# Electronic Devices

# Lecture 2

# 04-08-2018

| Group → | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ↓ Period | | | | | | | | | | | | | | | | | | |
| 1 | 1 H | | | | | | | | | | | | | | | | | 2 He |
| 2 | 3 Li | 4 Be | | | | | | | | | | | 5 B | 6 C | 7 N | 8 O | 9 F | 10 Ne |
| 3 | 11 Na | 12 Mg | | | | | | | | | | | 13 Al | 14 Si | 15 P | 16 S | 17 Cl | 18 Ar |
| 4 | 19 K | 20 Ca | 21 Sc | 22 Ti | 23 V | 24 Cr | 25 Mn | 26 Fe | 27 Co | 28 Ni | 29 Cu | 30 Zn | 31 Ga | 32 Ge | 33 As | 34 Se | 35 Br | 36 Kr |
| 5 | 37 Rb | 38 Sr | 39 Y | 40 Zr | 41 Nb | 42 Mo | 43 Tc | 44 Ru | 45 Rh | 46 Pd | 47 Ag | 48 Cd | 49 In | 50 Sn | 51 Sb | 52 Te | 53 I | 54 Xe |
| 6 | 55 Cs | 56 Ba | * | 72 Hf | 73 Ta | 74 W | 75 Re | 76 Os | 77 Ir | 78 Pt | 79 Au | 80 Hg | 81 Tl | 82 Pb | 83 Bi | 84 Po | 85 At | 86 Rn |
| 7 | 87 Fr | 88 Ra | ** | 104 Rf | 105 Db | 106 Sg | 107 Bh | 108 Hs | 109 Mt | 110 Ds | 111 Rg | 112 Uub | 113 Uut | 114 Uuq | 115 Uup | 116 Uuh | 117 Uus | 118 Uuo |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| * Lanthanides | 57 La | 58 Ce | 59 Pr | 60 Nd | 61 Pm | 62 Sm | 63 Eu | 64 Gd | 65 Tb | 66 Dy | 67 Ho | 68 Er | 69 Tm | 70 Yb | 71 Lu |
| ** Actinides | 89 Ac | 90 Th | 91 Pa | 92 U | 93 Np | 94 Pu | 95 Am | 96 Cm | 97 Bk | 98 Cf | 99 Es | 100 Fm | 101 Md | 102 No | 103 Lr |

# Importance Semiconductor Devices

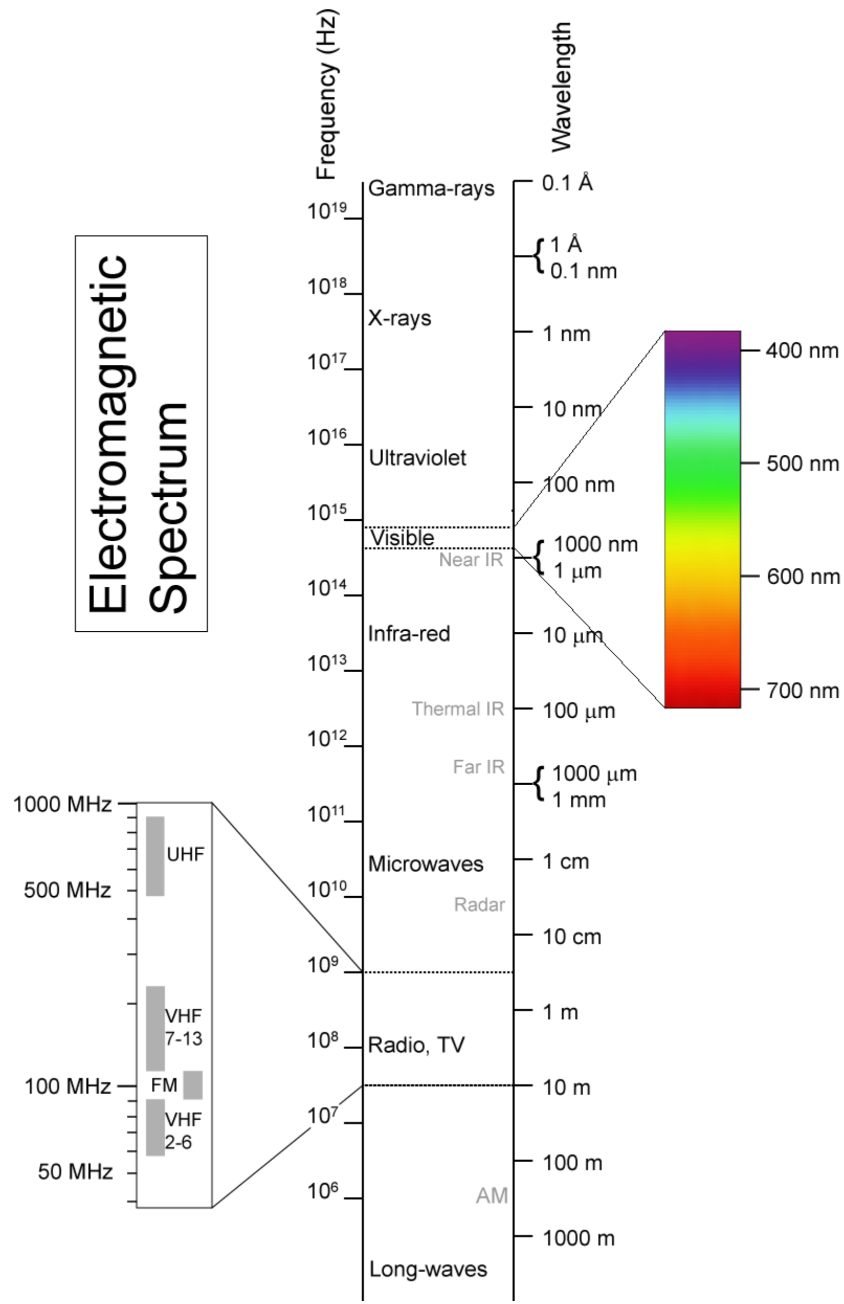
These devices enhance

- Performance
- Reliability
- Cost effectiveness

of

**Energy Systems**
Generate, distribute and regulate energy information

**Information Systems**
store, process and communicate


Electromagnetic Spectrum
Frequency (Hz)
Wavelength
Gamma-rays
0.1 Å
$10^{19}$
1 Å
0.1 nm
$10^{18}$
X-rays
1 nm
$10^{17}$
400 nm
10 nm
$10^{16}$
Ultraviolet
500 nm
100 nm
$10^{15}$
Visible
1000 nm
Near IR
1 μm
600 nm
$10^{14}$
Infra-red
10 μm
$10^{13}$
700 nm
Thermal IR
100 μm
$10^{12}$
Far IR
1000 μm
1 mm
1000 MHz
$10^{11}$
UHF
Microwaves
1 cm
500 MHz
$10^{10}$
Radar
10 cm
$10^{9}$
VHF
7-13
1 m
$10^{8}$
Radio, TV
100 MHz
FM
10 m
VHF
2-6
$10^{7}$
50 MHz
100 m
$10^{6}$
AM
1000 m
Long-waves

