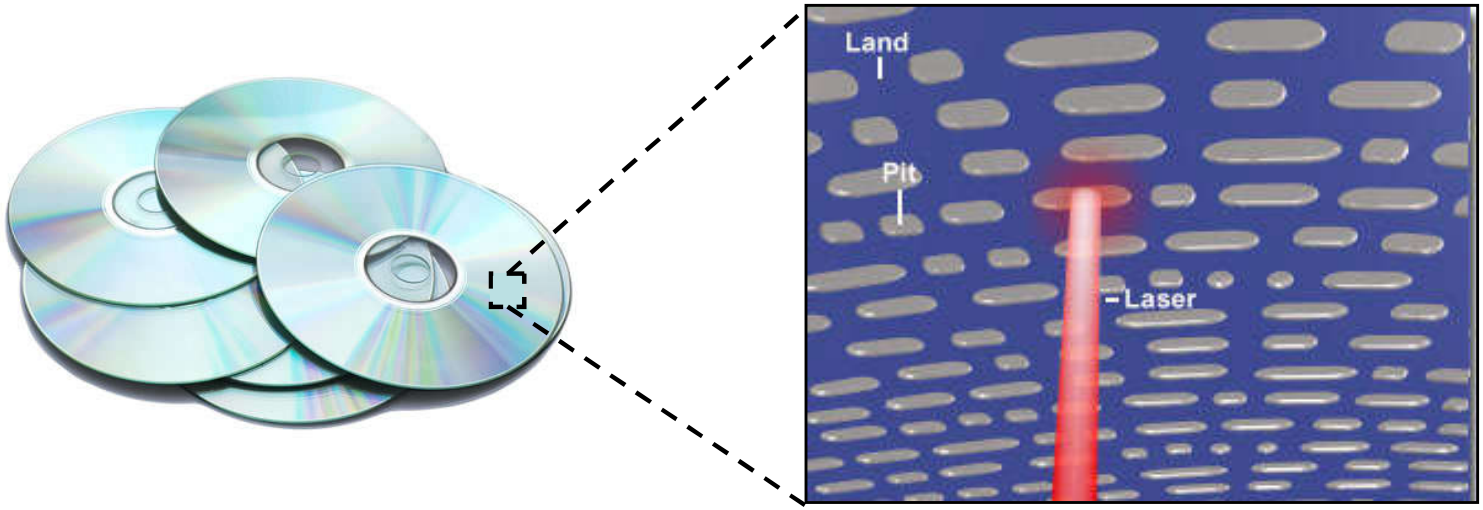


A Ho-Mg-Zn quasicrystal

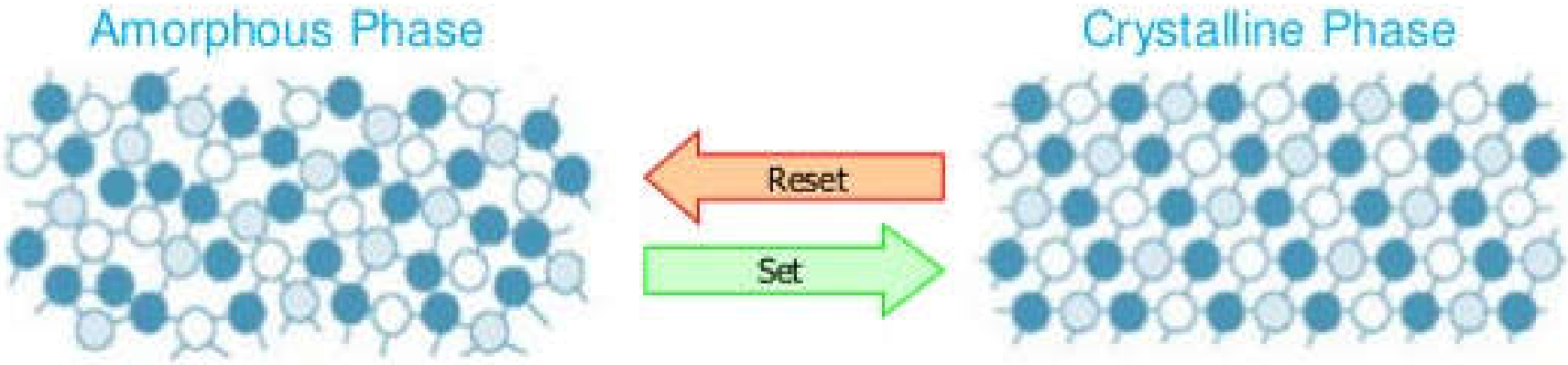
D. Shechtman
2011 Nobel Prize in Chemistry

Optical Disc

- **Phase Change Memory**

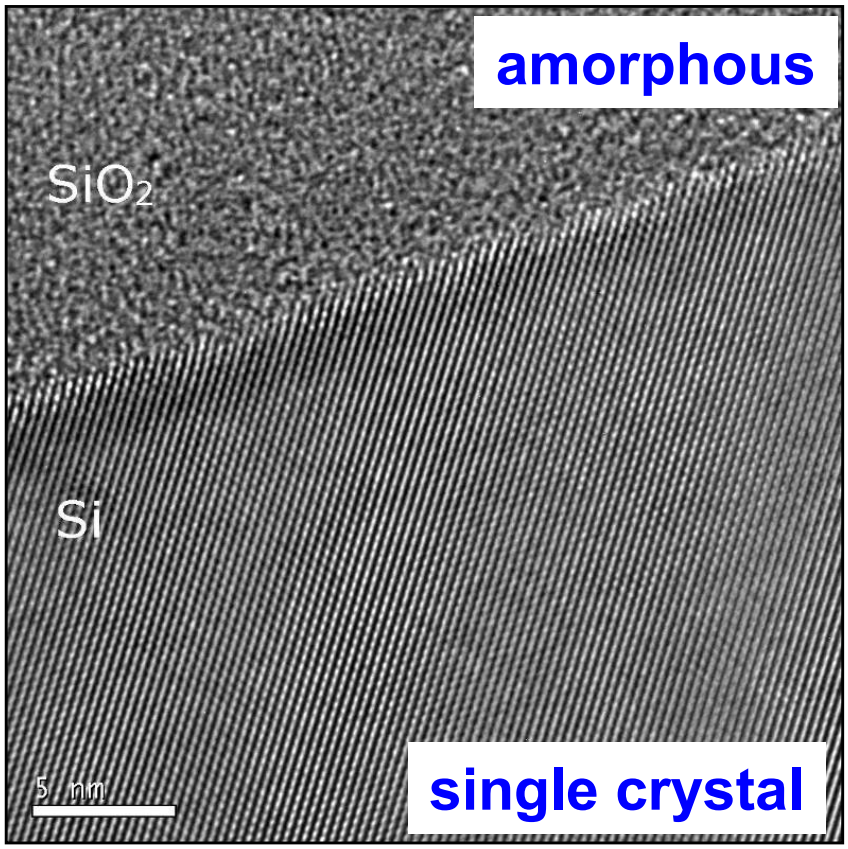


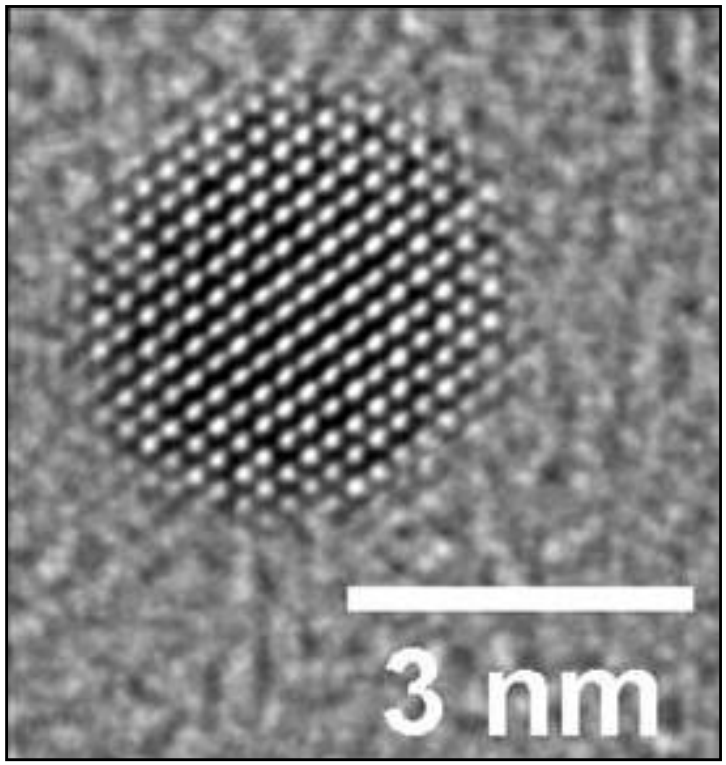
- Two Phases:



Materials Characterization

- **HRTEM**
  - **High Resolution Transmission Electron Microscope**



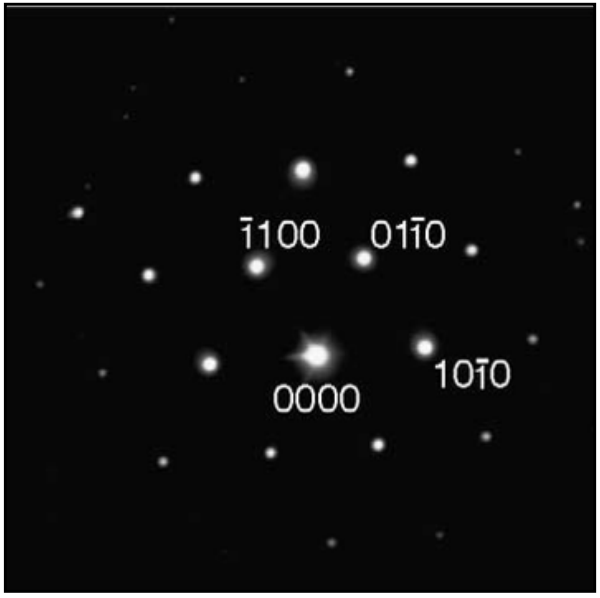


quantum dot

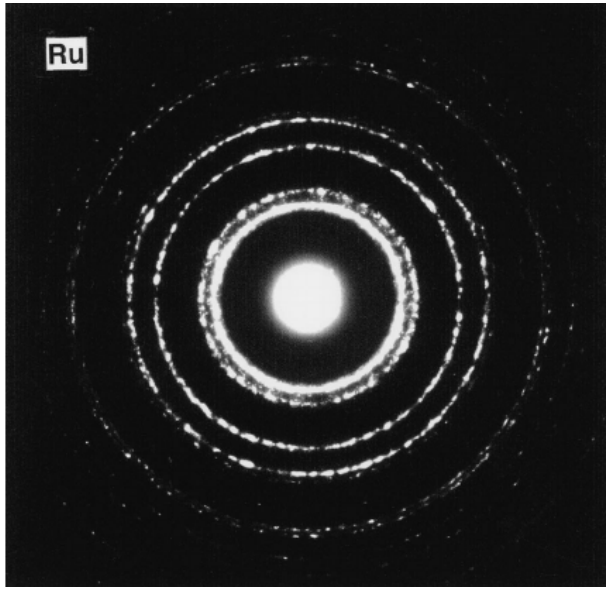
Materials Characterization

- **HRTEM**
  - **High Resolution Transmission Electron Microscope**

diffraction patterns



single crystal

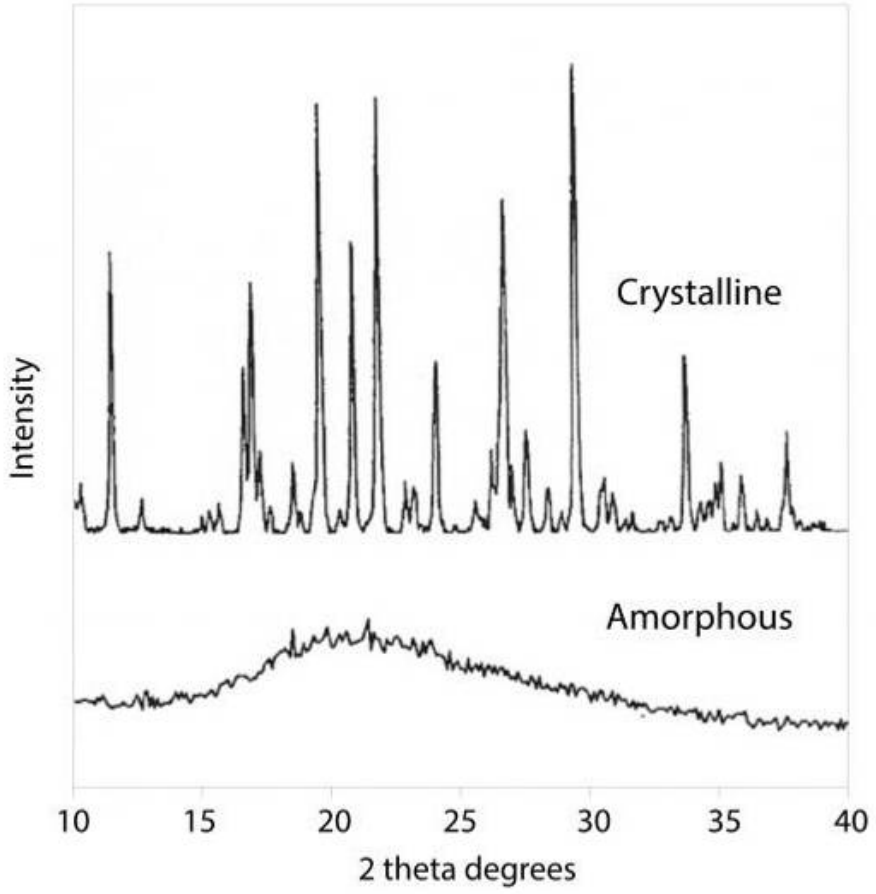


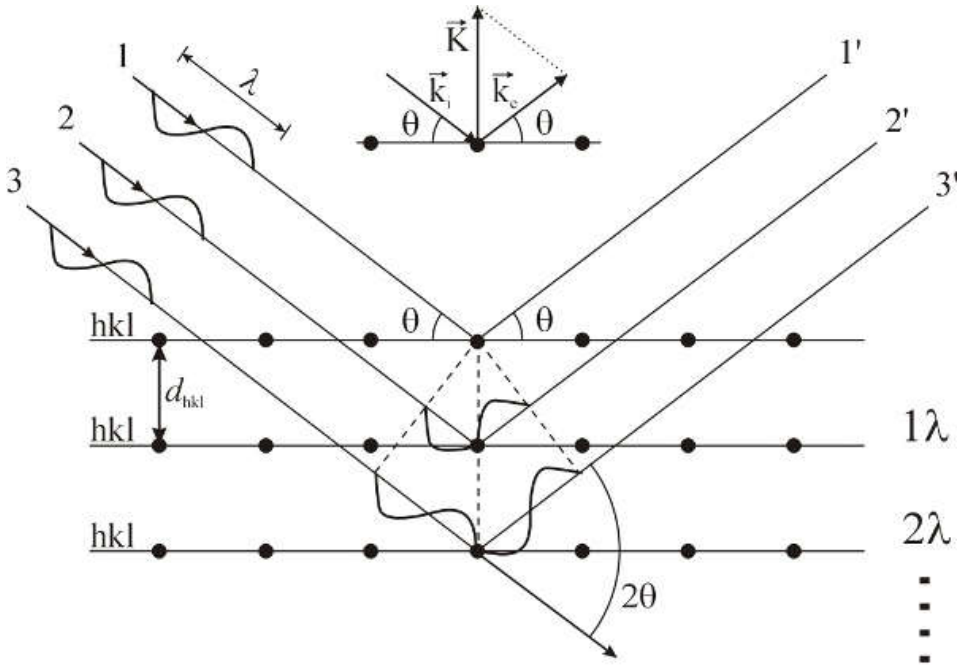
polycrystal

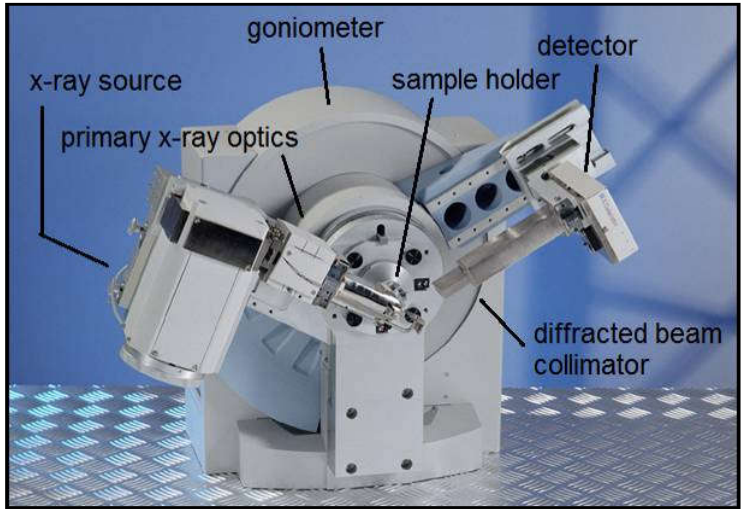
amorphous

Materials Characterization

- **XRD**
  - **X-ray Diffraction**

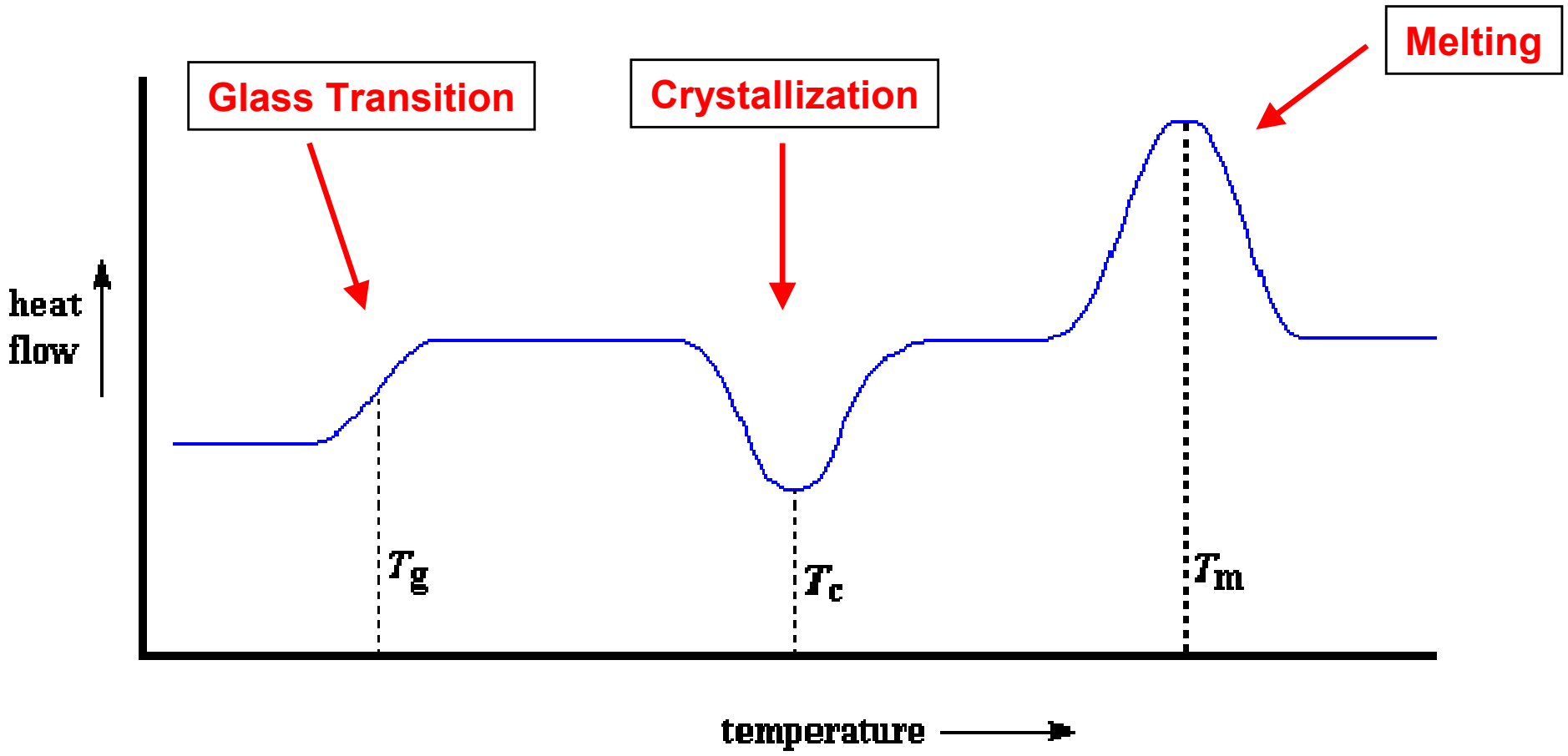






Materials Characterization

- DSC
  - Differential Scanning Calorimetry

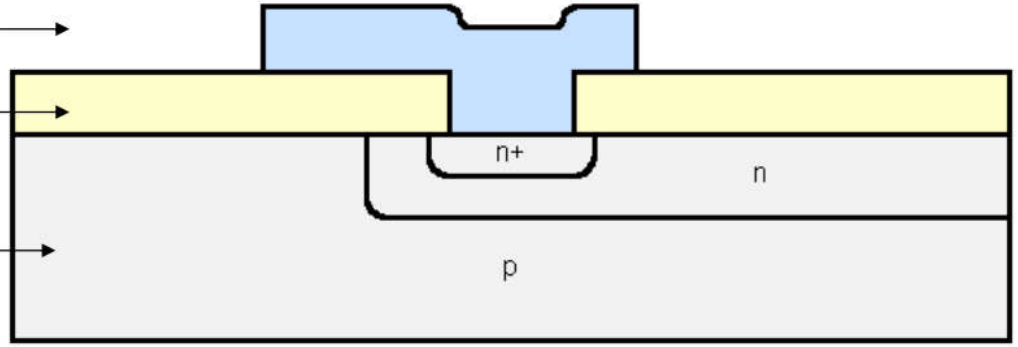


CMOS Device

polycrystalline → Al

amorphous → SiO_2

single crystalline → Si



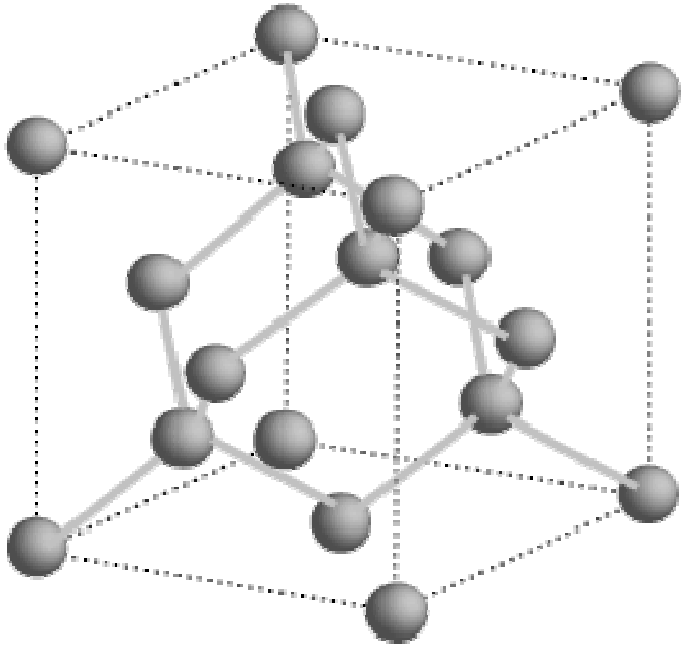
Silicon

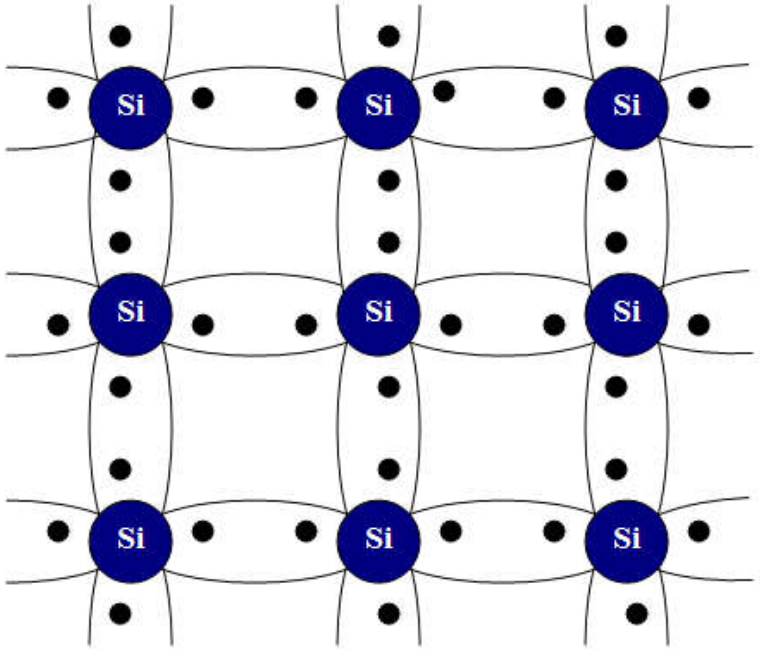
SiO_2

Metal

Substrates for Devices

