Semiconductor Device Physics

Lecture 1

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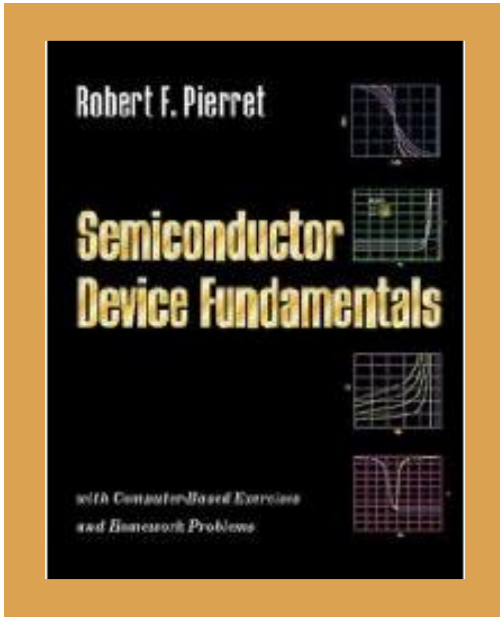
Textbook and Syllabus



Textbook:

"Semiconductor Device Fundamentals",
Robert F. Pierret, International Edition,
Addison Wesley, 1996.

Syllabus:

Chapter 1: Semiconductors: A General Introduction
Chapter 2: Carrier Modeling
Chapter 3: Carrier Action
Chapter 5: *pn* Junction Electrostatics
Chapter 6: *pn* Junction Diode: *I*–*V* Characteristics
Chapter 7: *pn* Junction Diode: Small-Signal Admittance
Chapter 8: *pn* Junction Diode: Transient Response
Chapter 14: MS Contacts and Schottky Diodes
Chapter 9: Optoelectronic Diodes
Chapter 10: BJT Fundamentals
Chapter 11: BJT Static Characteristics
Chapter 12: BJT Dynamic Response Modeling

References

The class materials are the Lecture note slides of the Semiconductor Device Physics course offered by Dr.-Ing. Erwin Sitompul, President University, Indonesia.

http://zitompul.wordpress.com/1-ee-lectures/2-semiconductor-device-physics/

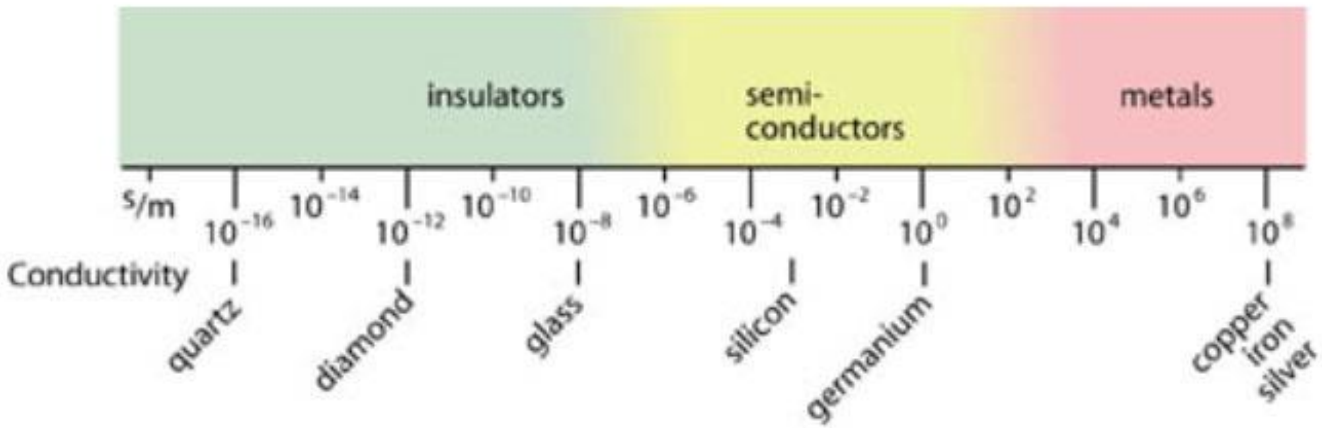
Chapter 1

Semiconductors: A General Introduction

What is a Semiconductor?

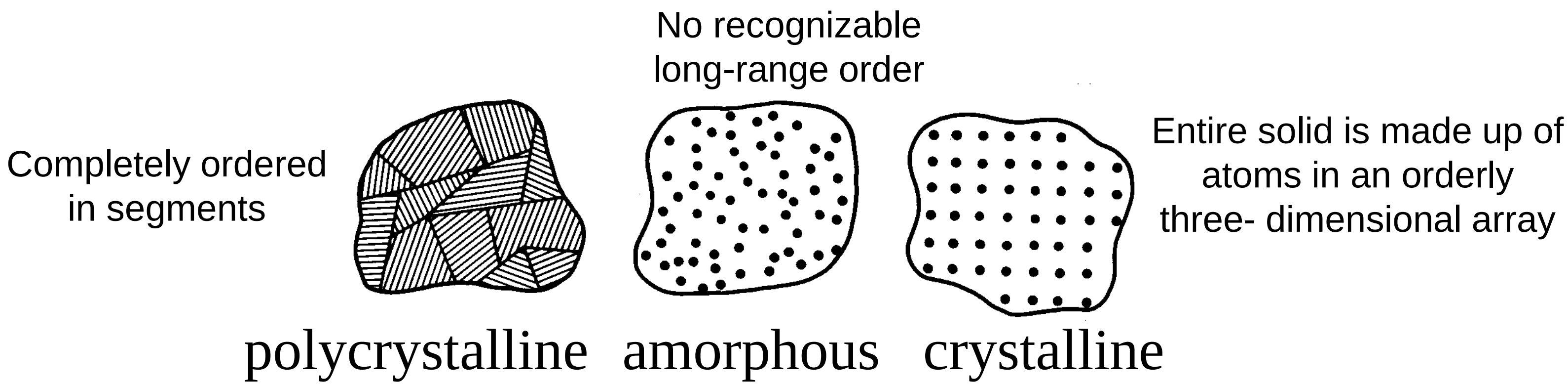
- Low resistivity $\Rightarrow$ "conductor"
- High resistivity $\Rightarrow$ "insulator"
- Intermediate resistivity $\Rightarrow$ "semiconductor"

- The conductivity (and at the same time the resistivity) of semiconductors lie between that of conductors and insulators.



What is a Semiconductor?

- Semiconductors are some of the purest solid materials in existence, because any trace of impurity atoms called "*dopants*" can change the electrical properties of semiconductors drastically.
- Unintentional impurity level:
1 impurity atom per 10^9 semiconductor atom.
- Intentional impurity ranging from 1 per 10^8 to 1 per 10^3.



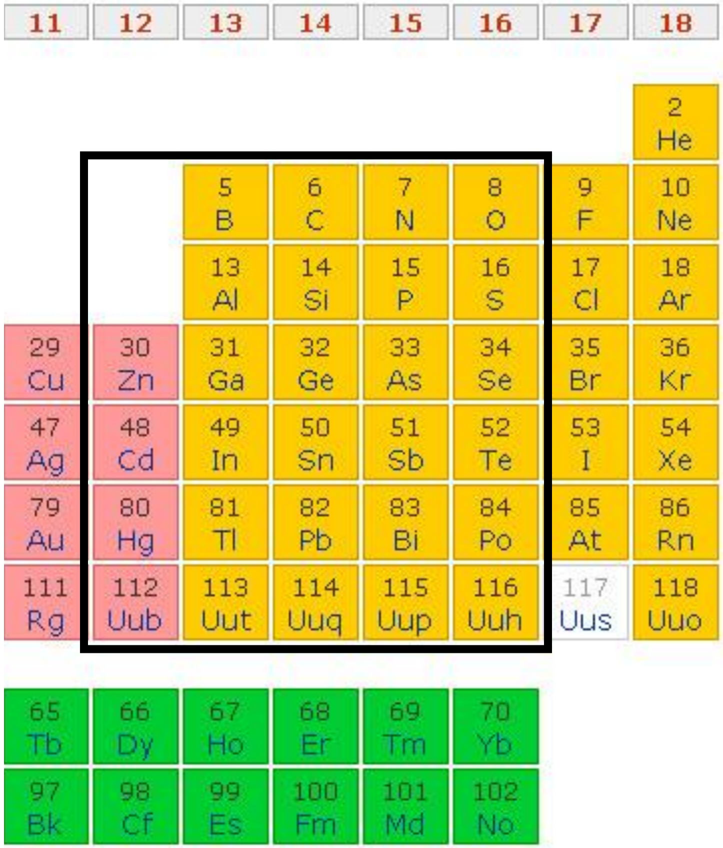
- Most devices fabricated today employ crystalline semiconductors.