# Course Objective

Terminal Characteristics $\longleftrightarrow$ Material Parameters

DC I-V

AC I-V

Transient

Geometry

Doping

Energy gap

Mobility

Life time

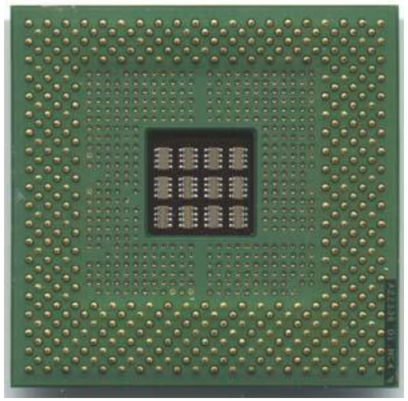
Dielectric constant

Ambient conditions:

Temperature

illumination

# Today's Electronic Devices



Front Back

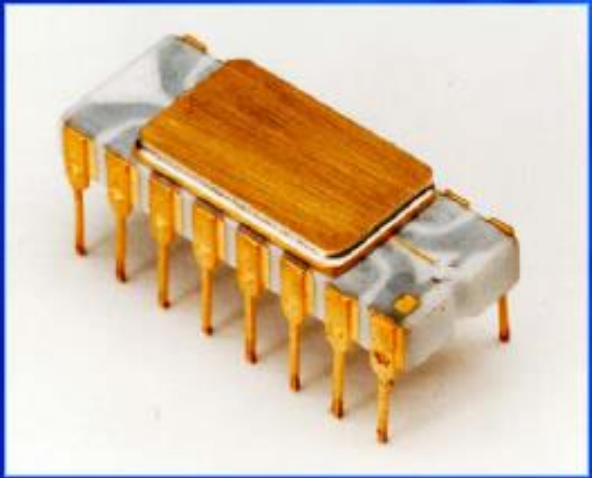
INTEL Pentium IV processor

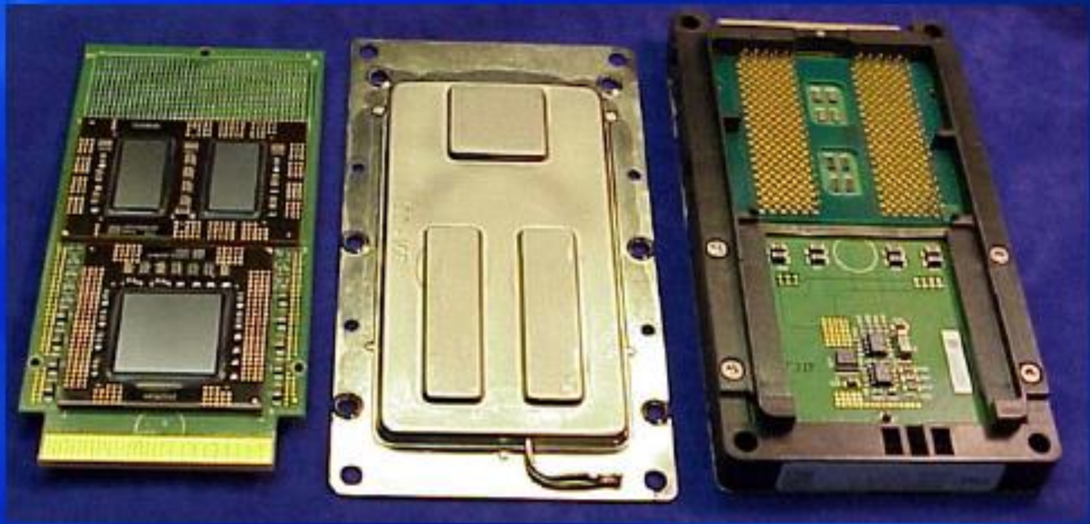

**Take the cover off a microprocessor. What do you see?**

•A thick web of interconnects, many levels deep.

• High density of very small transistors.