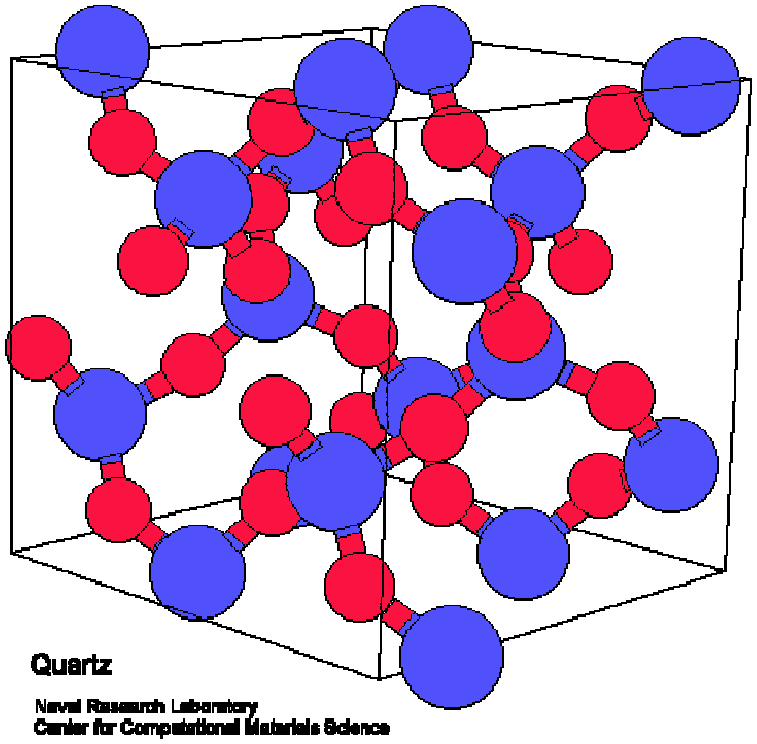
- **Usually single crystals (why?)**



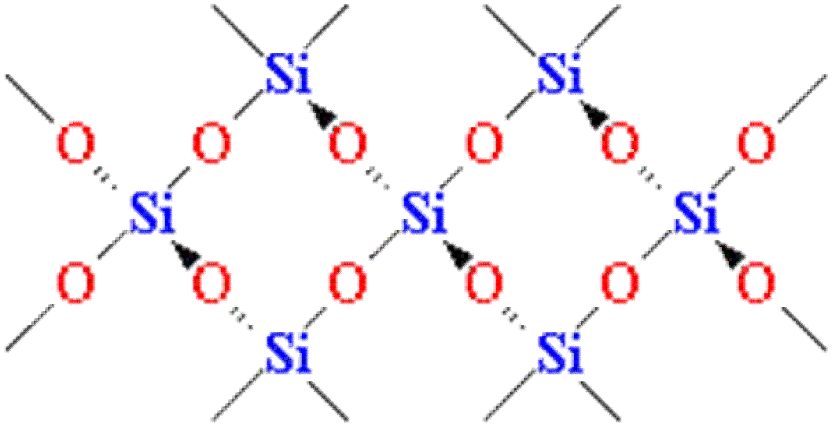


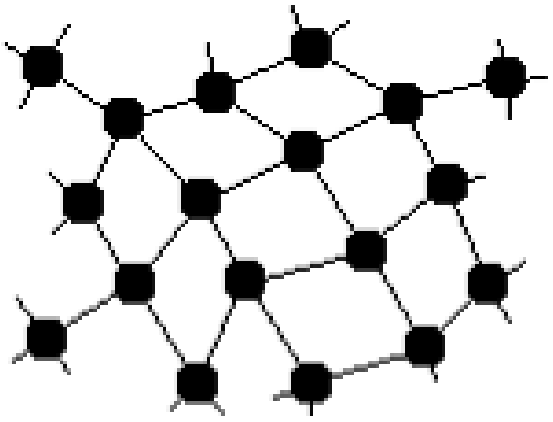
diamond structure:
Si, Ge, C, ...

Substrates for Devices



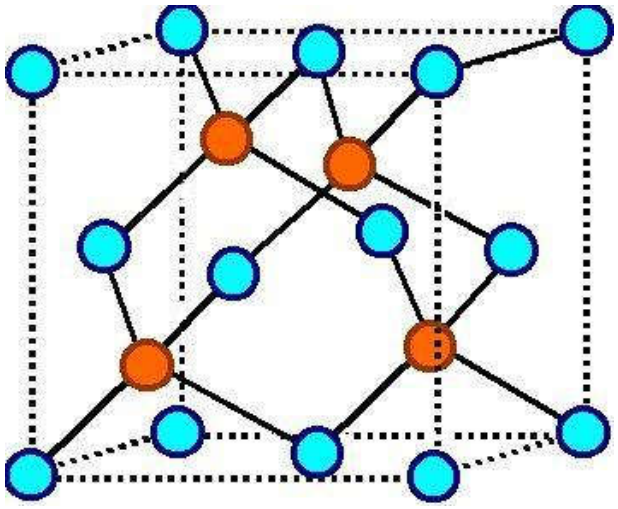
quartz (SiO_2)



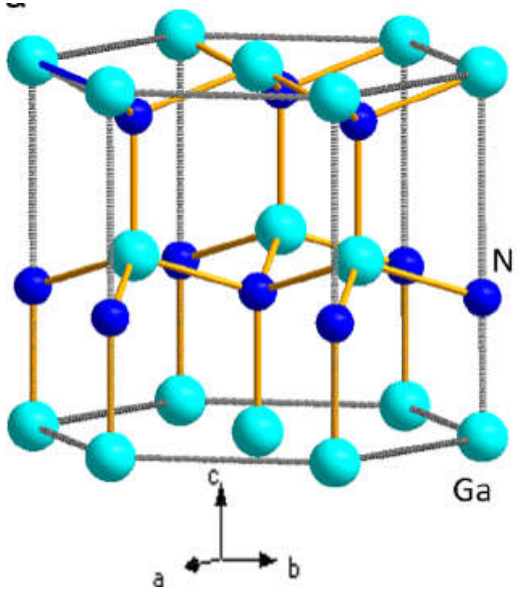


amorphous glass

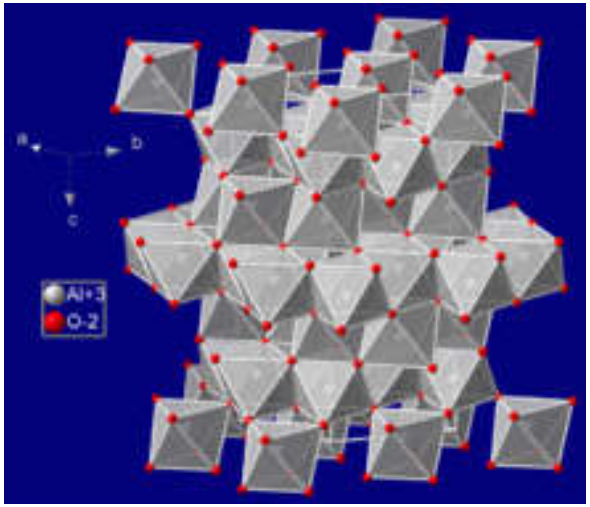
Substrates for Devices



zinc blende structure:
GaAs, InP, β-SiC, ...

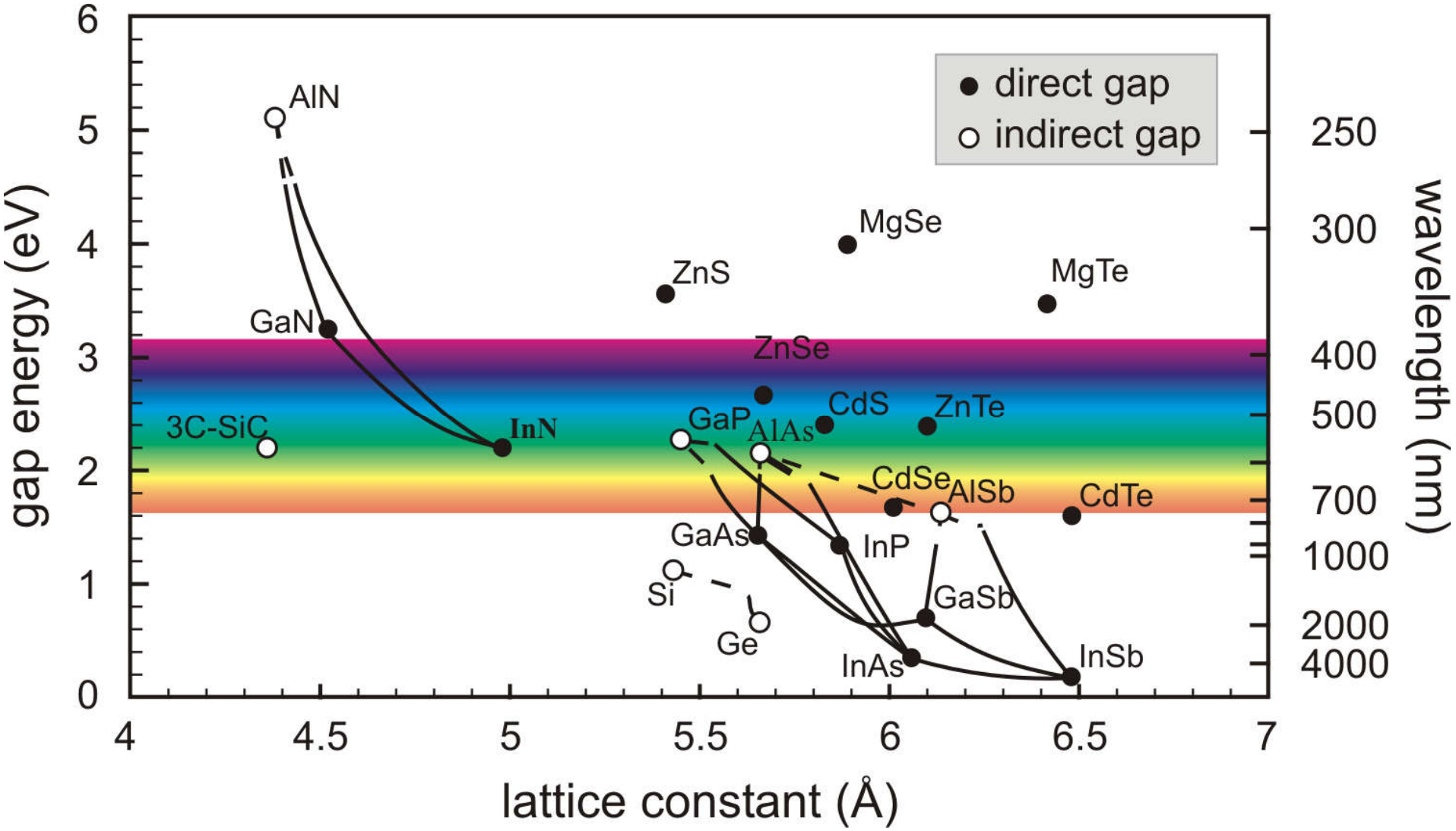


Wurtzite structure:
α-SiC, GaN, ZnO, ...



sapphire (Al_2O_3)

Lattice Constants vs. Bandgap



Requirement for Electronics

- low cost
- single crystal
- p-doping and n-doping
- low defect level
  - purity > 99.99999....%
  - dislocation < 1000 /cm^2
- suitable bandgap
  - too large -> high voltage, power, ...
  - too small -> thermal noise, leakage, defects, ...
- semiconductor/oxide interface quality
- mobility, surface uniformity, ...