Semiconductor Materials

Elemental: Si, Ge, C

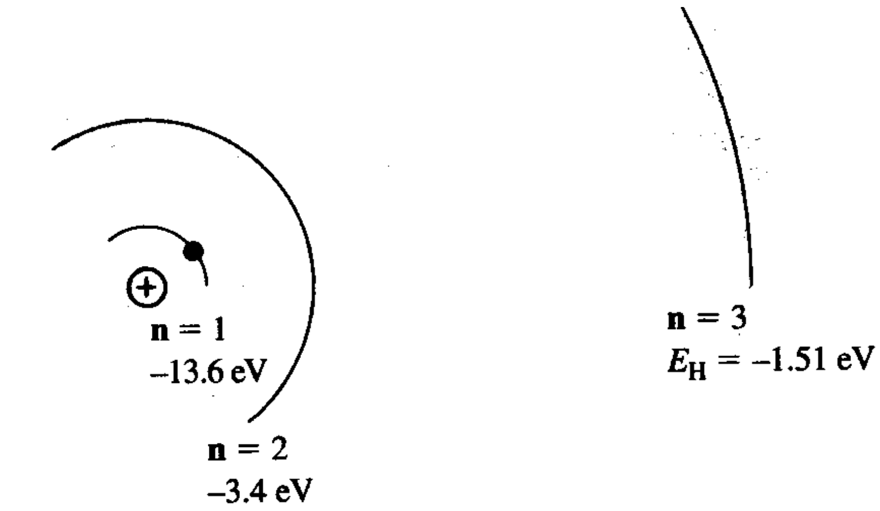
Compound:
- IV-IV SiC
- III-V GaAs, GaN
- II-VI CdSe

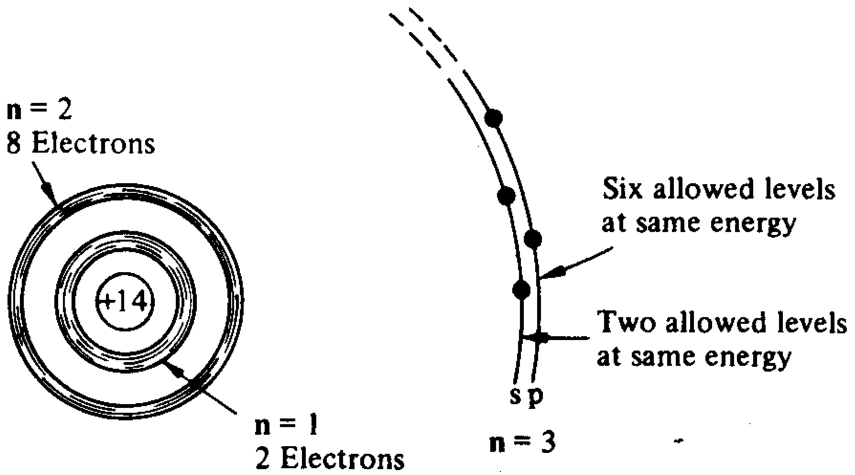
Alloy:
- $Si_{1-x}Ge_x$
- $Al_xGa_{1-x}As$



As : Arsenic
Cd : Cadmium
Se : Selenium
Ga : Gallium

From Hydrogen to Silicon

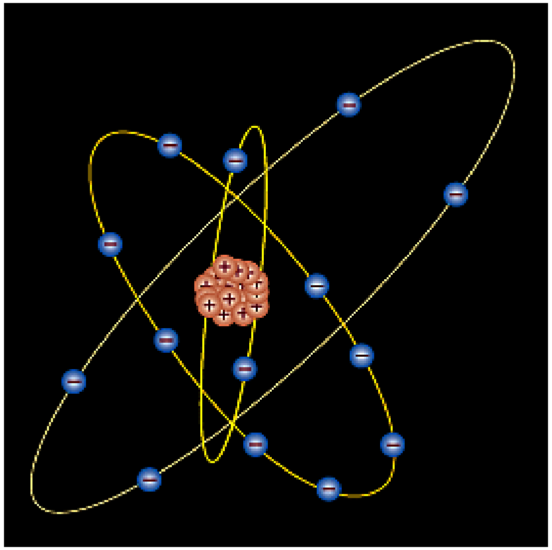


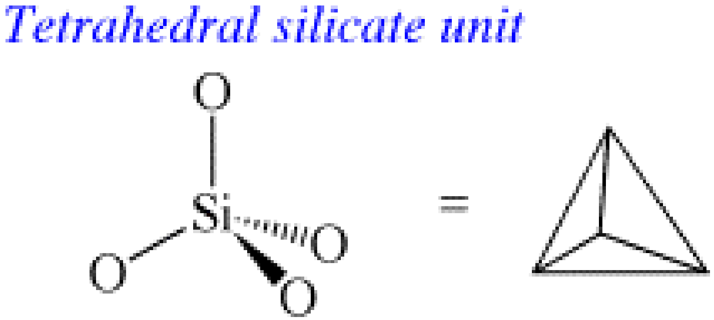


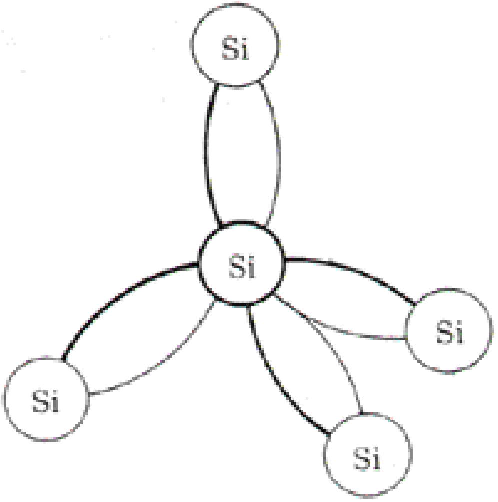
Z	Name	# of Electrons						Notation
		1	2		3			
		1s	2s	2p	3s	3p	3d	
1	H	1						$1s^1$
2	He	2						$1s^2$
3	Li	2	1					$1s^2 2s^1$
4	Be	2	2					$1s^2 2s^2$
5	B	2	2	1				$1s^2 2s^2 2p^1$
6	C	2	2	2				$1s^2 2s^2 2p^2$
7	N	2	2	3				$1s^2 2s^2 2p^3$
8	O	2	2	4				$1s^2 2s^2 2p^4$
9	F	2	2	5				$1s^2 2s^2 2p^5$
10	Ne	2	2	6				$1s^2 2s^2 2p^6$
11	Na	2	2	6	1			$1s^2 2s^2 2p^6 3s^1$
12	Mg	2	2	6	2			$1s^2 2s^2 2p^6 3s^2$
13	Al	2	2	6	2	1		$1s^2 2s^2 2p^6 3s^2 3p^1$
14	Si	2	2	6	2	2		$1s^2 2s^2 2p^6 3s^2 3p^2$
15	P	2	2	6	2	3		$1s^2 2s^2 2p^6 3s^2 3p^3$
16	S	2	2	6	2	4		$1s^2 2s^2 2p^6 3s^2 3p^4$
17	Cl	2	2	6	2	5		$1s^2 2s^2 2p^6 3s^2 3p^5$
18	Ar	2	2	6	2	6		$1s^2 2s^2 2p^6 3s^2 3p^6$