# Evolution of Microprocesor Packaging





1971

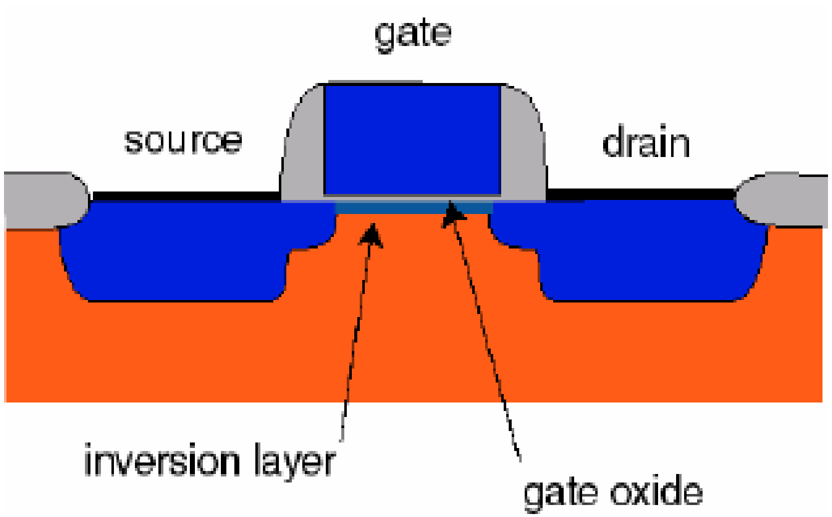
2001 onwards

PC Motherboard

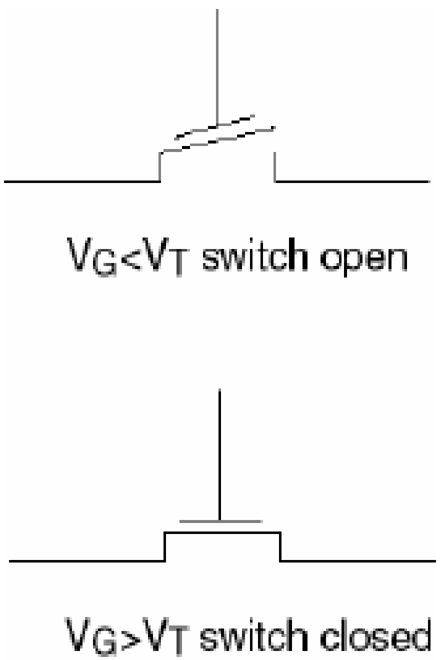
# Keys to success: I. MOSFET

Metal-Oxide-Semiconductor

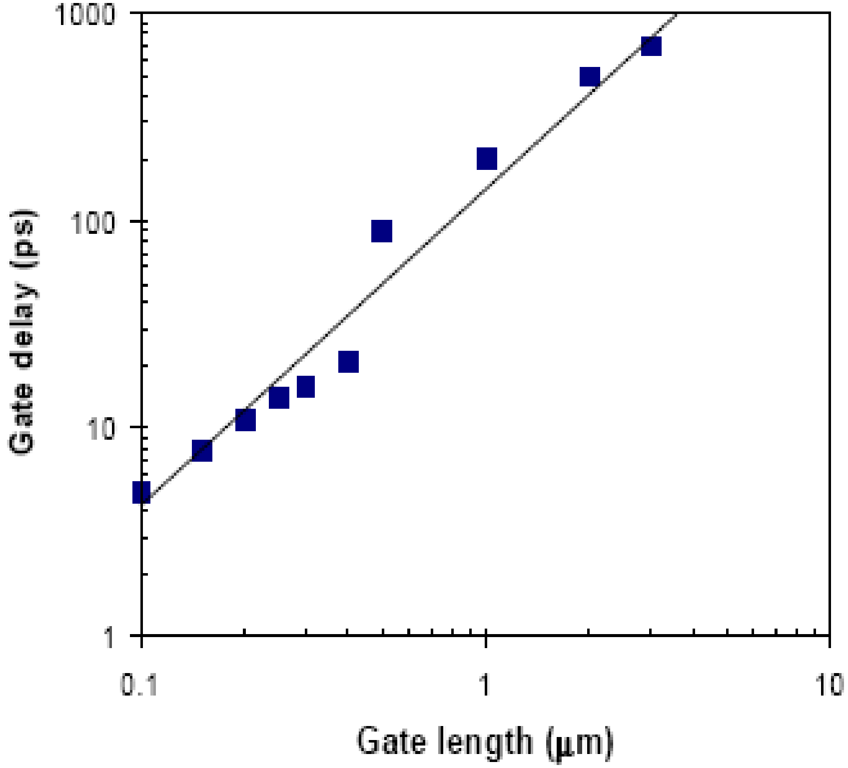
Field-Effect Transistor




MOSFET = switch



# Keys to success: II. MOSFET scaling

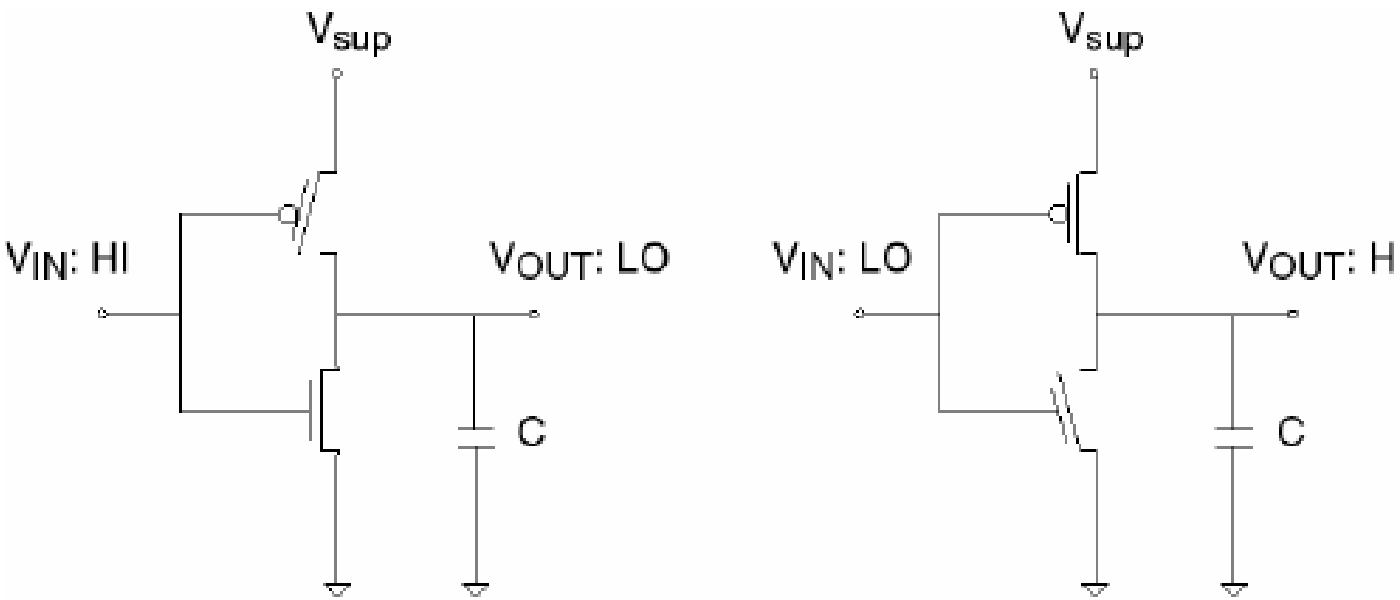



MOSFET performance improves as size is decreased:

- Shorter switching time
- Lower power consumption

# Keys to success: III. CMOS

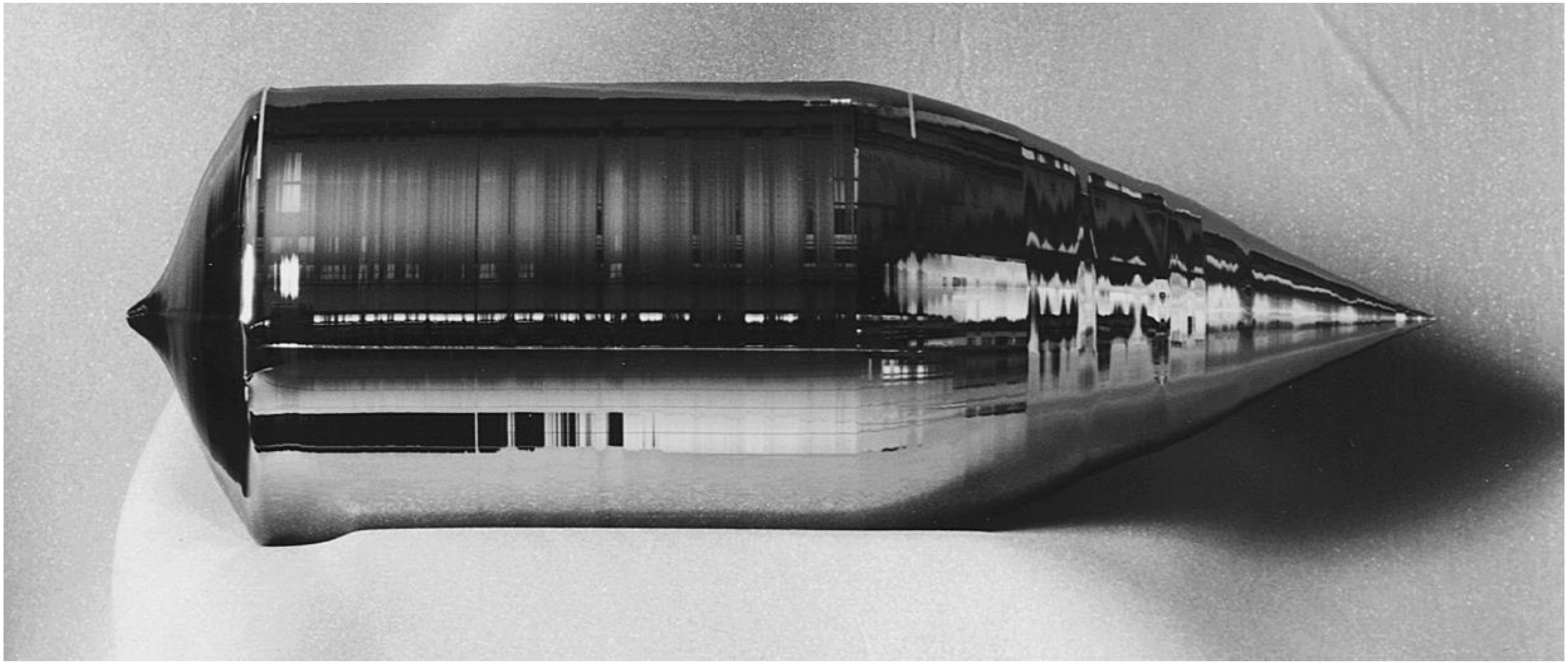
CMOS: Complementary Metal-Oxide-Semiconductor