Silicon vs. Germanium

Silicon

- earth abundant
  - > 25% on earth
- perfect Si/SiO_2 interface
- bandgap 1.1 eV

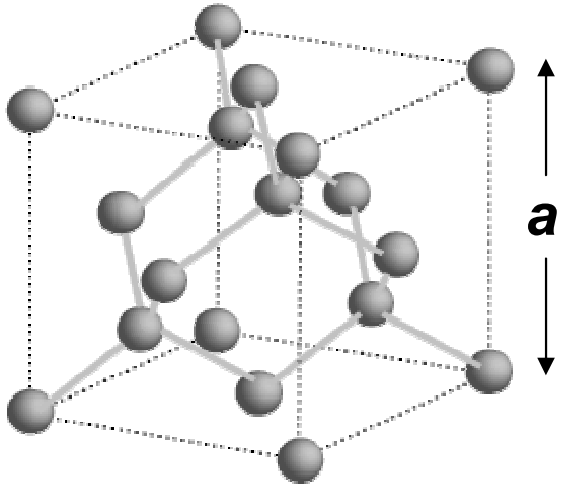
vs.

Germanium

- expensive
- GeO_2 is not stable
- bandgap 0.67 eV

Silicon wins
and will always win (?)

Properties of Silicon



- **Structural**
  - diamond structure (FCC)
  - lattice constant a = 5.431 Å
  - atomic density = 5×10^{22} /cm^3
  - melting point = 1417 ° C
- **Electronic**
  - bandgap E_g = 1.12 eV
  - dielectric constant ε_r = 11.9
  - mobility: electron μ_e = 1500 cm^2/V/s, hole μ_h = 450 cm^2/V/s
  - intrinsic carrier density $n_i = 1.45 \times 10^{10}$ /cm^3
- **Optical**
  - refractive index n = 3.6
  - absorbs < 1100 nm, transparent > 1100 nm

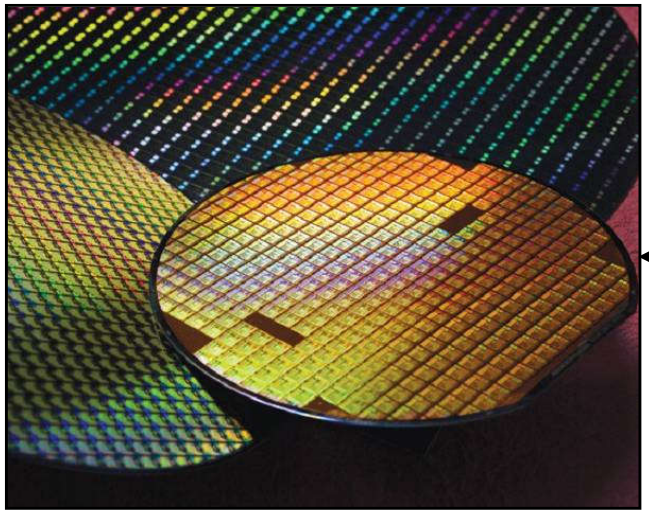
How to Make Silicon Wafers?

SiO_2

Video

raw Si

Si ingots and wafers



IC chips

How to Make Silicon Wafers?

SiO_2

raw Si

$$SiO_2 + 2C = Si + 2CO \qquad \text{at } 2000\ ^oC$$

Metallurgical Grade Silicon, purity ~ 98%

Applications: aluminum, silicone, ...

How to Make Silicon Wafers?

SiO_2

raw Si

$$Si + 4HCl = SiCl_4 + 2H_2$$
$$SiCl_4 + 2H_2 = Si + 4HCl$$

purification
(Siemens process)

Polycrystalline Silicon, purity > 99.99%
Applications: solar cells, ...

How to Make Silicon Wafers?

poly crystal -> single crystal

Czochralski process (CZ)

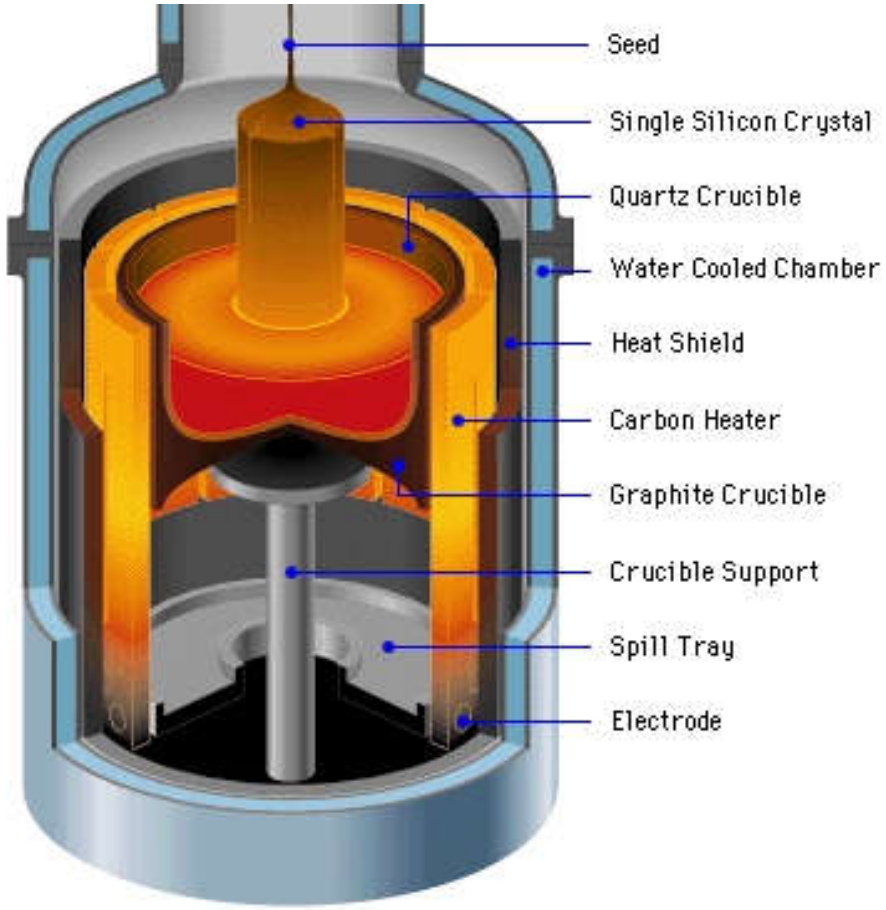
Float-zone process (FZ)

raw Si

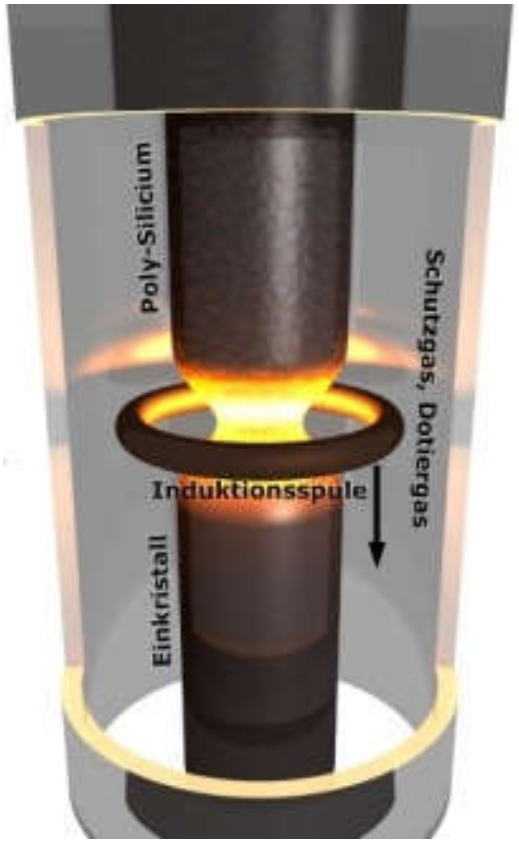
Si ingots and wafers

How to Make Silicon Wafers?

Czochralski process (CZ)

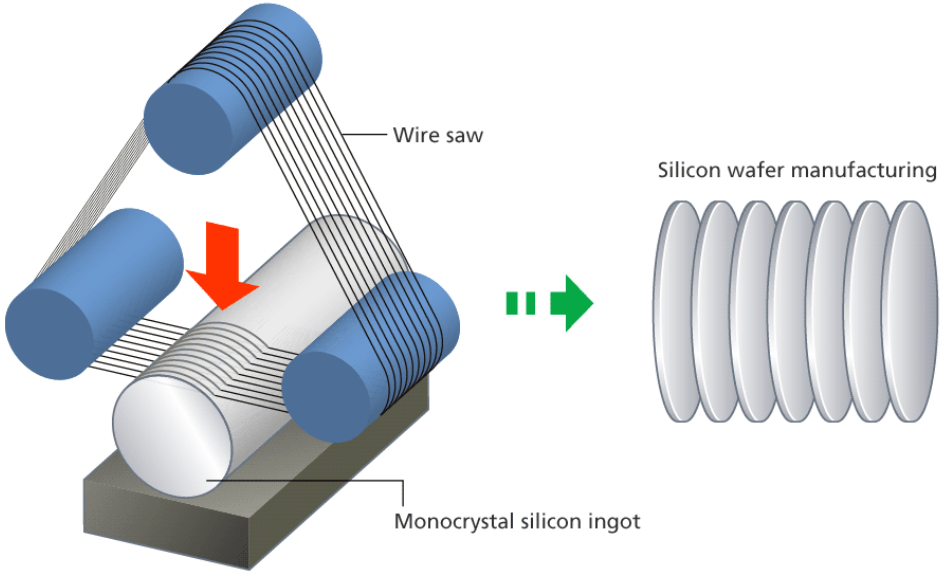


Float-zone process (FZ)

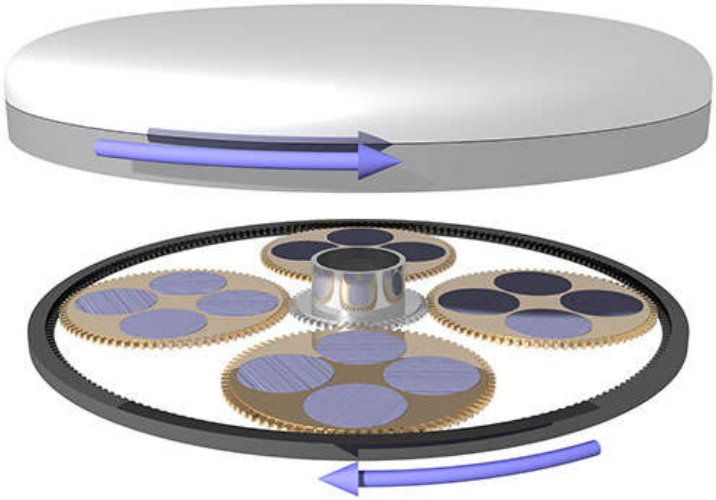


How to Make Silicon Wafers?