The Silicon Atom

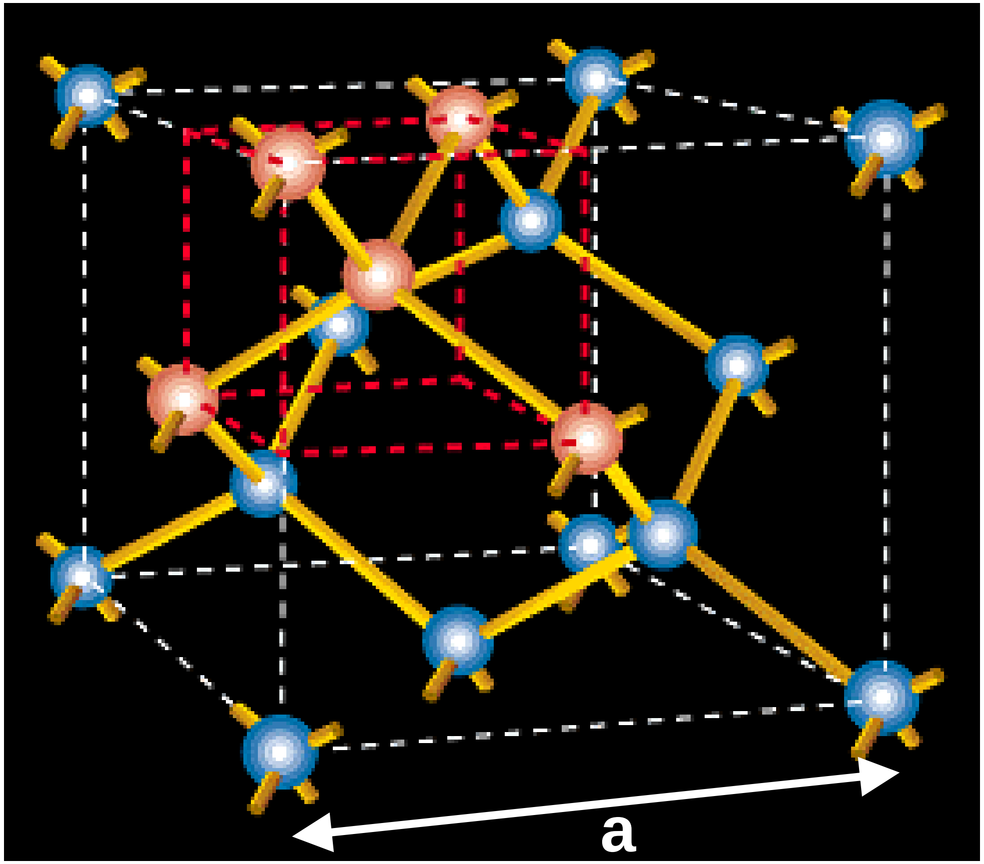
- 14 electrons occupying the first 3 energy levels:
  - 1s, 2s, 2p orbitals are filled by 10 electrons.
  - 3s, 3p orbitals filled by 4 electrons.
- To minimize the overall energy, the 3s and 3p orbitals hybridize to form four tetrahedral 3sp orbital.
- Each has one electron and is capable of forming a bond with a neighboring atom.







The Si Crystal



"Diamond Lattice"

- Each Si atom has 4 nearest neighbors.
- Atom lattice constant
  (length of the unit cell side)
  a = 5.431Å, 1Å=10^{-10}m
- Each cell contains:
  - 8 corner atoms
  - 6 face atoms
  - 4 interior atoms

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 8 cells → count as 1 atom inside cell
  - Each of the 6 atoms on the faces are shared among 2 cells → count as 3 atoms inside cell
  - ⇨ 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 atom**

  = (8 atoms) / (cell volume)

  = $\mathbf{5 \times 10^{22}}$ **atoms/cm**^{3}

  - **What is density of silicon in g/cm^3?**

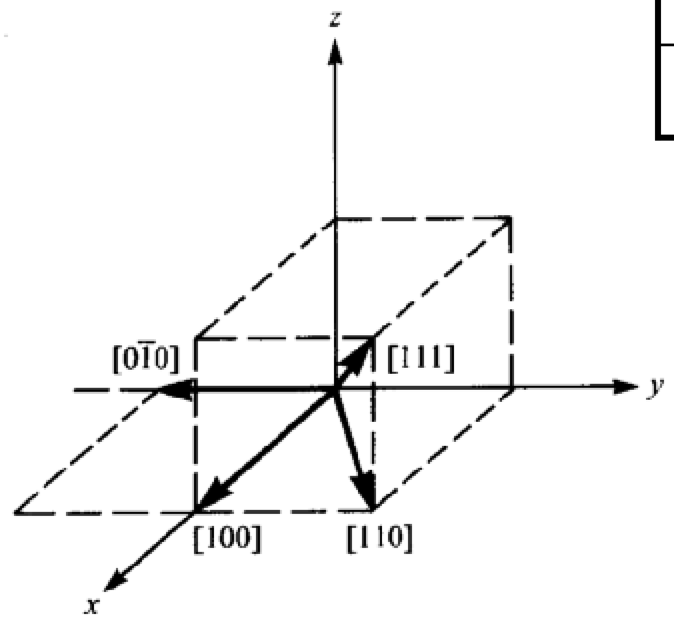
Crystallographic Notation

Miller Indices

Notation	Interpretation
(***h k l***)	crystal plane
{ ***h k l*** }	equivalent planes
[***h k l***]	crystal direction
< ***h k l*** >	equivalent directions

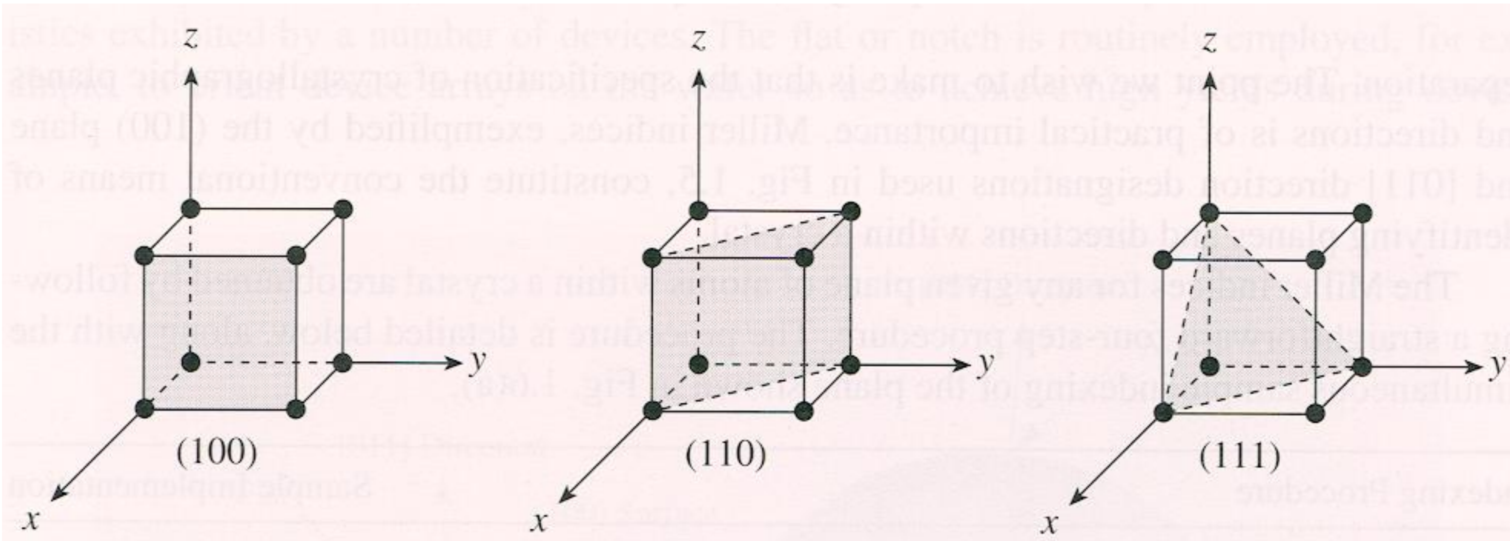
***h*: inverse *x*-intercept of plane**
***k*: inverse *y*-intercept of plane**
***l*: inverse *z*-intercept of plane**