- "Complementary" switch activates with V<0.
- Logic without DC power consumption.

## SEMICONDUCTORS: They are here, there, and everywhere

| | |
|---|---|
| • **Computers, palm pilots, laptops, anything "intelligent"** | Silicon (Si) MOSFETs, ICs, CMOS |
| • **Cell phones, pagers** | Si ICs, GaAs FETs, BJTs |
| • **CD players** | AlGaAs and InGaP laser diodes, Si photodiodes |
| • **TV remotes, mobile terminals** | Light emitting diodes |
| • **Satellite dishes** | InGaAs MMICs |
| • **Fiber networks** | InGaAsP laser diodes, pin photodiodes |
| • **Traffic signals, car taillights** | GaN LEDs (green, blue)<br>InGaAsP LEDs (red, amber) |
| • **Air bags** | Si MEMs, Si Ics |



# Semiconductor materials

- If we look at the periodic table, the element semiconductors, such as silicon (Si) or germanium (Ge), can be found in column IV of the table.
- In the early 1950s, Ge was the most important semiconductor material, but, since the early 1960s, Si has played a major role and virtually displaced Ge as the main material for semiconductor material.

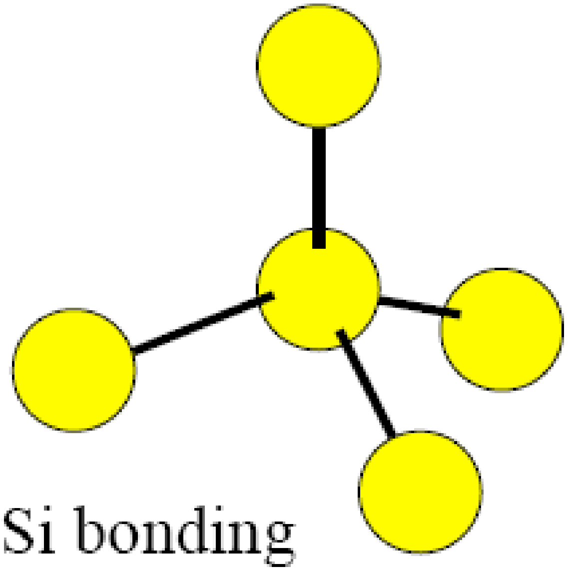
# Silicon: our primary example and focus

Atomic no. 14

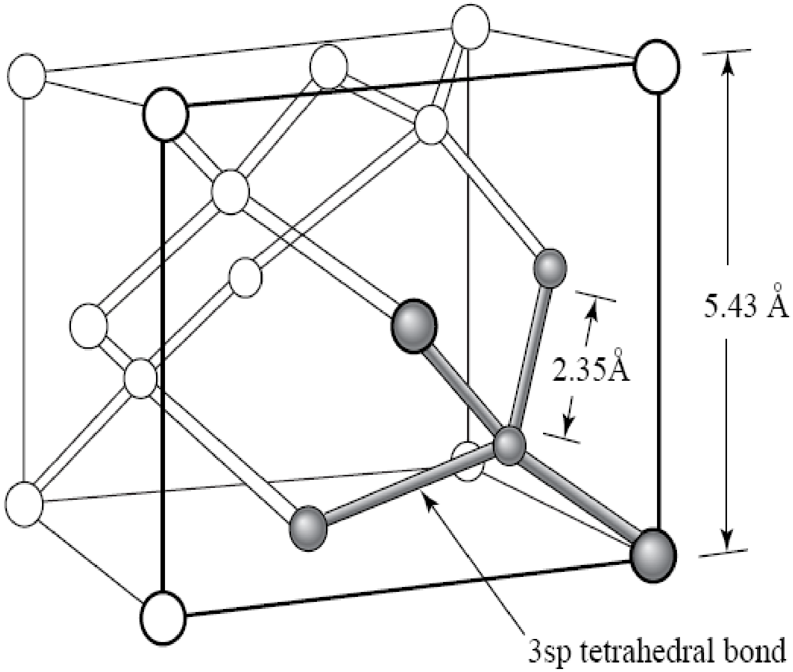
14 electrons in three shells: 2 ) 8 ) 4

i.e., 4 electrons in the outer "bonding" shell

Silicon forms strong covalent bonds with 4 neighbors



Si bonding configuration



## Electronic structure of Si atom:

- 10 core electrons (tightly bound)
- 4 valence electrons (loosely bound, responsible for most chemical properties)

## Other semiconductors:

- Ge, C (diamond form), SiGe
- GaAs, InP, InGaAs, InGaAsP, ZnSe, CdTe (on average, 4 valence electrons per atom)

# Semiconductor materials

- The reasons of that are:
  - Better properties at room temperature
  - High-quality silicon dioxide ($SiO_2$) can be grown thermally.
  - Si is second only to oxygen in great quantity.
  - Devices made from Si cost less than any other semiconductor material
  - Silicon technology is by far the most advanced among all semiconductor technologies.