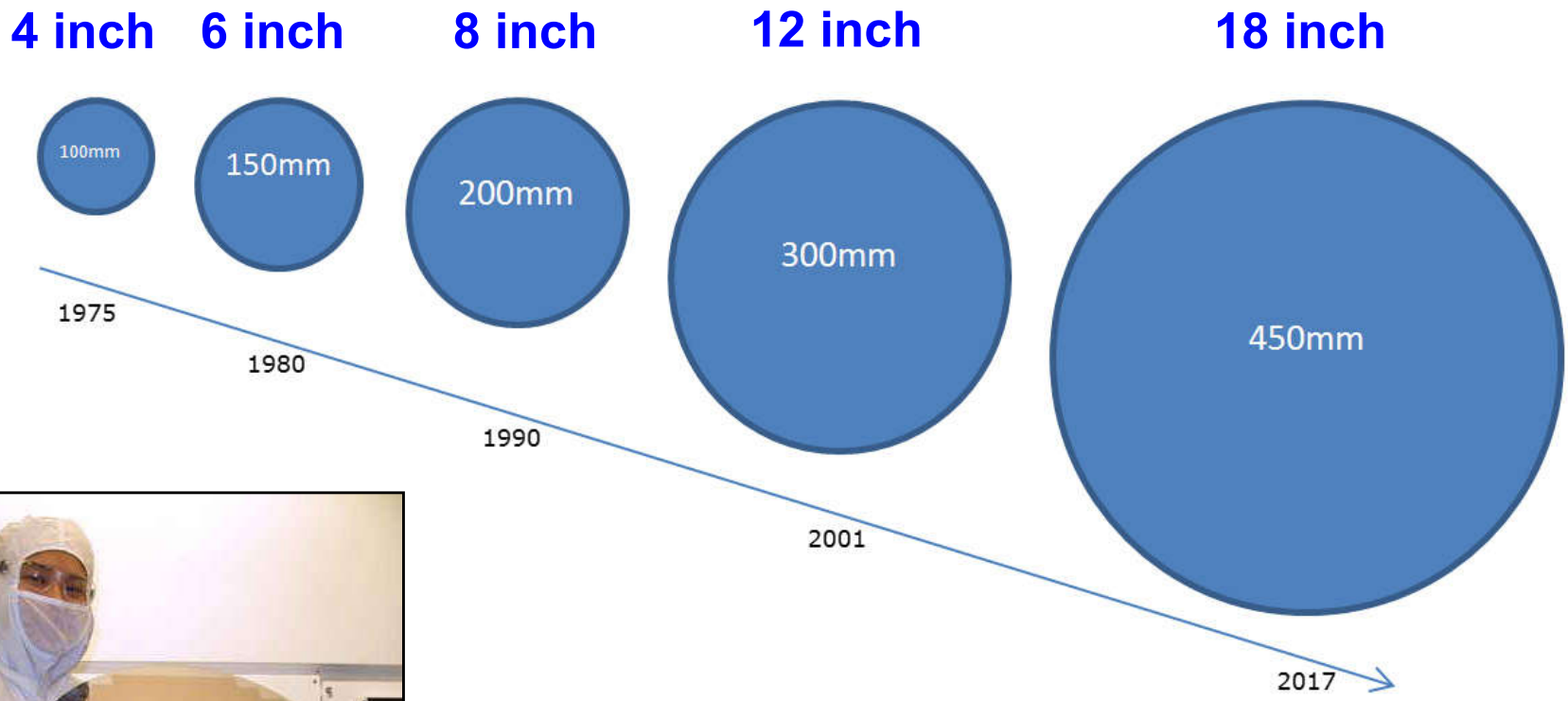
wafer slicing



wafer polishing



Silicon wafers: size



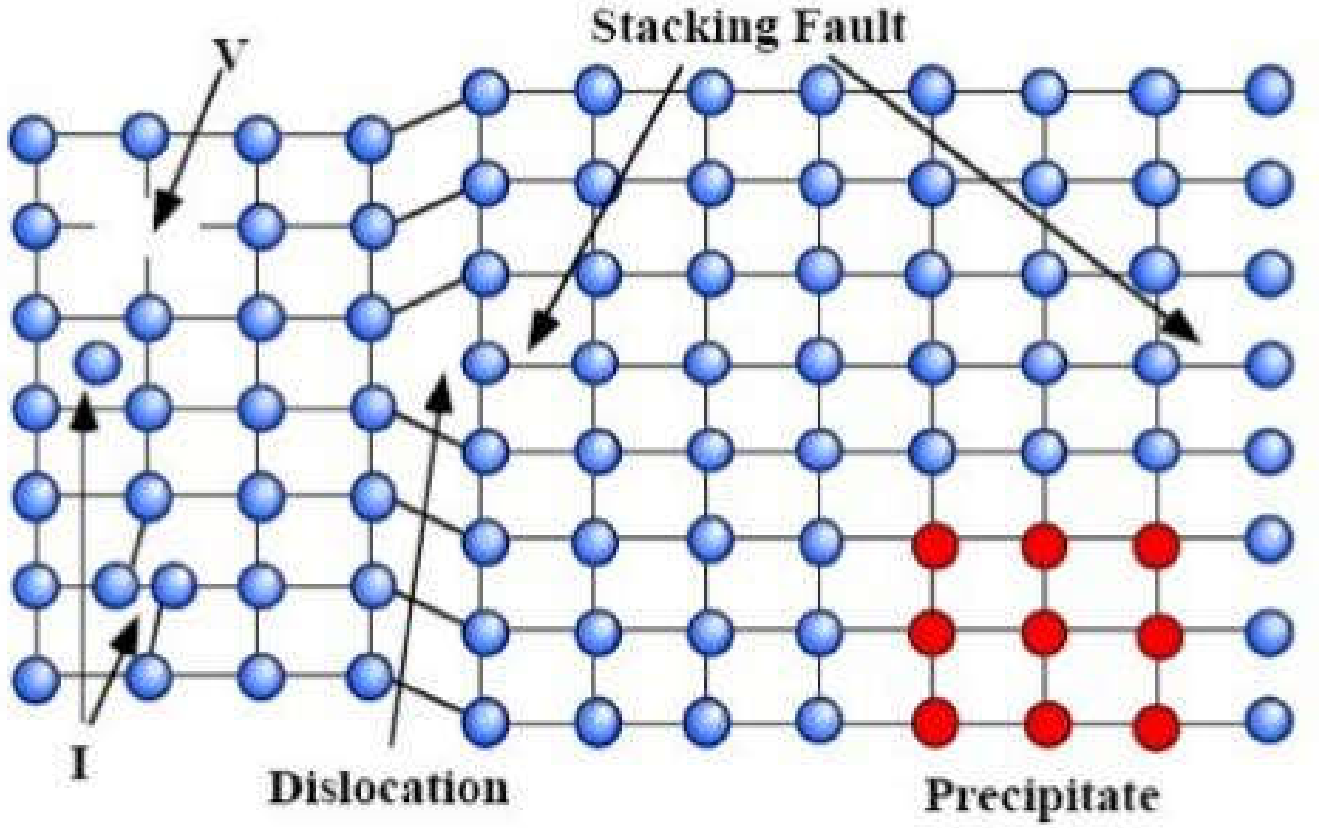
18 inch wafer

Silicon wafers: purity

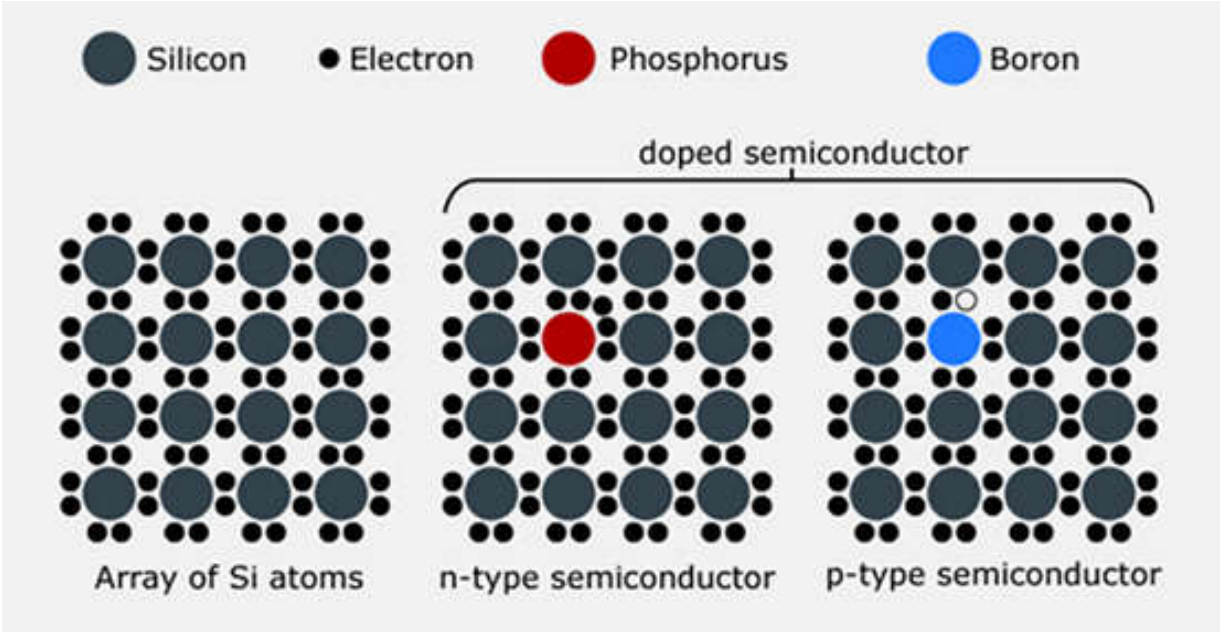
- **Metallurgical grade**
  - polycrystalline
  - purity > 98%
  - application: aluminum alloy, silicone
- **Solar grade**
  - polycrystalline
  - purity > 99.99% (4N)
  - application: solar cells
- **Electronic grade**
  - single crystalline
  - purity > 99.9999999% (9N)
  - application: IC industry, high efficiency solar cells

Silicon wafers: defects

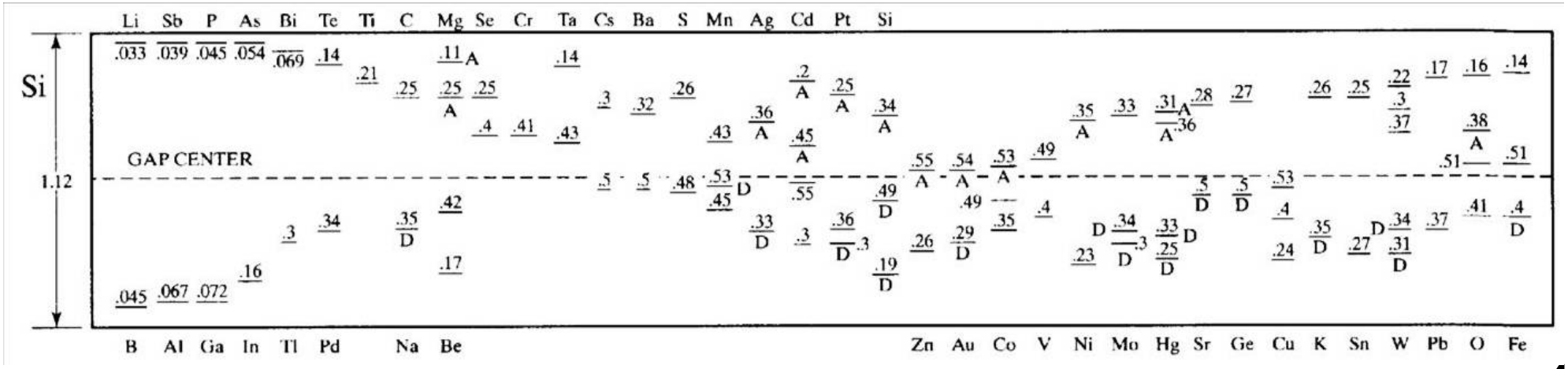
- Point Defects e.g. Vacancies (V), Interstitials (I)
- Line Defects e.g. Dislocations
- Area Defects e.g. Stacking Faults ("extrinsic" or "intrinsic" form along {111} planes)
- Volume Defects e.g. Precipitates, Collection of Vacancies