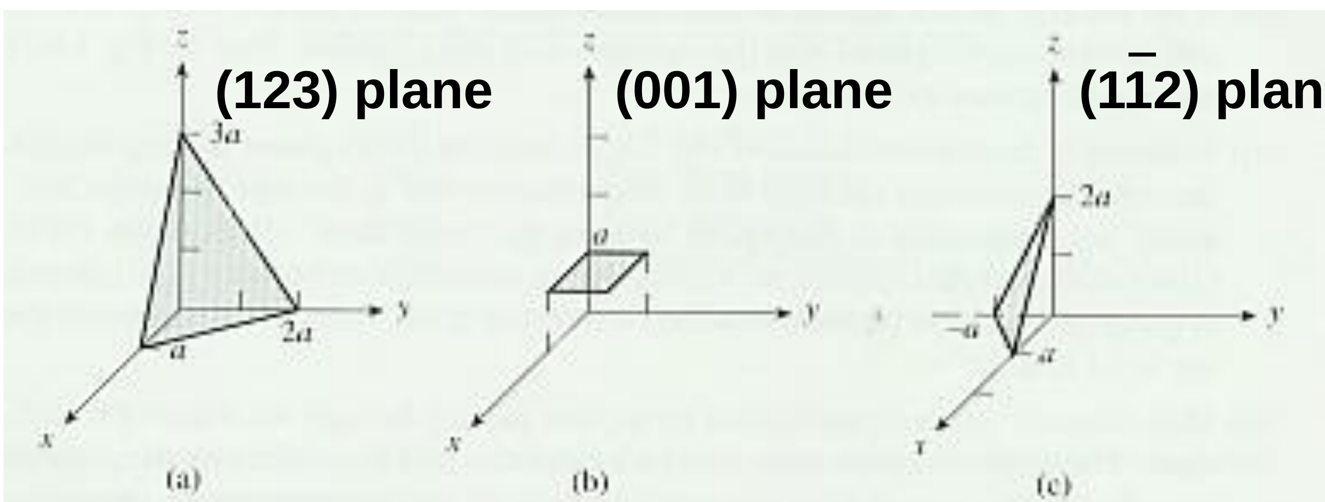
(*h*, *k* and *l* are reduced to 3 integers having the same ratio.)



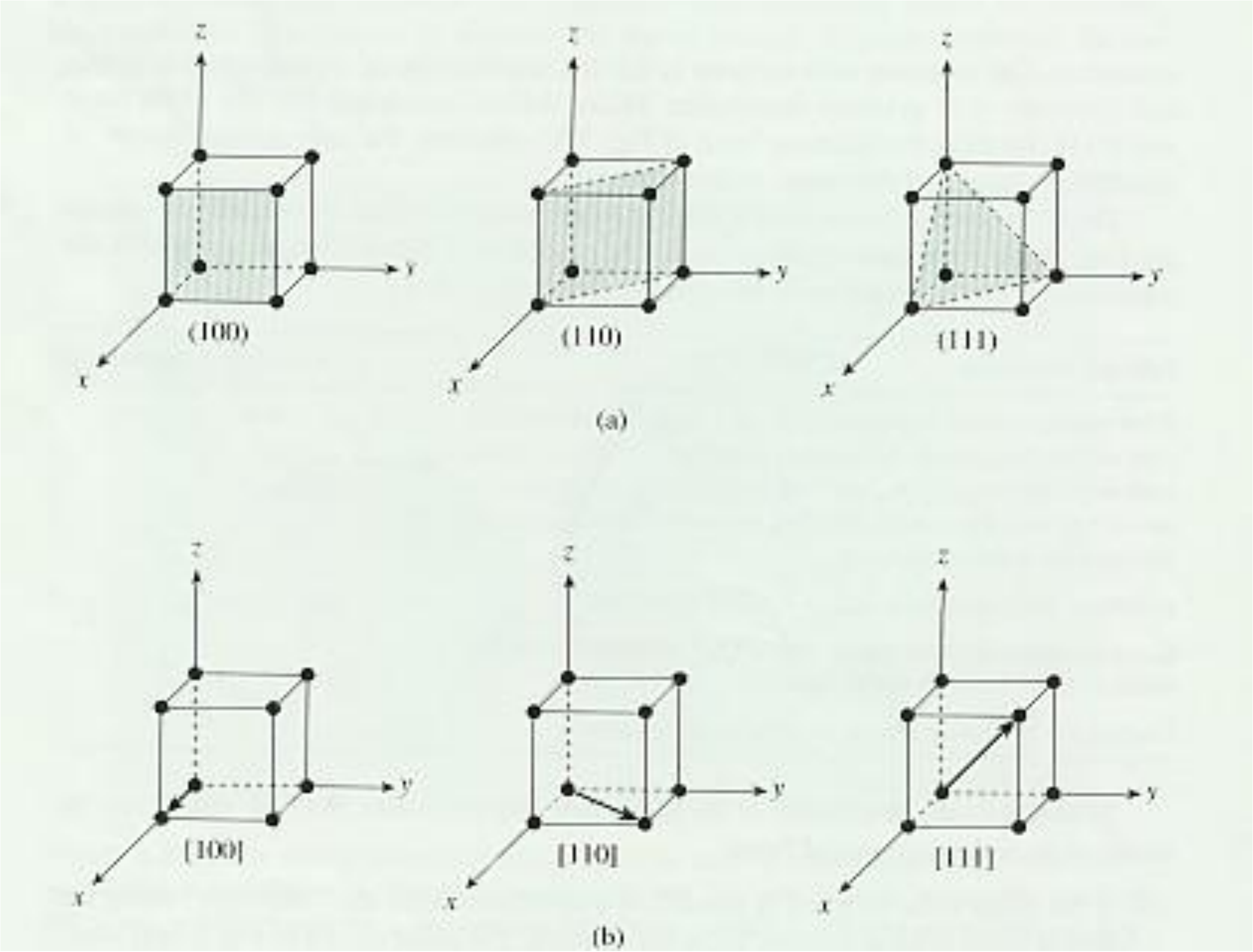
Sample direction vectors and their corresponding Miller indices.