# Significance of Si

1. Easily oxidized to form $SiO_2$, a high quality electrical insulator
2. Oxide layer provides an excellent barrier layer for the selective diffusion steps needed in integrated-circuit fabrication
3. Abundant element in nature, providing the possibility of a low-cost starting material
4. Wider bandgap than Ge and operate at higher temperature than Ge

| General Classification | Semiconductor Symbol | Semiconductor Name |
|---|---|---|
| Element | Si | Silicon |
| | Ge | Germanium |
| Binary compound | | |
| IV-IV | SiC | Silicon carbide |
| III-V | AlP | Aluminum phosphide |
| | AlAs | Aluminum arsenide |
| | AlSb | Aluminum antimonide |
| | GaN | Gallium nitride |
| | GaP | Gallium phosphide |
| | GaAs | Gallium areside |
| | GaSb | Gallium antimonide |
| | InP | Indium phosphide |
| | InAs | Indium arsenide |
| | InSb | Indium antimonide |
| II-VI | ZnO | Zinc oxide |
| | ZnS | Zinc sulfide |
| | ZnSe | Zinc selenide |
| | ZnTe | Zinc telluride |
| | CdS | Cadmium sulfide |
| | CdSe | Cadmium selenide |
| | CdTe | Cadmium telluride |
| | HgS | Mercury sulfide |
| IV-VI | PbS | Lead sulfide |
| | PbSe | Lead selenide |
| | PbTe | Lead telluride |
| Ternary compound | $Al_xGa_{1-x}As$ | Aluminum gallium arsenide |
| | $Al_xIn_{1-x}As$ | Aluminum indium arsenide |
| | $GaAs_{1-x}P_x$ | Gallium arsenic phosphide |
| | $Ga_xIn_{1-x}As$ | Gallium indium arsenide |
| | $Ga_xIn_{1-x}P$ | Gallium indium phosphide |
| Quaternary compound | $Al_xGa_{1-x}As_ySb_{1-y}$ | Aluminum gallium arsenic antimonide |
| | $Ga_xIn_{1-x}As_{1-y}P_y$ | Gallium indium arsenic phosphide |

# Important properties of silicon

- **Physical, structural**

| | | |
|---|---|---|
| Crystal structure | diamond | |
| Lattice period (Å) | 5.431 | |

- **Energy levels**

| | | |
|---|---|---|
| Energy gap (eV) | 1.1 | |
| Band symmetry | indirect gap | |
| Density of states ($cm^{-3}$) | $N_c = 2.8 \times 10^{19}$ | $N_v = 1.02 \times 10^{19}$ |

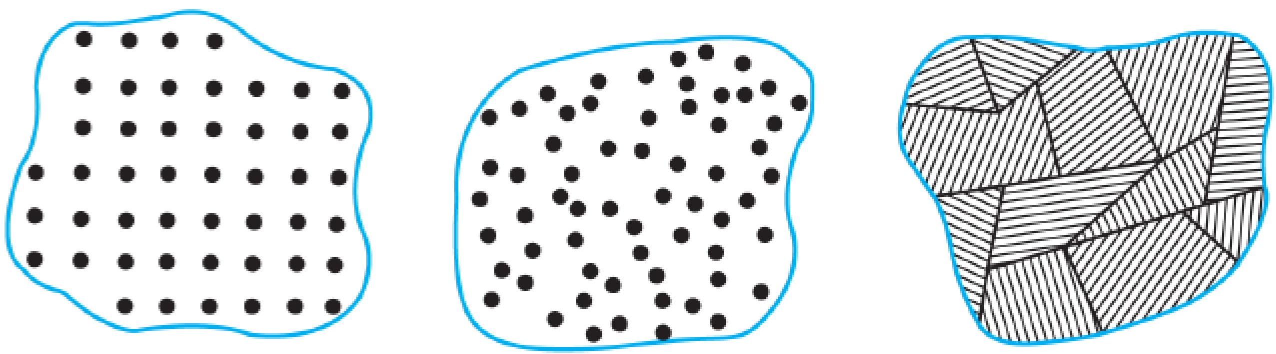
- **Electrical, charge carriers**

| | Electrons | Holes |
|---|---|---|
| Low field mobility ($cm^2/V\text{-}s$) | 1450 | 450 |
| Critical E-field (V/cm) | $10^4$ | $5 \times 10^4$ |
| Saturation velocity (cm/s) | $10^7$ | $10^7$ |
| Effective mass (relative) | $m_l$ 0.98 | $m_{lh}$ 0.16 |
| | $m_t$ 0.19 | $m_{hh}$ 0.5 |

- **Optical**

| | |
|---|---|
| Absorption edge ($\lambda_{gap}$) | 1.1 $\mu m$ |
| Radiative lifetime (s) | few ms |
| Typical radiative Efficiency (%) | <<1% |

# Crystal structures



(a) Crystalline (b) Amorphous (c) Polycrystalline

# Unit cell

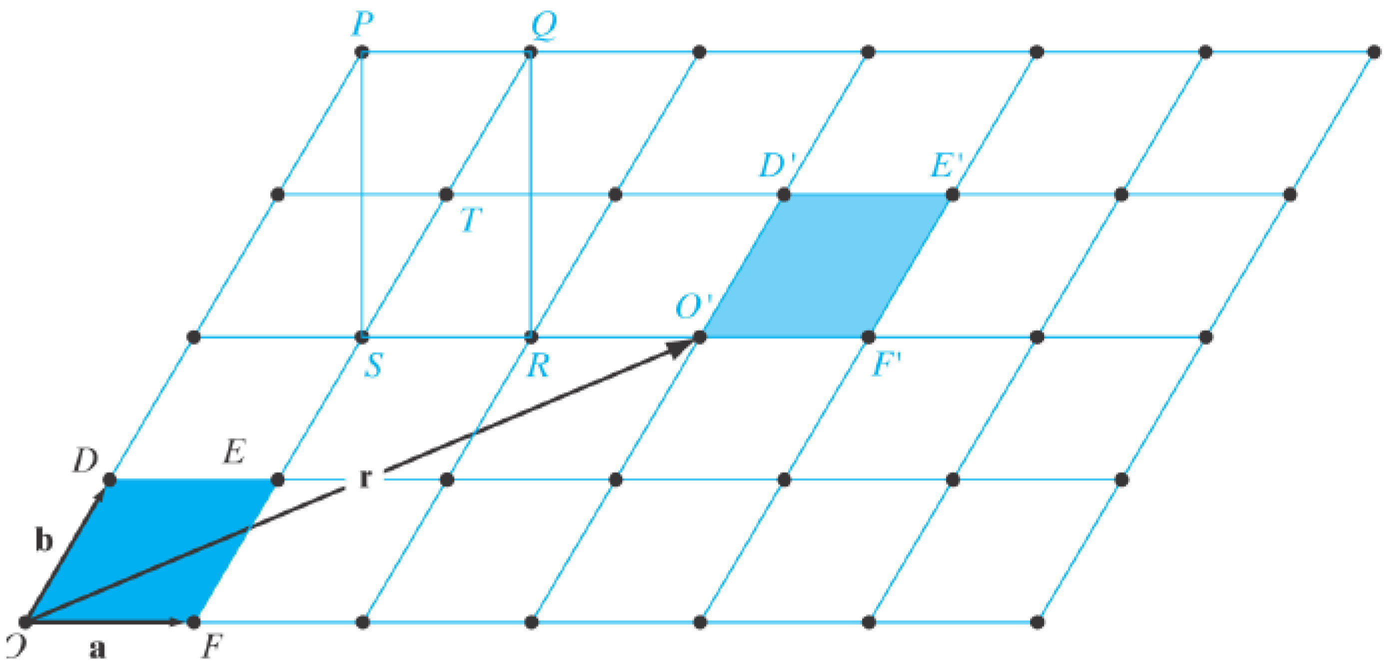



Figure 1.2

A two-dimensional lattice showing translation of a unit cell by $\mathbf{r} = 3\mathbf{a} + 2\mathbf{b}$.