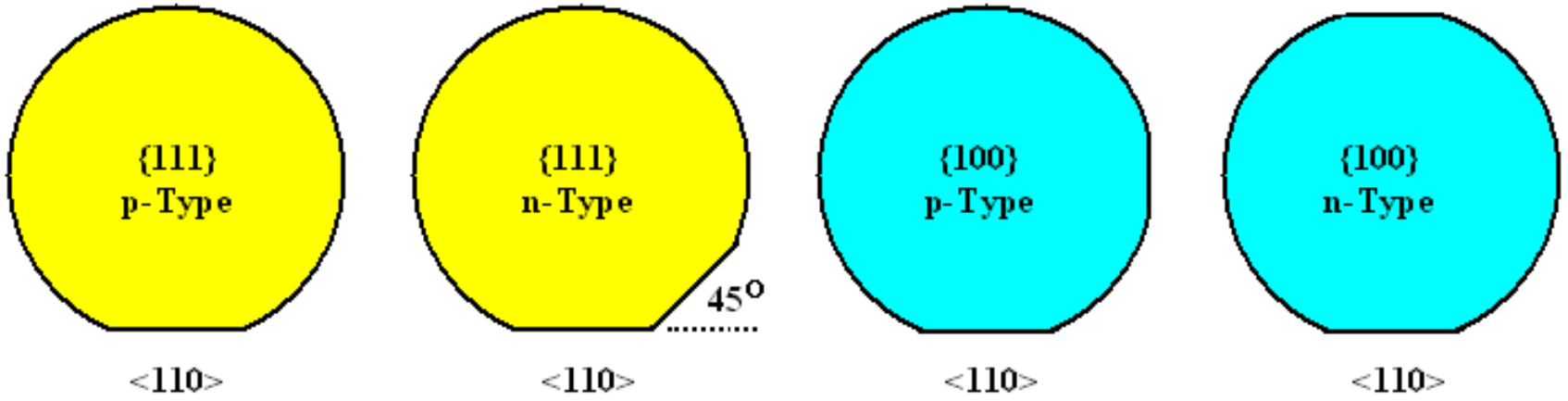
Silicon wafers: doping



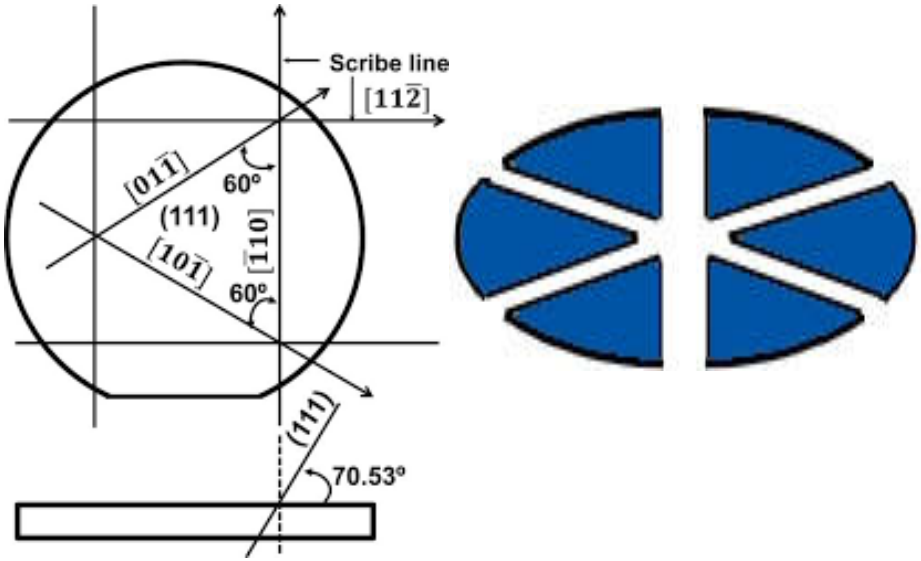
					2 He
5 B	6 C	7 N	8 O	9 F	10 Ne
13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn

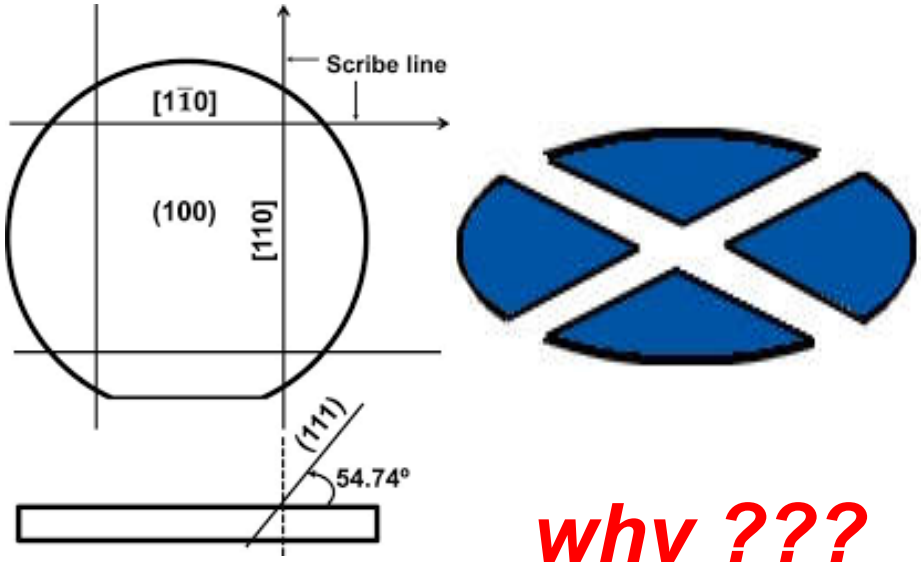


Silicon wafers: orientation



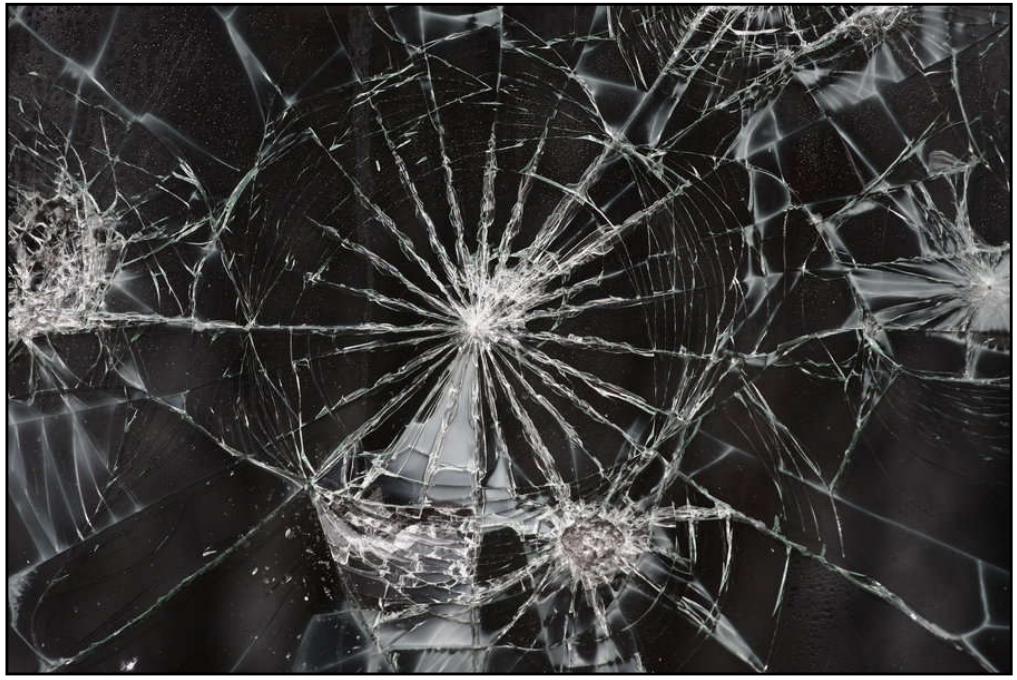
cleavage direction

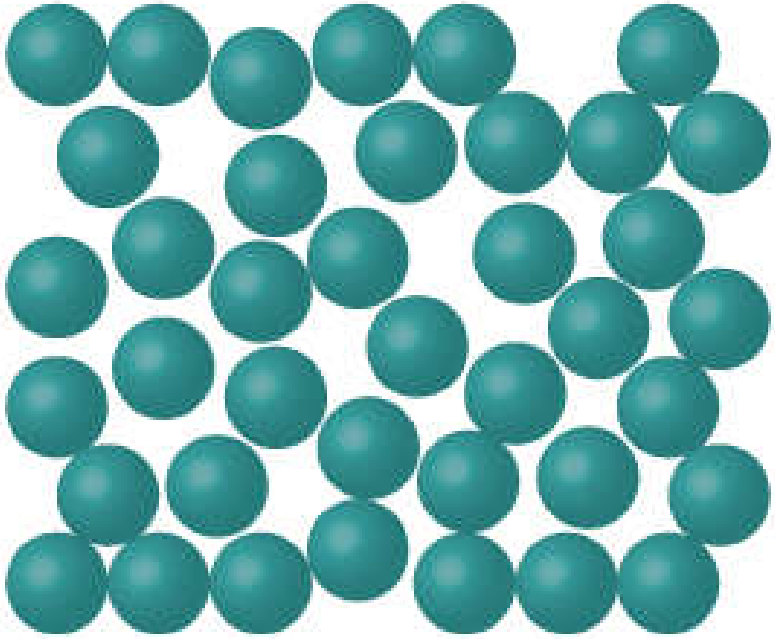




why ???

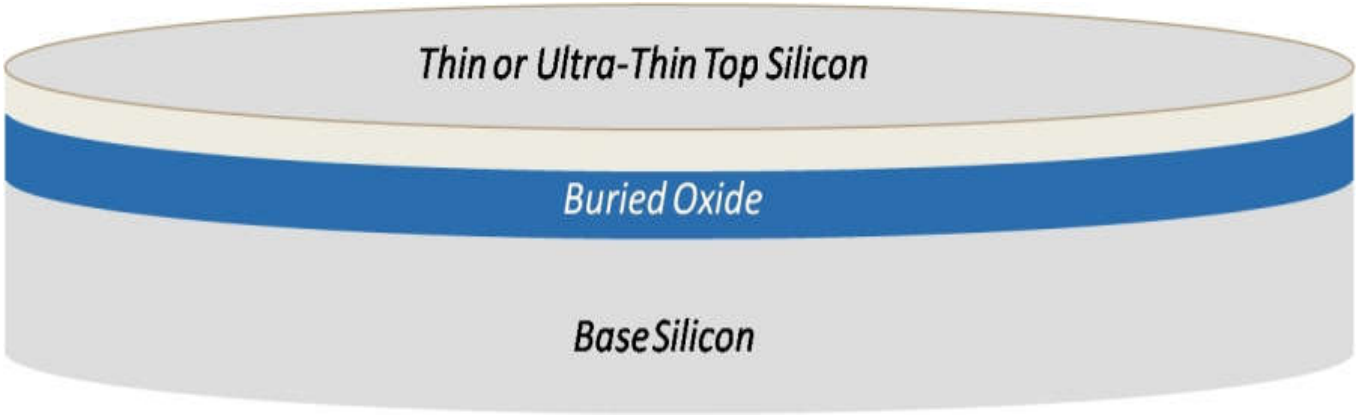
Breaking Amorphous Materials

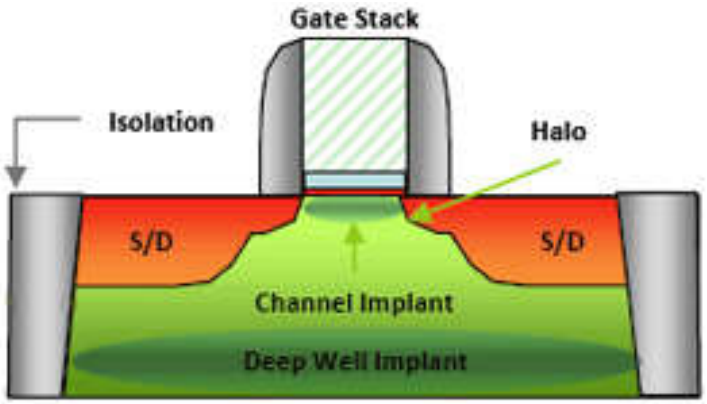




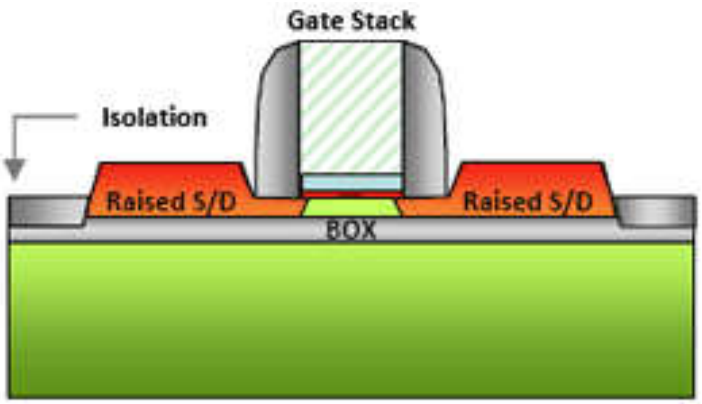
Amorphous

Silicon-on-Insulator (SOI)