Crystallographic Planes



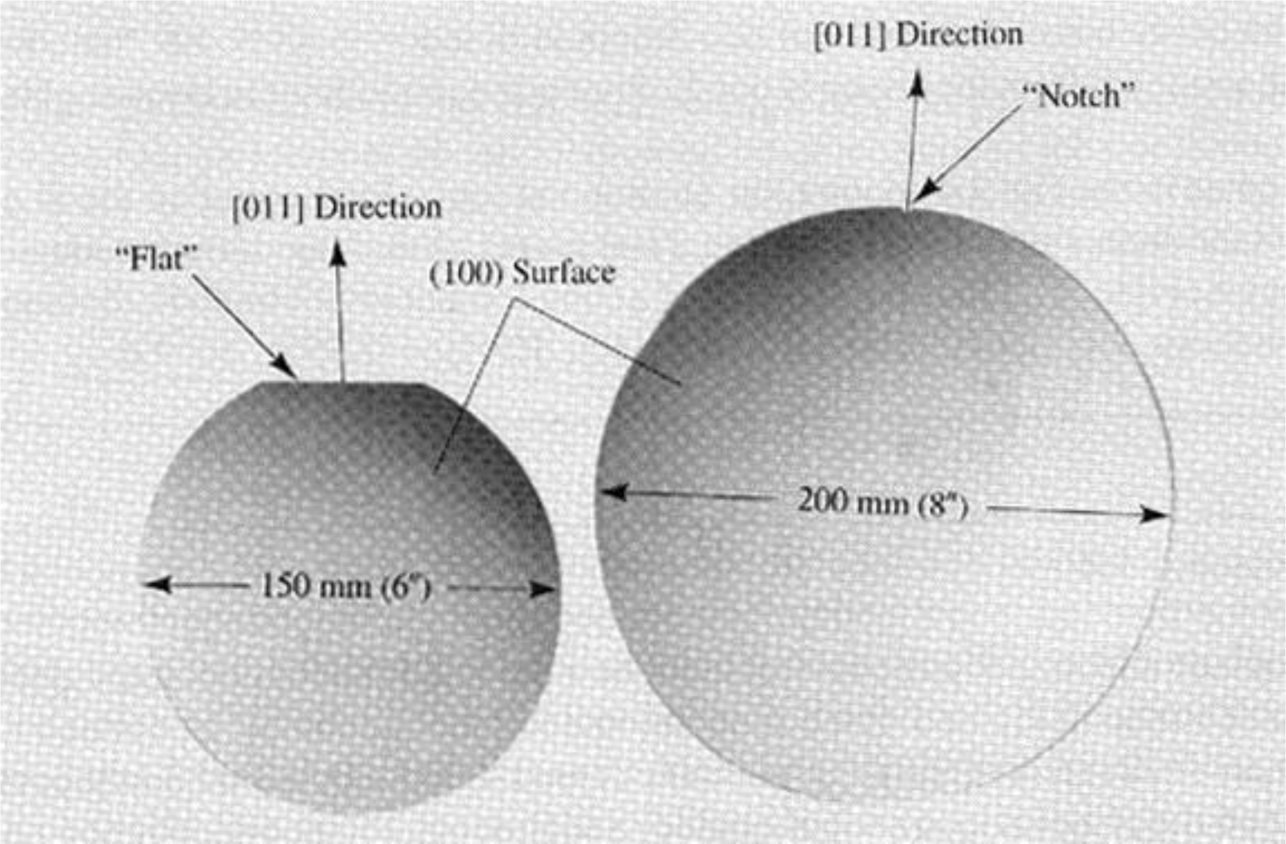


Crystallographic Planes

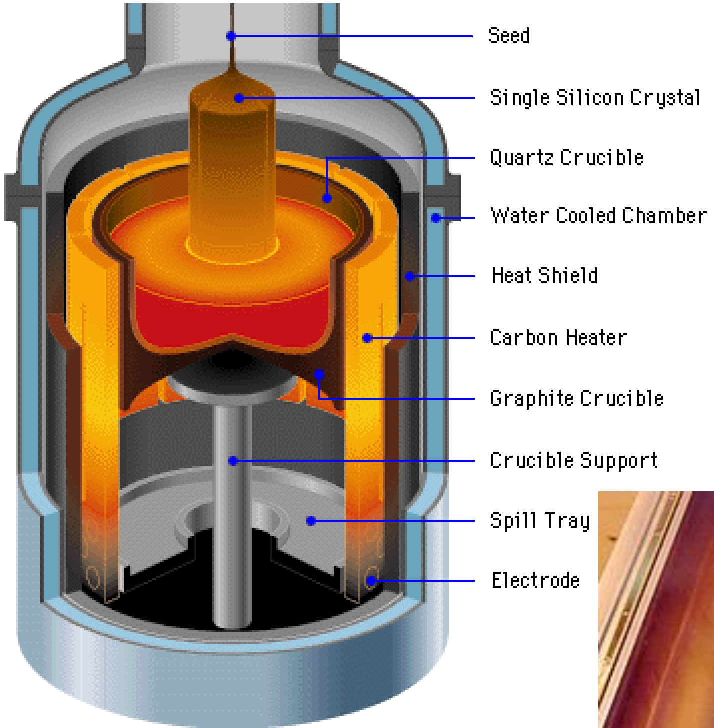


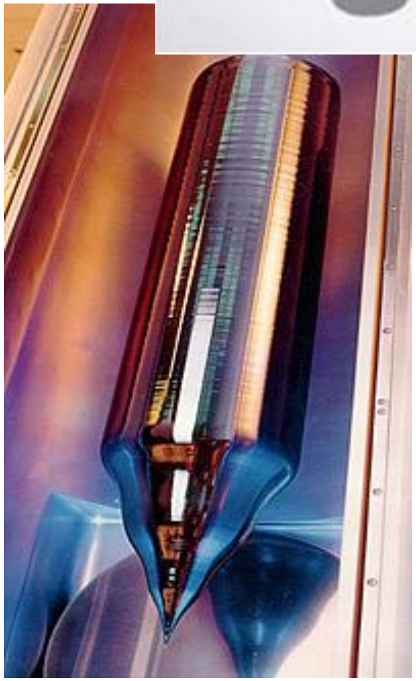
Crystallographic Planes of Si Wafers

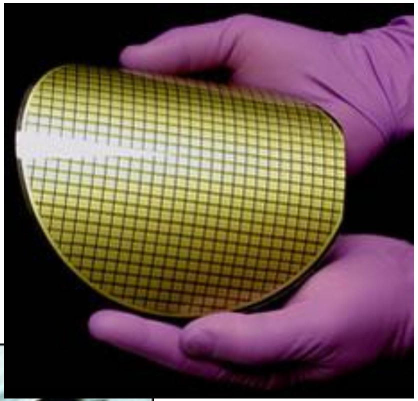
- Silicon wafers are usually cut along a {100} plane with a flat or notch to orient the wafer during integrated-circuit fabrication.
- The facing surface is polished and etched yielding mirror-like finish.

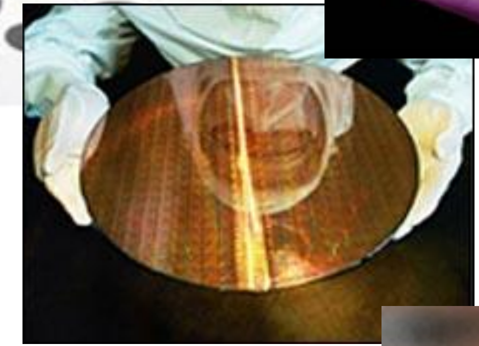


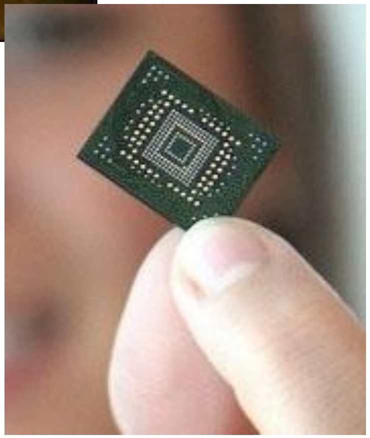
Crystal Growth Until Device Fabrication





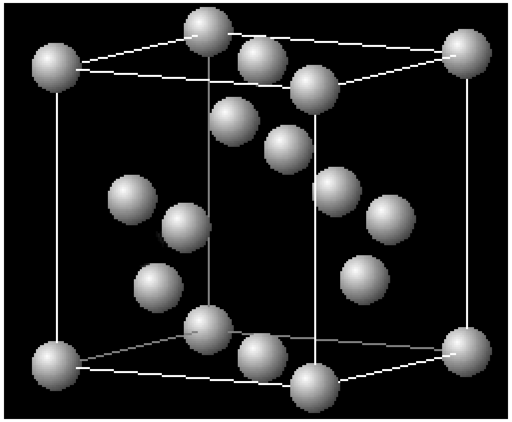




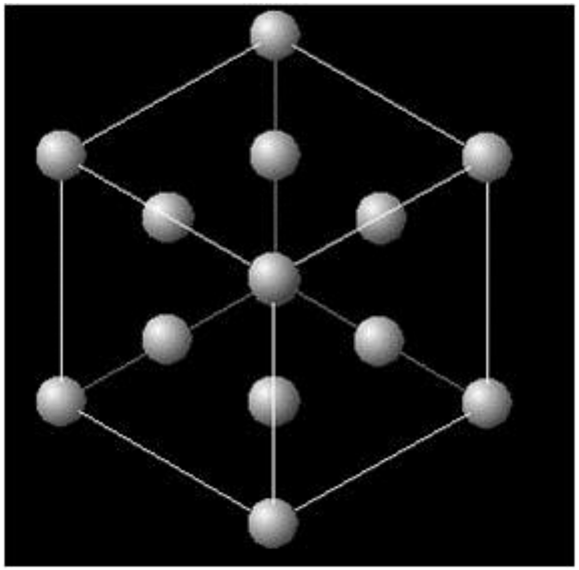


Crystallographic Planes of Si

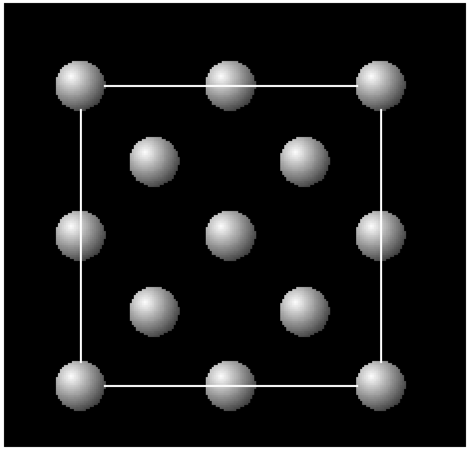
Unit cell:



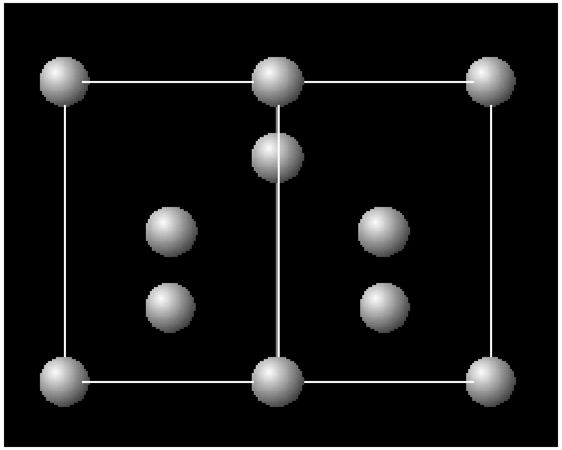
View in <111> direction



View in <100> direction



View in <110> direction



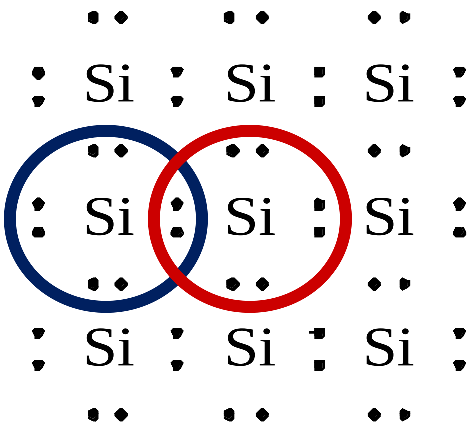
Chapter 2
Carrier Modeling

Electronic Properties of Si

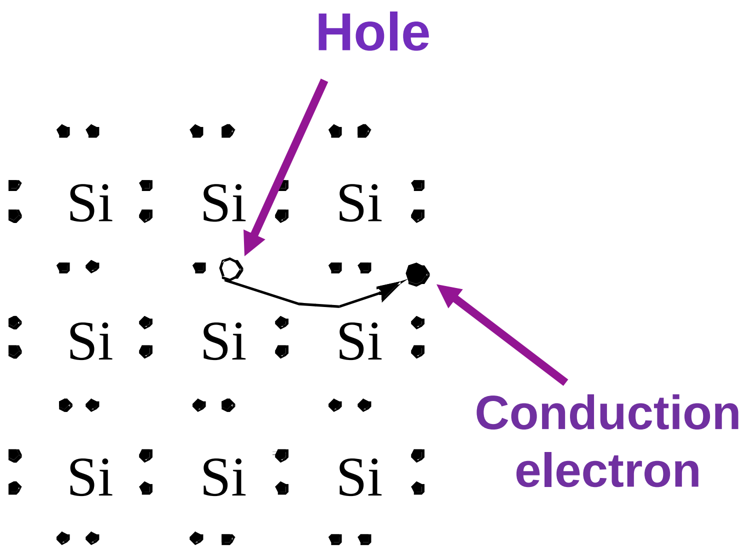
- Silicon is a semiconductor material.
  - Pure Si has a relatively high electrical resistivity at room temperature.
- There are 2 types of mobile charge-carriers in Si:
  - Conduction electrons are negatively charged, $e = -1.602 \times 10^{-19}$ C
  - Holes are positively charged, $p = +1.602 \times 10^{-19}$ C
- The concentration (number of atoms/cm^3) of conduction electrons & holes in a semiconductor can be influenced in several ways:
  - Adding special impurity atoms (dopants)
  - Applying an electric field
  - Changing the temperature
  - Irradiation

Bond Model of Electrons and Holes

- 2-D Representation

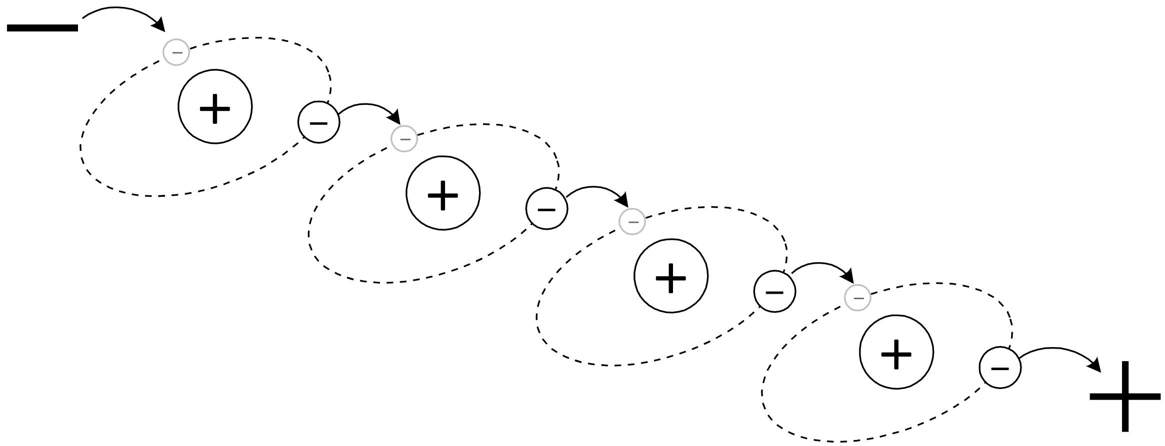


- When an electron breaks loose and becomes a ***conduction electron***, then a ***hole*** is created.