# Cubic unit cell

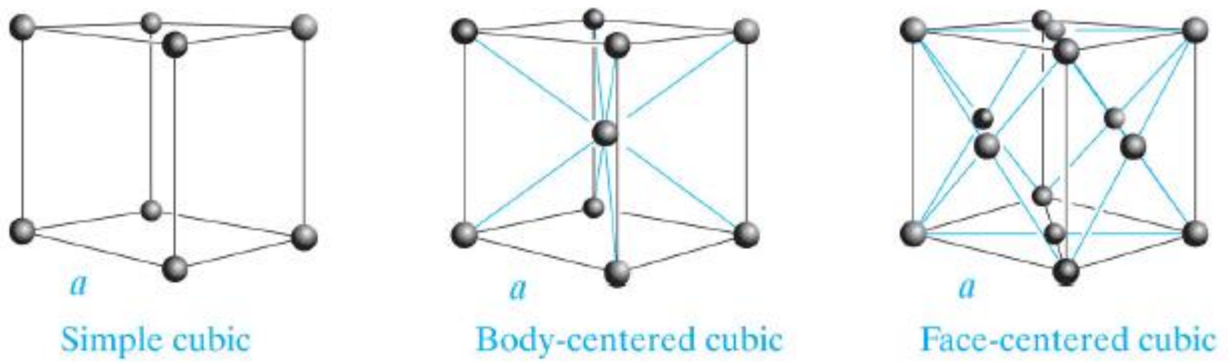
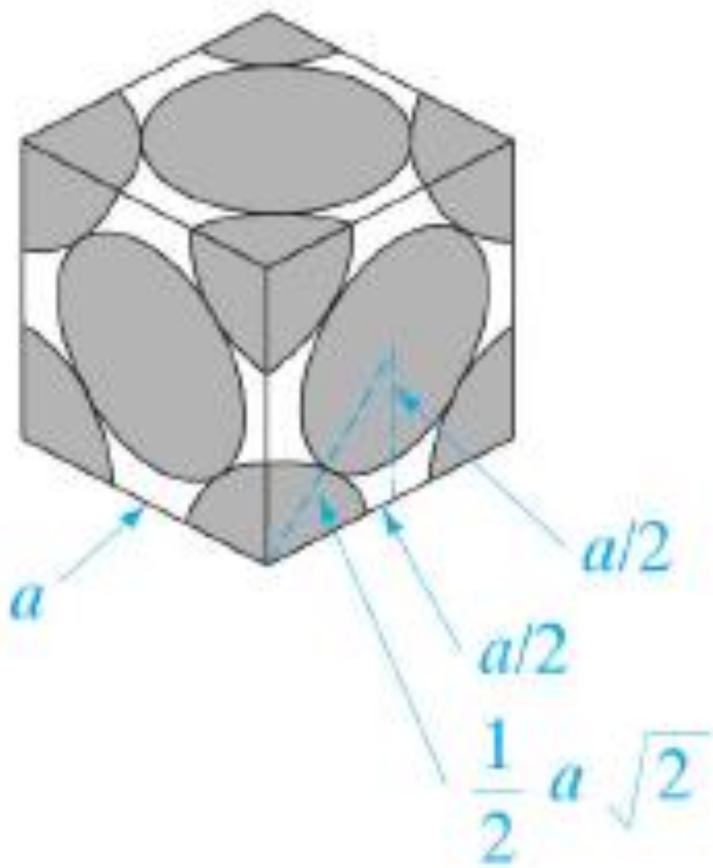



Figure 1.3

Unit cells for three types of cubic lattice structures.

