Analog & Digital Electronics

Course No: PH-218

Lecture 1: Semiconductor Materials

Course Instructors:

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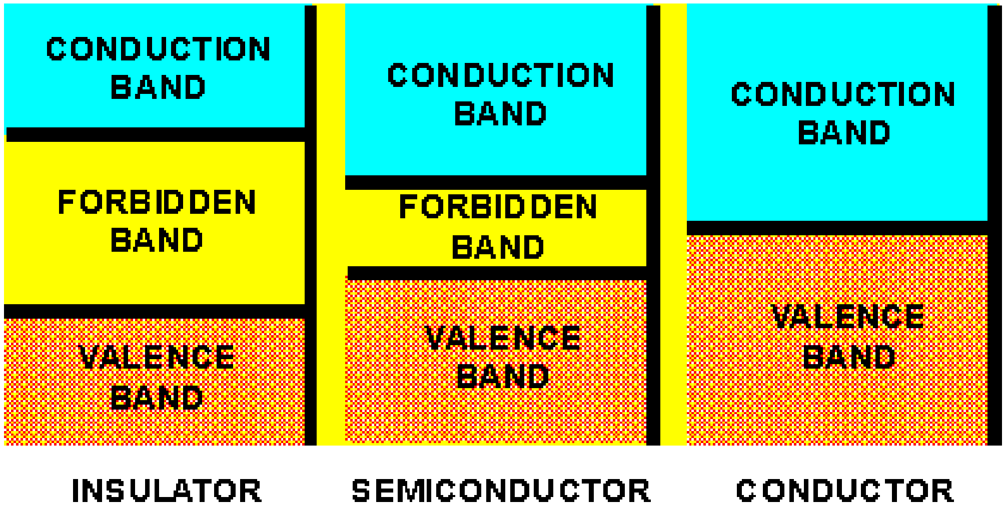
Semiconductors

- Semiconductors are those materials whose conductivity lies in between the conductivity of conductors and insulators.
- At 0K, semiconductors behave like a insulators.
- At room temperature the resistivity of semiconducting materials lies in the range of 10^{-3} to 10^{-8} ohm cm.
- The three most important semiconductors used in the construction of electronic devices are Si, Ge and GaAs.

Important properties of semiconductors (at RT)

	Si	Ge	GaAs
Electrons mobility ((m^2 / V / s))	0.14	0.39	0.85
Holes mobility (m^2 / V / s)	0.05	0.19	0.04
Bandgap (eV)	1.1	0.67	1.43
Intrinsic carrier (/cm^3)	1.5×10^{10}	2.5×10^{13}	1.7×10^{6}

Conductors, Insulators and Semiconductors



➢ In conductors valence band (VB) and conduction band (CB) overlap hence no bandgap.

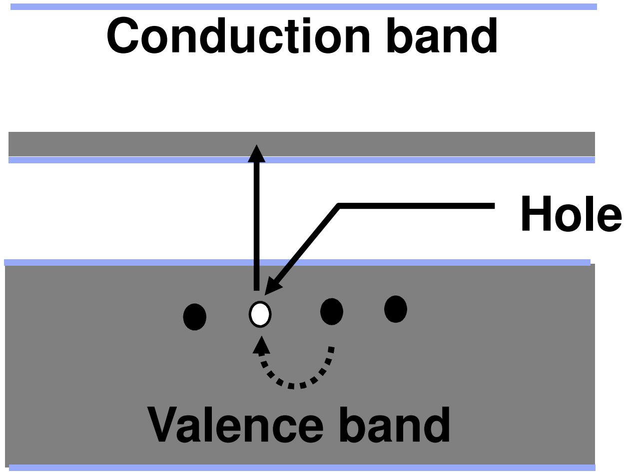
➢ In insulators there is large bandgap (typically 5 to 10eV) between VB and CB. In insulators VB is completely filled and CB is completely empty.

➢ In semiconductors bandgap between VB and CB is low.

➢The resistivity of semiconductors generally decrease with increasing temperature (resistivity of Si is -.07/^{o}C and that of Ge is -0.05/^{o}C) in contrast with that of metals which generally increases. (Why?)

Semiconductors

When an electron in the valence band of a semiconductor makes a transition to the conduction band, it leaves behind a vacant state known as a ‘hole’.
When a potential difference is applied across the semiconductor sample, the electrons in the conduction band result in a current flow.