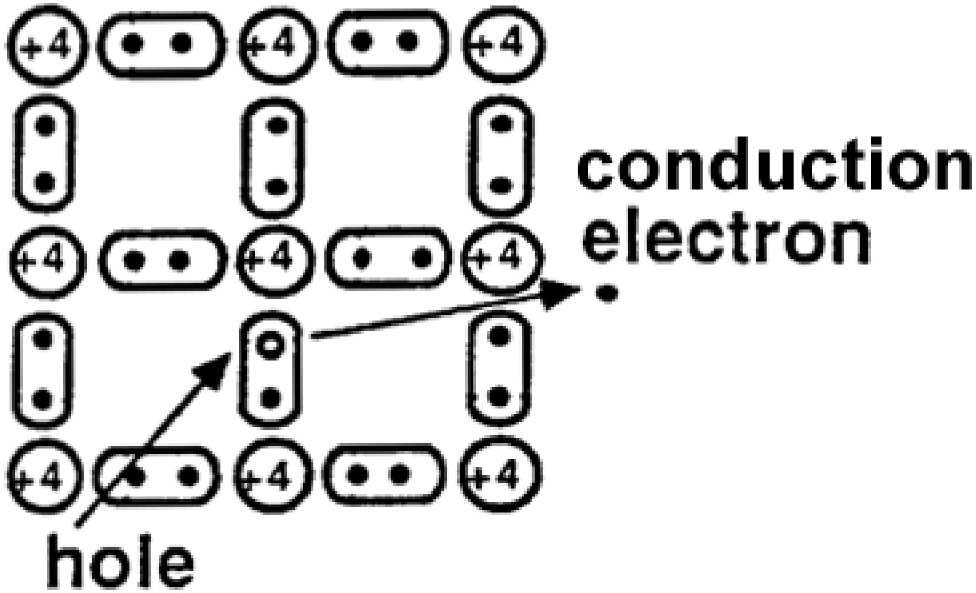


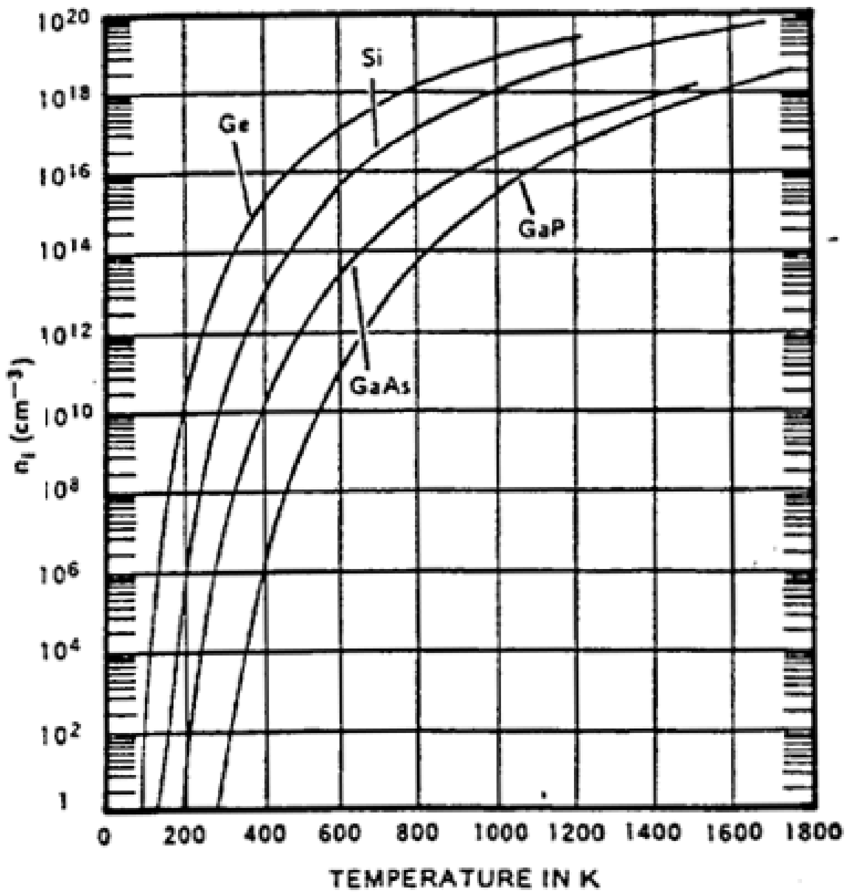
What is a Hole?

- A hole is a positive charge associated with a half-filled covalent bond.
- A hole is treated as a positively charged mobile particle in the semiconductor.



Conduction Electron and Hole of Pure Si



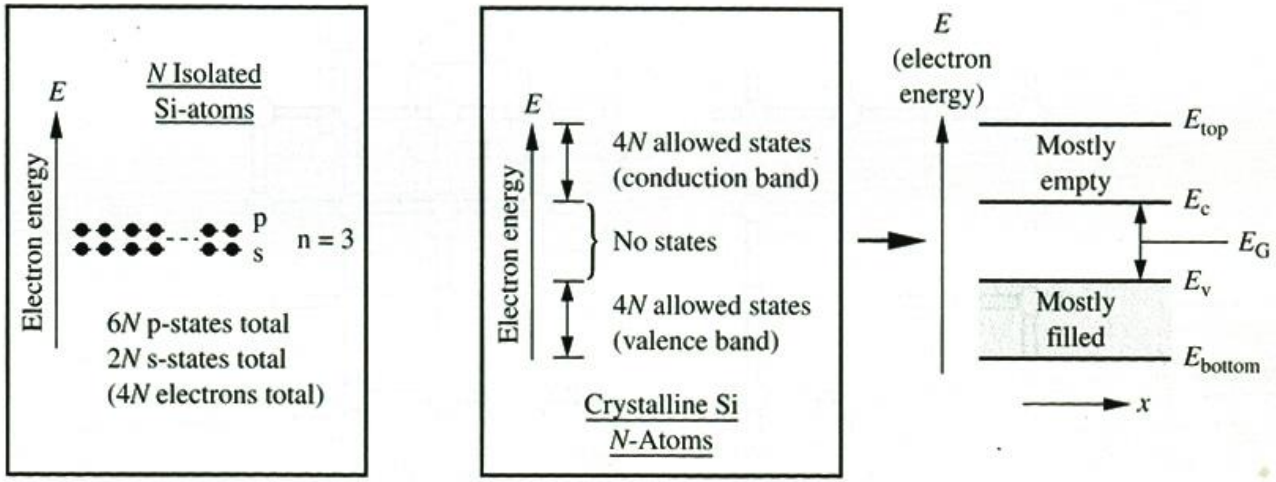


- Covalent (shared e^-) bonds exists between Si atoms in a crystal.
- Since the e^- are loosely bound, some will be free at any T, creating hole-electron pairs.

n_i = intrinsic carrier concentration

$n_i \approx 10^{10}$ cm^{-3} at room temperature

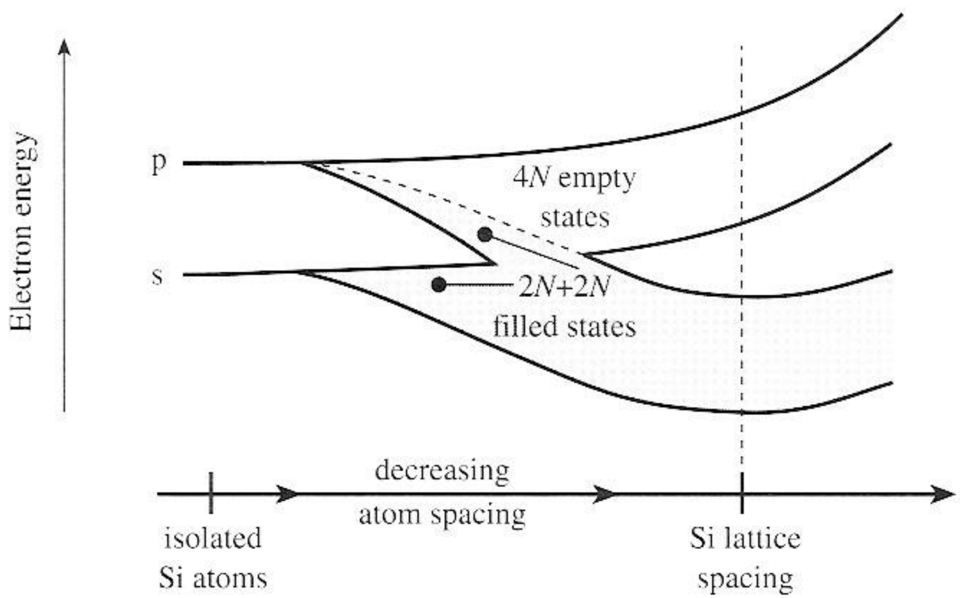
Si: From Atom to Crystal



Energy states
(in Si atom)

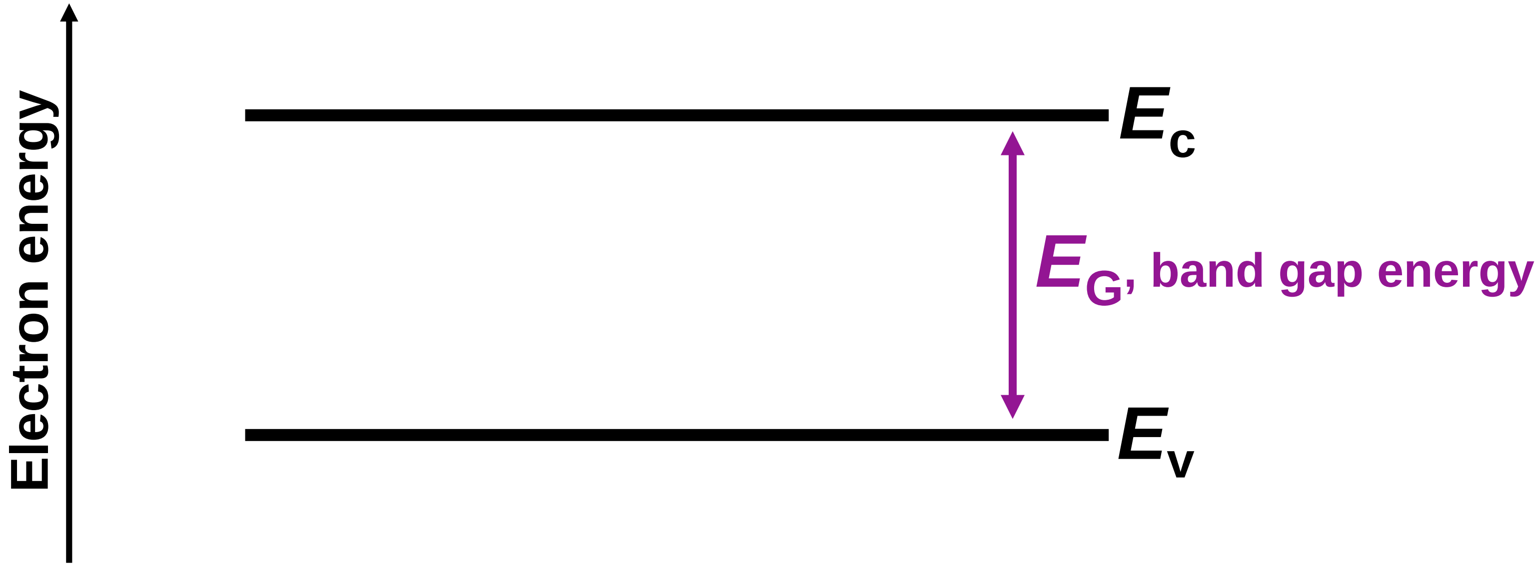
⇩

Energy bands
(in Si crystal)