# FCC structure



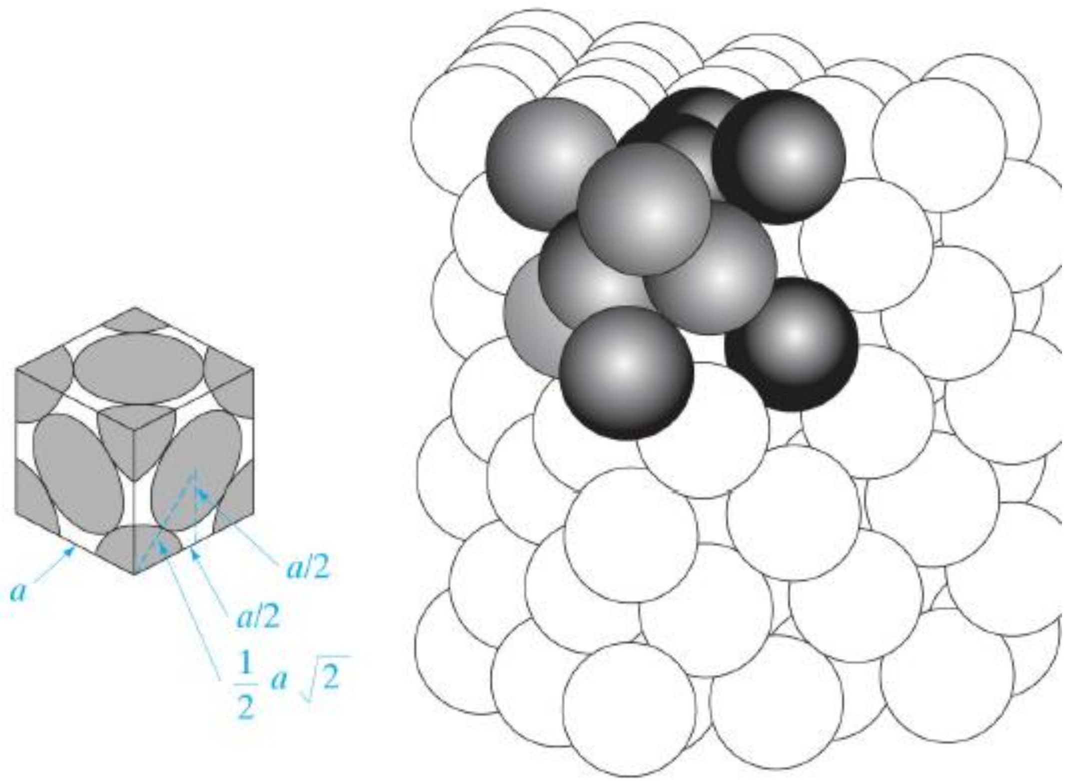




Figure 1.4

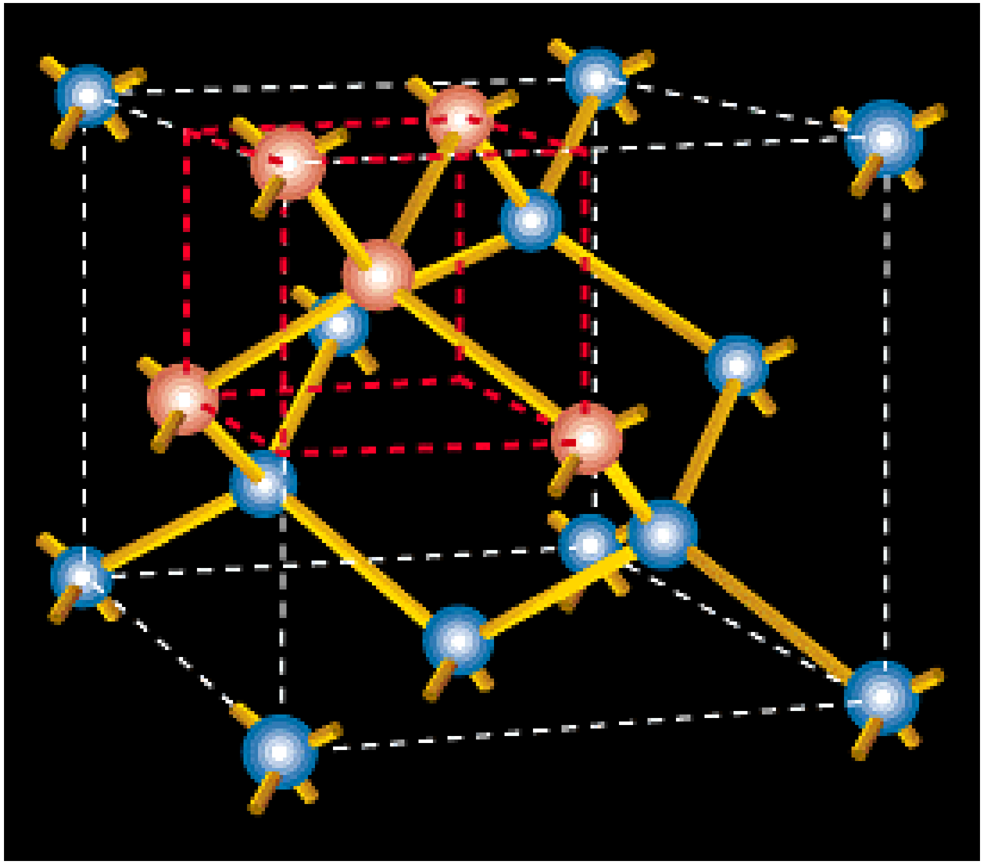
Packing of hard spheres in an fcc lattice.

# The Si Crystal

**Each Si atom has 4 nearest neighbors**

**lattice constant**

**= 5.431Å**



**"diamond cubic" lattice**

# How Many Silicon Atoms per cm$^{-3}$?

- **Number of atoms in a unit cell:**
  - 4 atoms completely inside cell
  - Each of the 8 atoms on corners are shared among cells $\rightarrow$ count as 1 atom inside cell
  - Each of the 6 atoms on the faces are shared among 2 cells $\rightarrow$ count as 3 atoms inside cell

  $\Rightarrow$ Total number inside the cell = 4 + 1 + 3 = **8**

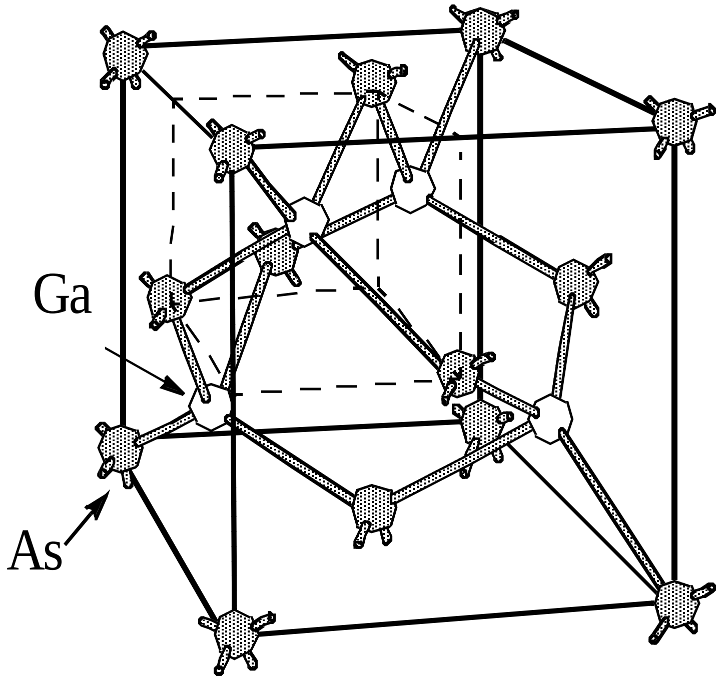
- **Cell volume:**

  $(.543\ \text{nm})^3 = 1.6 \times 10^{-22}\ \text{cm}^3$

- **Density of silicon atoms**

  = (8 atoms) / (cell volume) = **$5 \times 10^{22}$ atoms/cm$^3$**

# Compound Semiconductors




- "zincblende" structure
- III-V compound semiconductors: GaAs, GaP, GaN, *etc.*
    - ✓ important for optoelectronics and high-speed ICs

# Miller Indices (h, k , l)

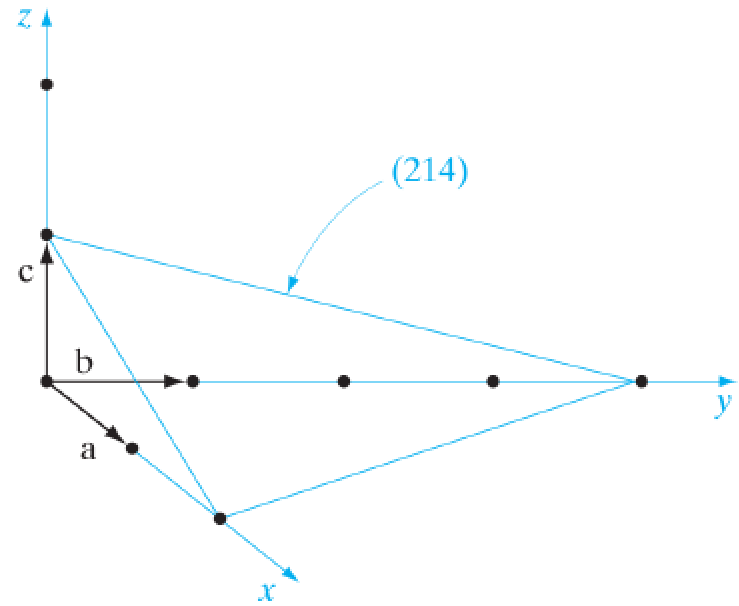



Figure 1.5

A (214) crystal plane.