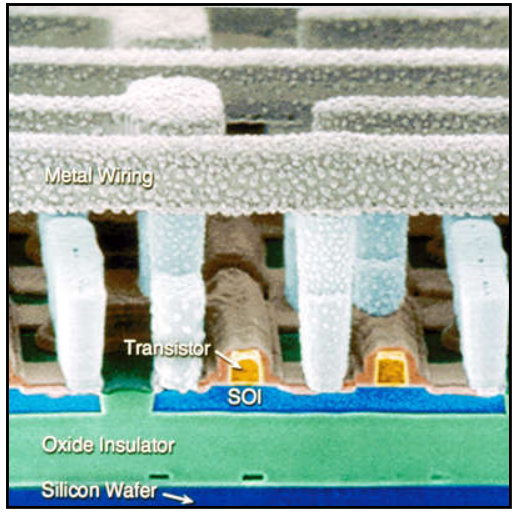




Bulk Device

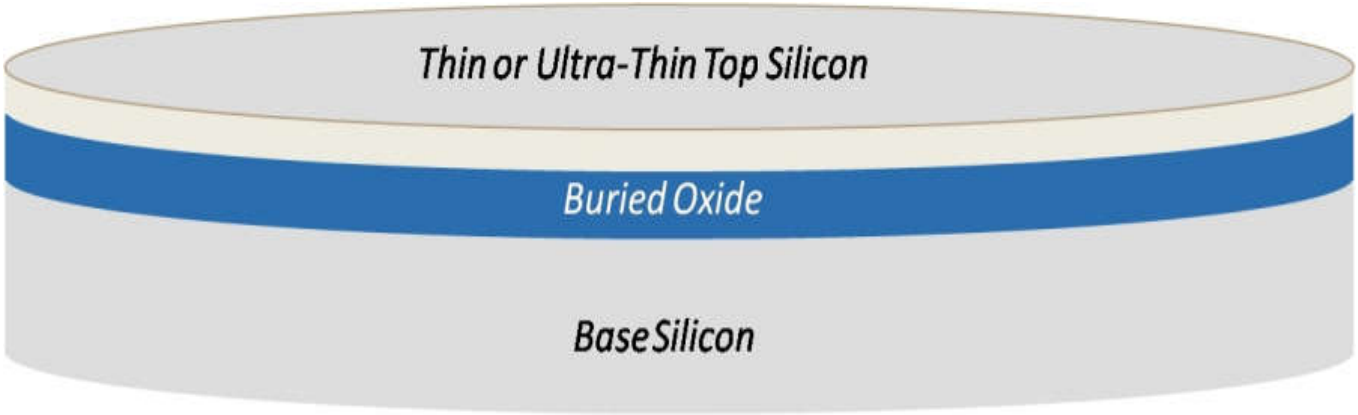


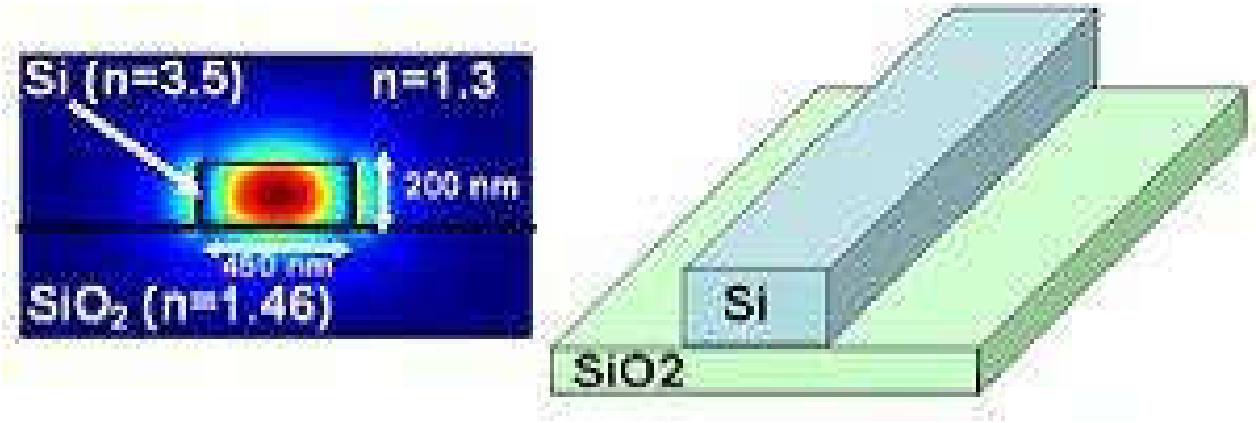
FD-SOI Device



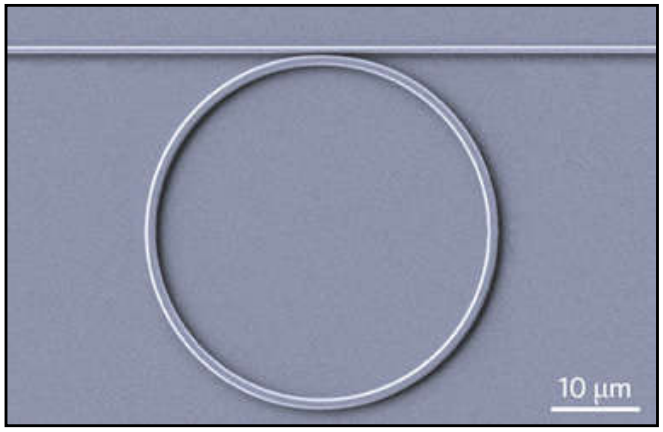
The fully depleted SOI transistor at 20 nm is significantly simpler than even a simplified version of the bulk CMOS transistor.

Silicon-on-Insulator (SOI)





Silicon waveguide



Ring resonator

Other single crystals

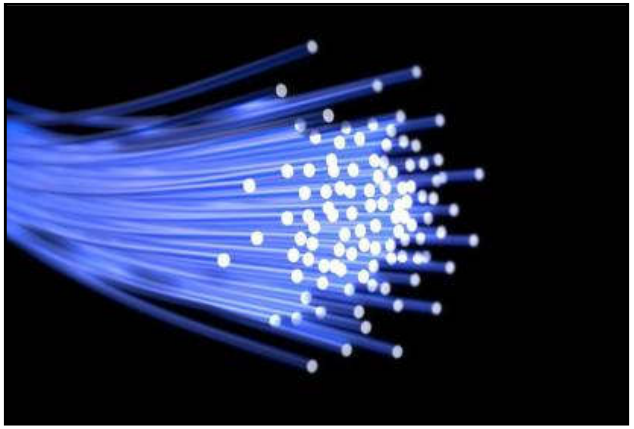
Ge

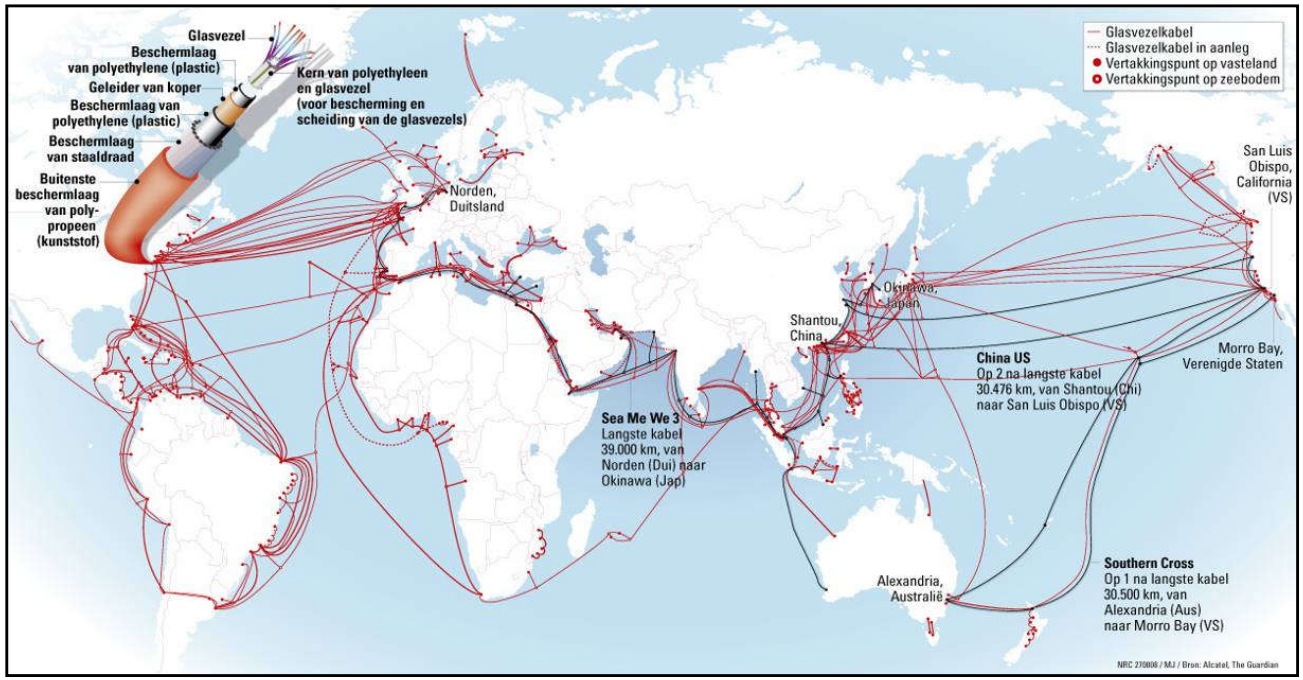
GaAs

sapphire

Q: Can we make diamond crystal?

