How to Make Micro/Nano Devices?

- **Science:** Physics, Chemistry, Biology, nano/biotech
- **Materials:** inorganic, organic, biological, rigid/flexible
- **Fabrication:** photo/e-beam lithography, self-assembly, 2D/3D print
- **Dimensions:** quantum dots, nanowires, 2D, 3D
- **Functions:** logic, sensing, actuation, energy conversion
- **Power:** wired, wireless
- **e-waste:** 41.8 Mt (2014), circular economy

1 nm MoS$_2$ transistor, Science 354, 99 (2016)

Soft-robotic ray, Science 353, 158 (2016)


Nature 539, 284 (2016)
Cubic Systems

Simple cubic (sc)
Lattice point per unit cell: 1
Packing fraction: 52%

Body-centered cubic (bcc)
Lattice point per unit cell: 2
Packing fraction: 68%

Face-centered cubic (fcc)
Lattice point per unit cell: 4
Packing fraction: 74%

Ref: Campbell: 2.2
NaCl can be described as a fcc lattice of lattice constant $a$, with a basis of a Cl atom at (000), and a Na atom at $a/2(1,0,0)$.
Diamond Structure

Packing fraction: 34%

Elemental crystal - C, Si, Ge

One can view a diamond lattice as a fcc lattice with a 2-point basis \( \mathbf{0} \), and
\[
a(\hat{x} + \hat{y} + \hat{z})/4
\]

It can also be viewed as two interpenetrating fcc lattices.

Distance between two atoms in Si: 2.35 Å

Si density = \[
\frac{8}{(5.43 \times 10^{-8})^3} \approx 5 \times 10^{-22} \text{ cm}^{-3}
\]

3D models at this website

http://upload.wikimedia.org/wikipedia/commons/thumb/2/22/Diamond_Cubic-F_lattice_animation.gif/250px-Diamond_Cubic-F_lattice_animation.gif
Diamond Structure

Packing fraction: 34%

Covalent compound- GaAs, AlAs, GaP, InP, ZnS, SiC

Perovskite structure

CaTiO$_3$ (Calcium Titanate)
Miller Indices of Crystal Planes

\[
\frac{x}{a} + \frac{y}{b} + \frac{z}{c} = 1
\]

Miller Indices \((hkl)\):

\[
\frac{1}{x} \frac{1}{y} \frac{1}{z} \rightarrow (210)
\]

Unit cell

\[(100), (010), (001), (\bar{1}00), (0\bar{1}0), (00\bar{1})\] = \{100\}
Crystal Plane Directions

Family of <111> directions

$$\{[100], [010], [001], [\bar{1}00], [0\bar{1}0], [00\bar{1}]\} = <100>$$

In cubic lattices, the [hkl] direction is always perpendicular to (hkl) plane.

The separation between two adjacent parallel planes (hkl) is

$$d = \frac{a}{\sqrt{h^2 + k^2 + l^2}}$$

The separation is $a$ for \{100\} planes, 0.707$a$ for \{110\} planes, and 0.577$a$ for \{111\} planes.

Thus the \{111\} planes are the closest spaced among the low-index planes.
Silicon Wafers

• The angle between two planes \((h_1k_1l_1)\) and \((h_2k_2l_2)\) is

\[
\cos \theta = \frac{h_1h_2 + k_1k_2 + l_1l_2}{\sqrt{(h_1^2 + k_1^2 + l_1^2)(h_2^2 + k_2^2 + l_2^2)}}
\]

• Si \(<111>\) directions has the fastest rate for crystal growth and the slowest etch rate. V-grooves can be etched in \(<100>\) wafers.

• The tensile strength and modulus of elasticity are maxima in the \(<111>\) directions. Thus, Si tends to cleave on the \{111\} planes.
• The angle between two planes \((h_1, k_1, l_1)\) and \((h_2, k_2, l_2)\) is
  \[
  \cos \theta = \frac{h_1 h_2 + k_1 k_2 + l_1 l_2}{\sqrt{(h_1^2 + k_1^2 + l_1^2)(h_2^2 + k_2^2 + l_2^2)}}
  \]

• Si <111> directions has the fastest rate for crystal growth and the slowest etch rate. V-grooves can be etched in <100> wafers.

• The tensile strength and modulus of elasticity are maxima in the <111> directions. Thus, Si tends to cleave on the \{111\} planes.

Dangling bonds-
surface state density for <100> is lower than <111> - device appl.
Crystal Growth

Czochralski growth

- Pull rate: 10µm/s
- O-contamination from quartz crucible

Float zone growth

Bridgman growth of single crystal GaAs

Polycrystalline GaAs

Ref: Campbell: 2.4-2.6
Point defects: vacancies, interstitials, impurity atoms – could behave like acceptors or donors affecting device performance

Dissolved oxygen: $10^{16} - 10^{18} \text{ cm}^{-3}$ forming complexes and a donor level at $E_c - 0.16$ eV.

Dissolved carbon: $4 \times 10^{18} \text{ cm}^{-3}$ forming microprecipitates of Si-C complexes
Crystal Defects (II)

Line defects: It occurs when the crystal is subjected to stresses in excess of the elastic limit during the growth from a melt. Some dislocations can be annealed out. Defects have dangling bonds and behave like acceptors.

Screw dislocation

GaN surface, dislocation density $10^8 \text{ cm}^{-2}$

Dislocation line: AD
Slip plane: ABCD

JVST A 16, 1641 (1998)
Crystal Defects (III)

Twinning:

Composition plane: x-x’
Annealing Enhances Crystal Growth

After fabrication

Cu: 300 nm
Si (001)

Map Data 3

Electron Image 3

IPF Z Color 3

After vacuum anneal 518 °C- 5 s

Si (001)
Cu: 300 nm

FSD Mixed Image 8

IPF Z Color 9

Map Data 9

After vacuum anneal 700 °C- 15 min

CuSi-5_01

CuSi-5_04