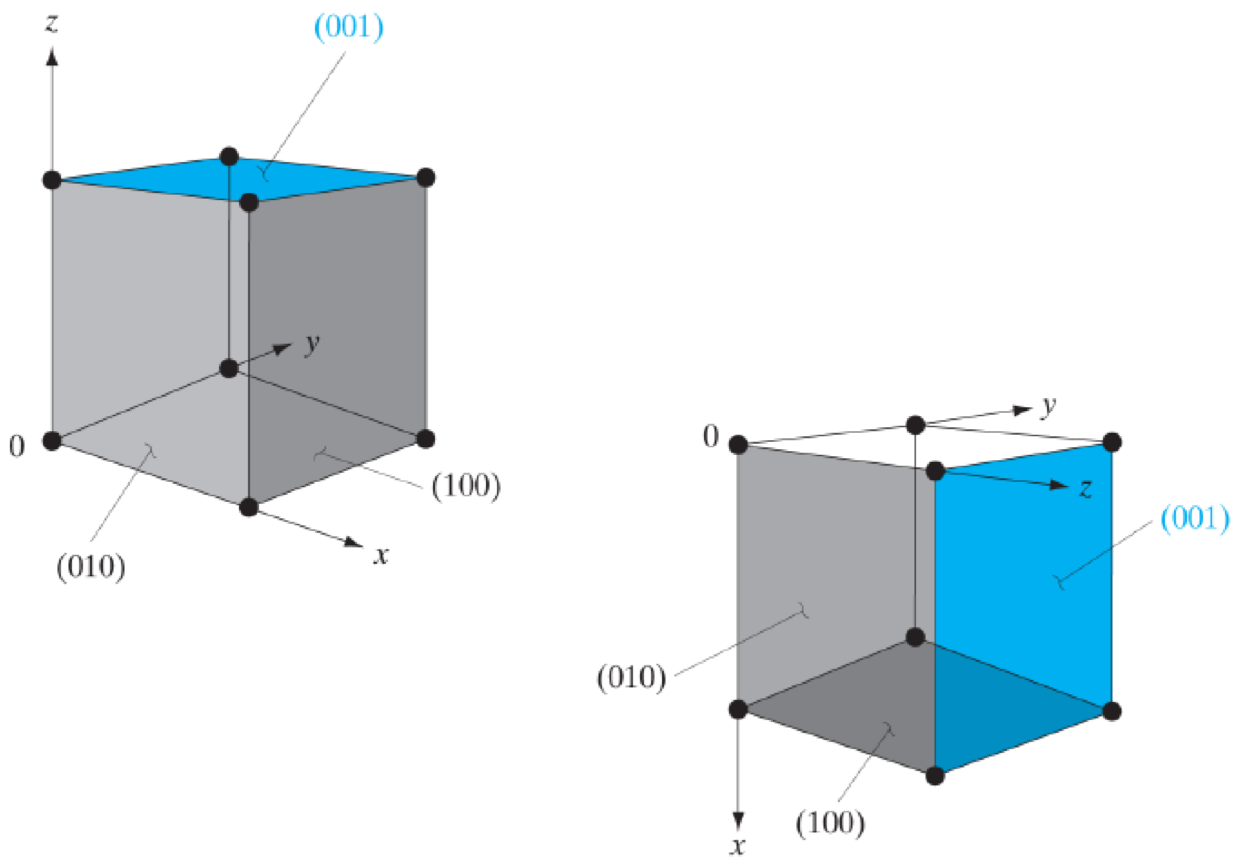



Figure 1.6

Equivalence of the cube faces ({100} planes) by rotation of the unit cell within the cubic lattice.

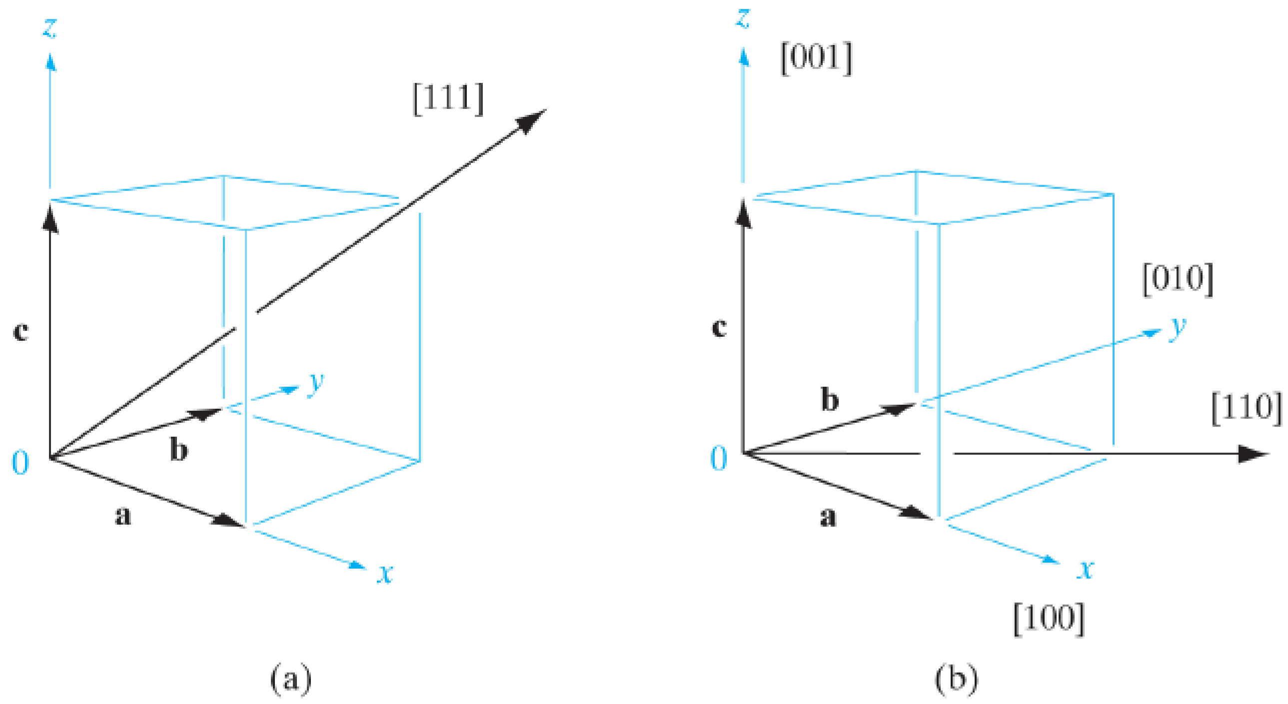



Figure 1.7

Crystal directions in the cubic lattice.