Optical Fibers

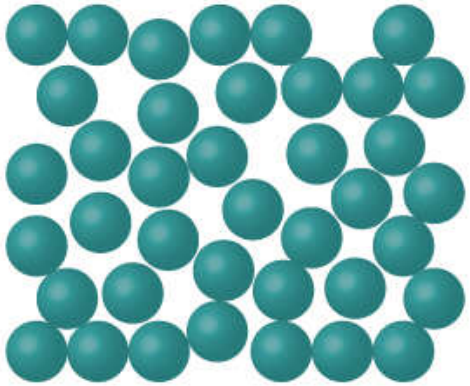




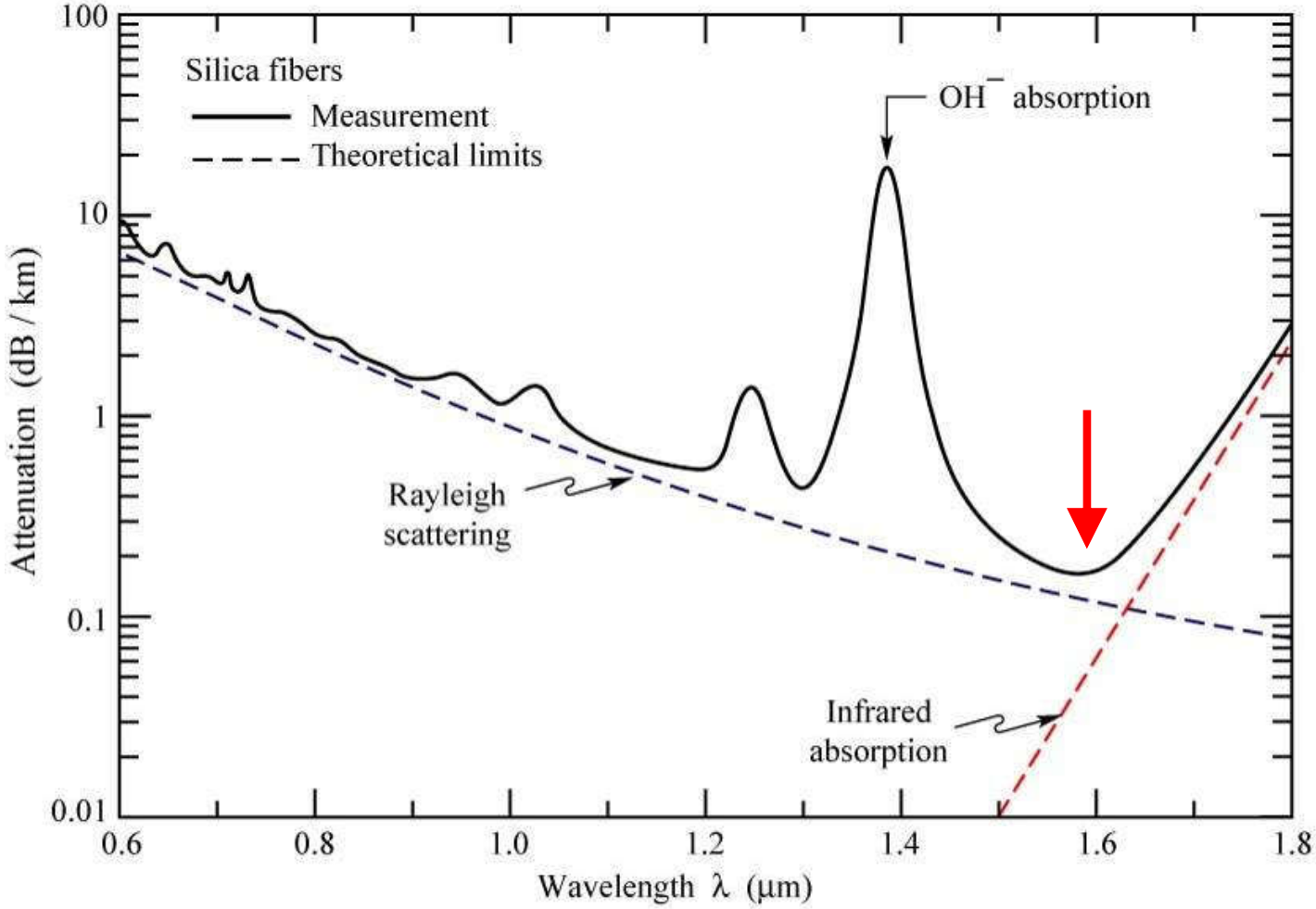
K. Kao (高锟)
2009 Nobel Prize in Physics

K. C. Kao, G. A. Hockham, *Proc. IEE* **113,** 1151 (1966)

Absorption of Silica (SiO_2)



Amorphous

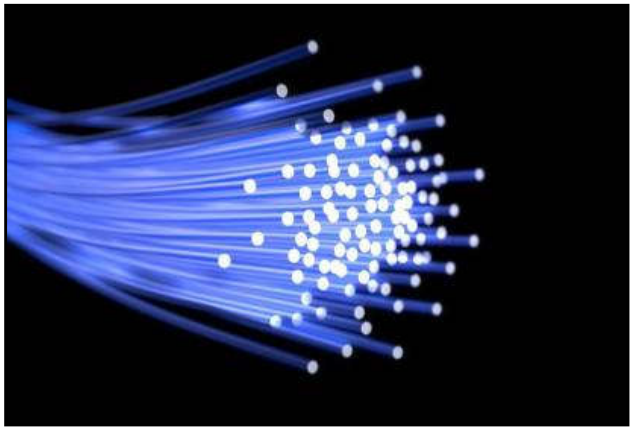


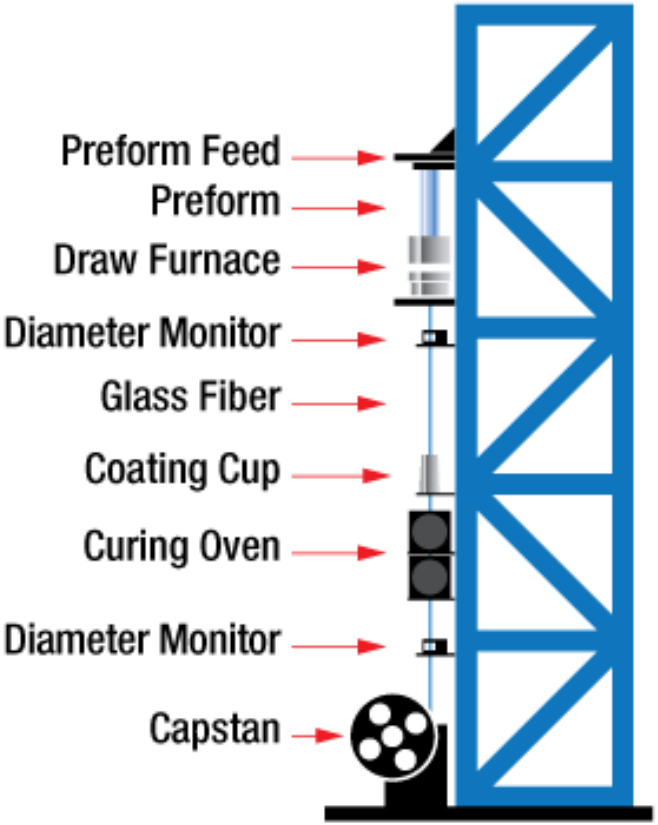
minimum loss at 1550 nm, 0.2 dB/km
~ 2% loss every kilometer

Optical Fiber Drawing

preform

fibers

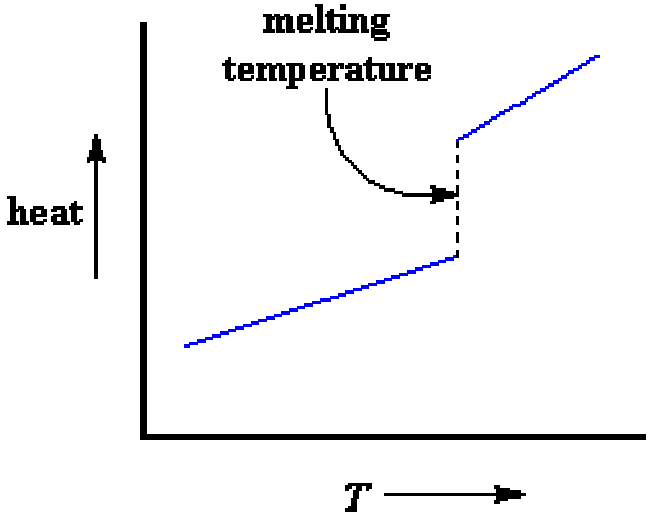




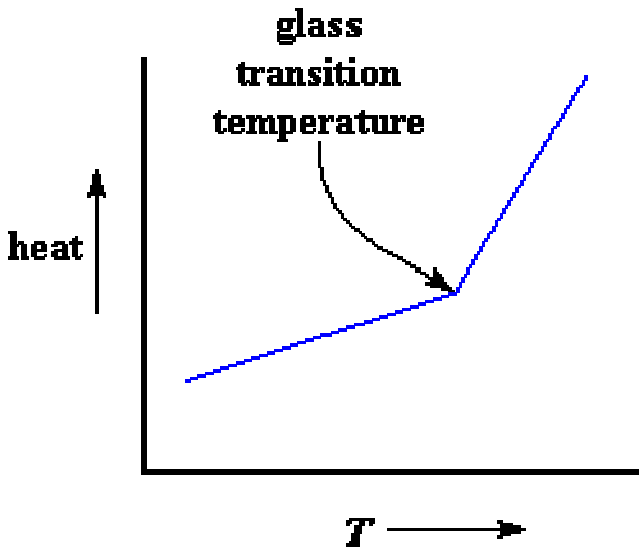
Video

Glass Transition

‘吹’玻璃



1st order tansistion

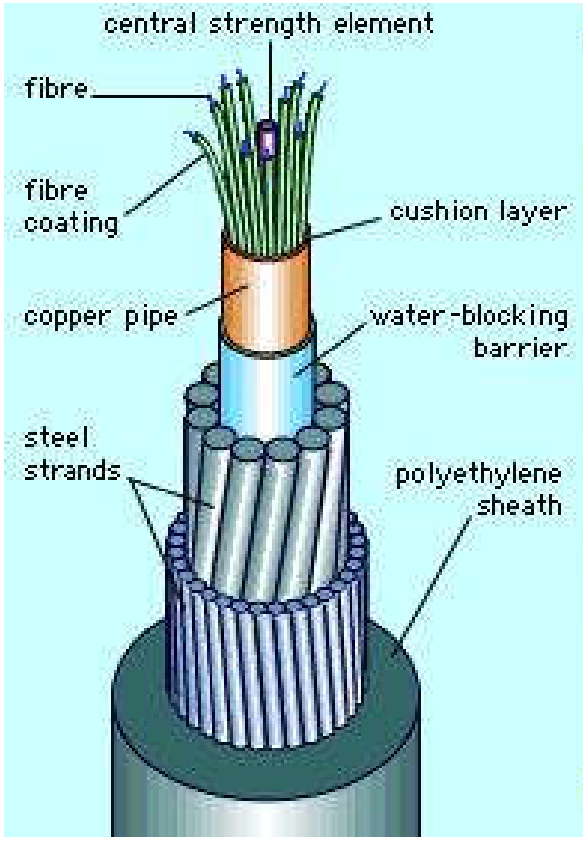


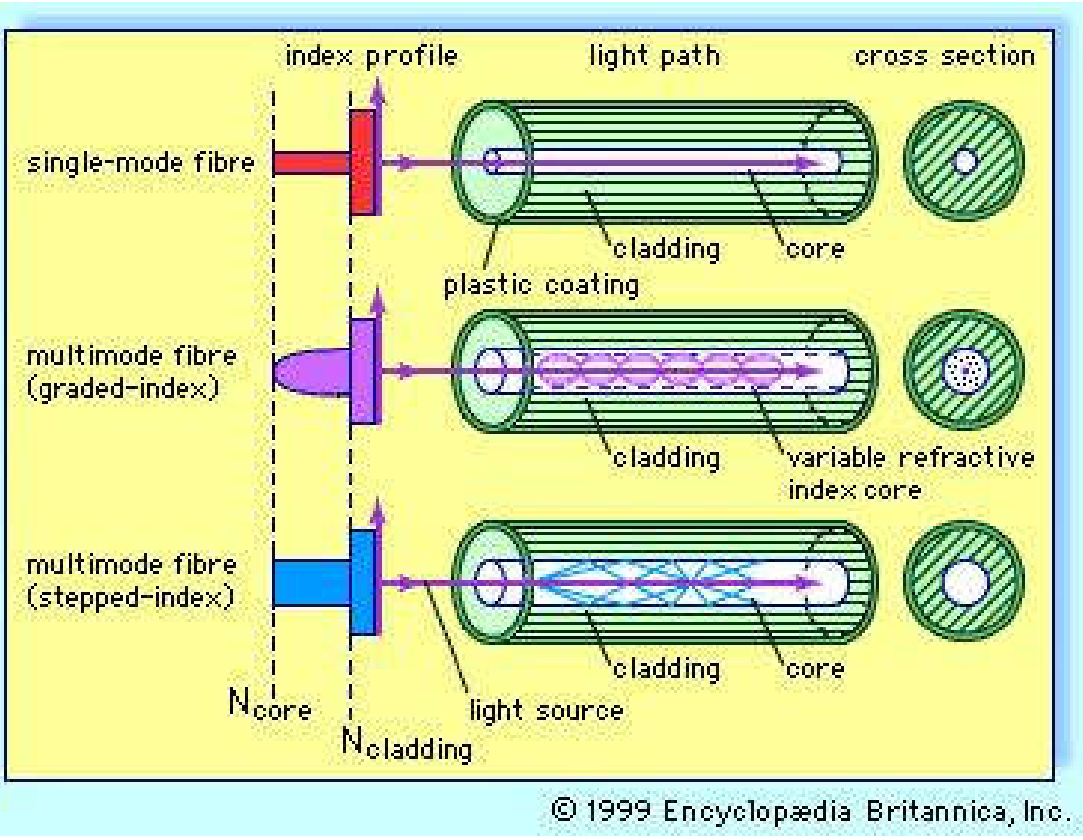
2nd order tansistion

glassy / plastic state

viscous / rubbery state

Optical Fibers





Thank you for your attention