- **The highest mostly-filled band is the *valence band*.**
- **The lowest mostly-empty band is the *conduction band*.**

Energy Band Diagram

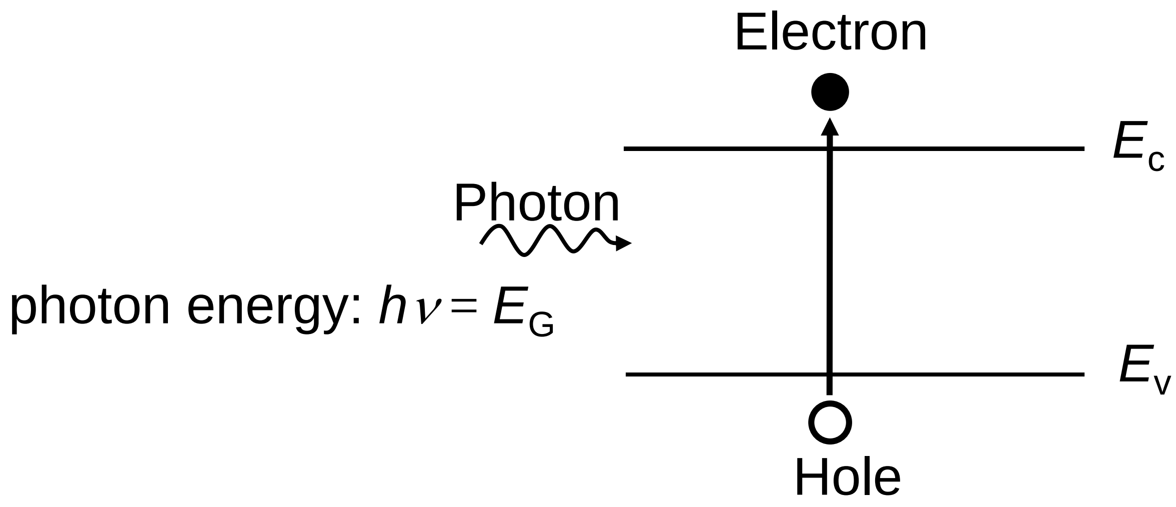


- For Silicon at 300 K, E_G = 1.12 eV
- 1 eV = 1.6 x 10^{-19} J

- Simplified version of energy band model, indicating:
  - Lowest possible conduction band energy (E_c)
  - Highest possible valence band energy (E_v)
- E_c and E_v are separated by the band gap energy E_G.

Measuring Band Gap Energy

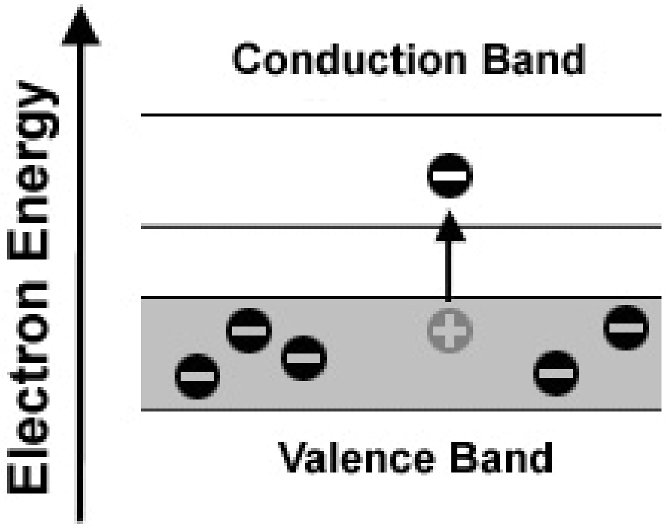
- E_G can be determined from the minimum energy ($h\nu$) of photons that can be absorbed by the semiconductor.
- This amount of energy equals the energy required to move a single electron from valence band to conduction band.



Band gap energies

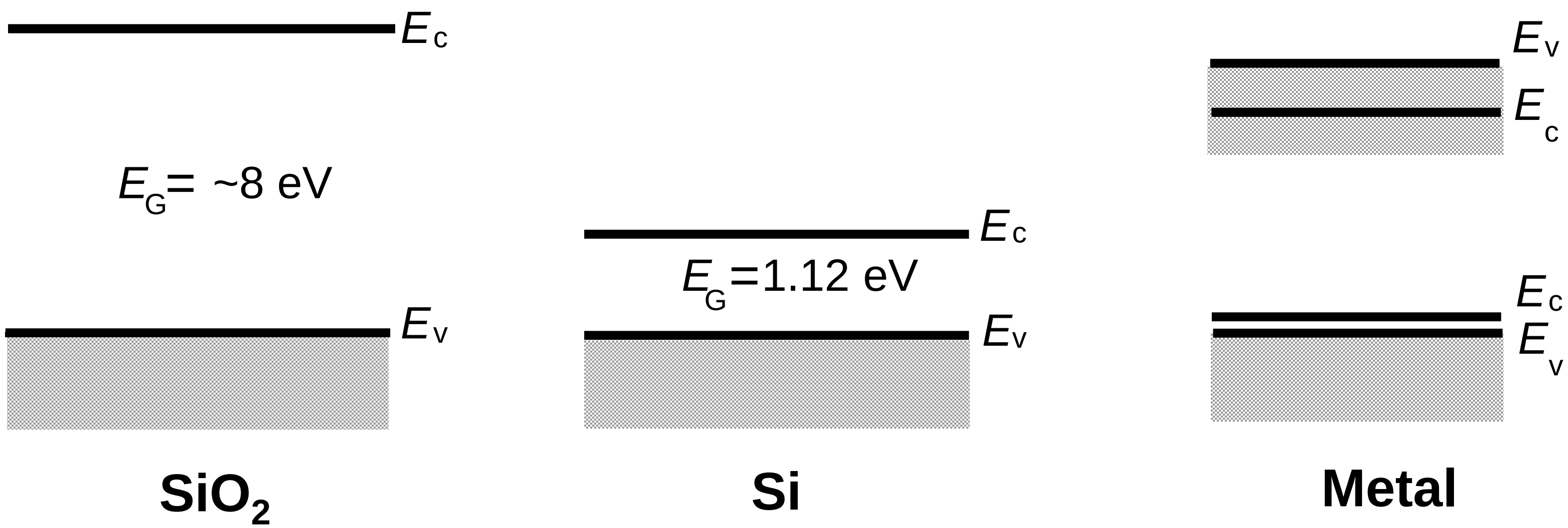
Semiconductor	Ge	Si	GaAs	Diamond
Band gap (eV)	0.66	1.12	1.42	6.0

Carriers



- Completely filled or empty bands do not allow current flow, because no carriers available.
- Broken covalent bonds produce carriers (electrons and holes) and make current flow possible.
- The excited electron moves from valence band to conduction band.
  - Conduction band is not completely empty anymore.
  - Valence band is not completely filled anymore.

Band Gap and Material Classification



- Insulators have large band gap E_G.
- Semiconductors have relatively small band gap E_G.
- Metals have very narrow band gap E_G .
  - Even, in some cases conduction band is partially filled, $E_v > E_c$.

Carrier Numbers in Intrinsic Material

- More new notations are presented now:
  - n : number of electrons/cm^3
  - p : number of holes/cm^3
  - n_i : intrinsic carrier concentration
- In a pure semiconductor, $n = p = n_i$.
- At room temperature,

$n_i = 2 \times 10^6$ /cm^3 in GaAs
$n_i = 1 \times 10^{10}$ /cm^3 in Si
$n_i = 2 \times 10^{13}$ /cm^3 in Ge