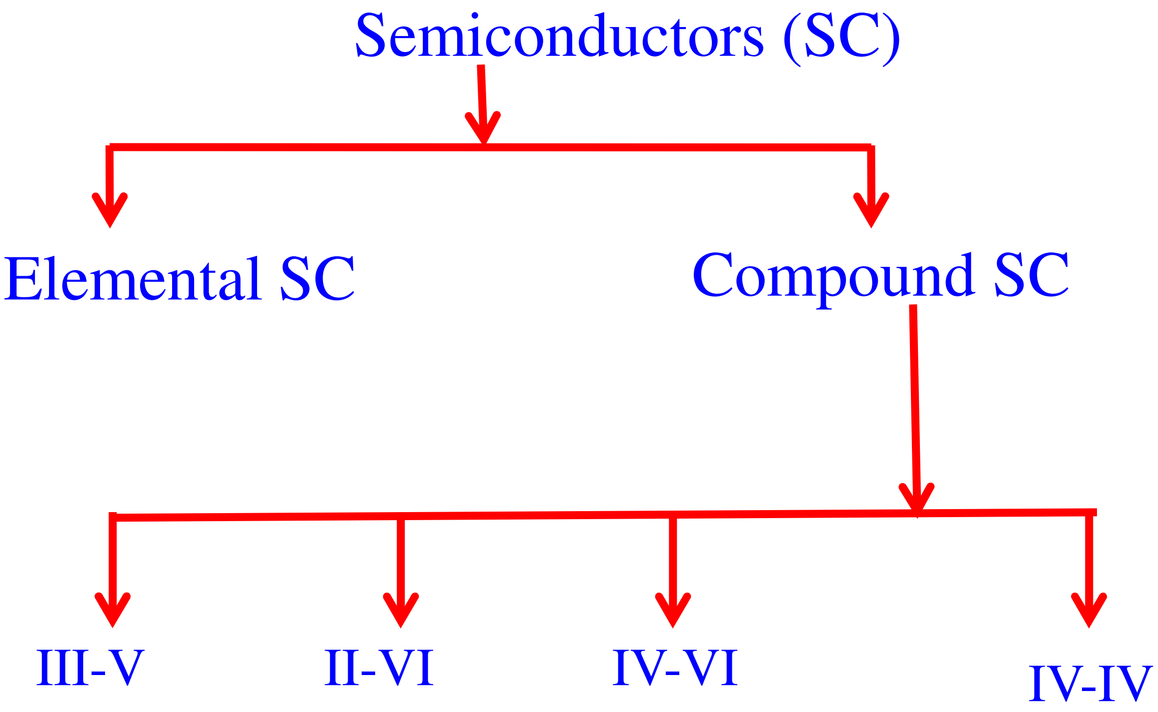
Conduction band

Hole

Valence band

- However the electrons in the valence band also contribute to the current by filling the empty states (or holes) left behind by electrons that have made transitions to the conduction band.

- Both electrons and holes contribute to conduction, and the resistivity decreases.



Semiconductors (SC)

Elemental SC

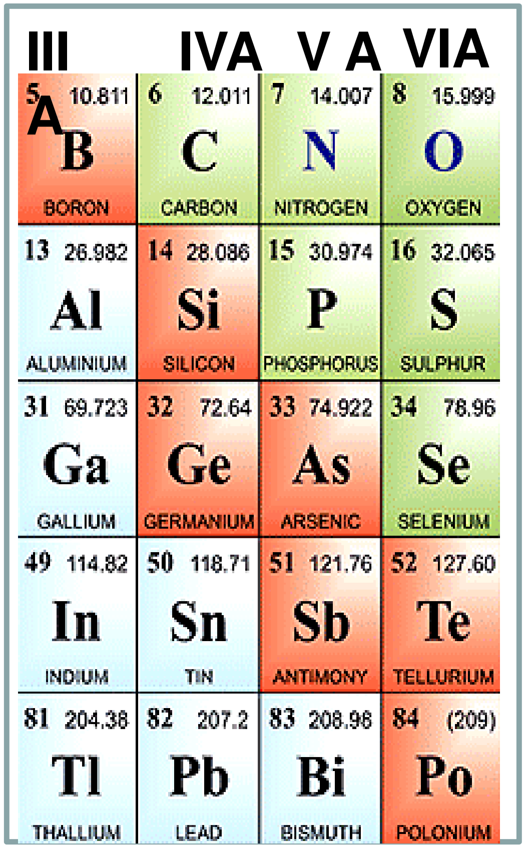
Compound SC

III-V

II-VI

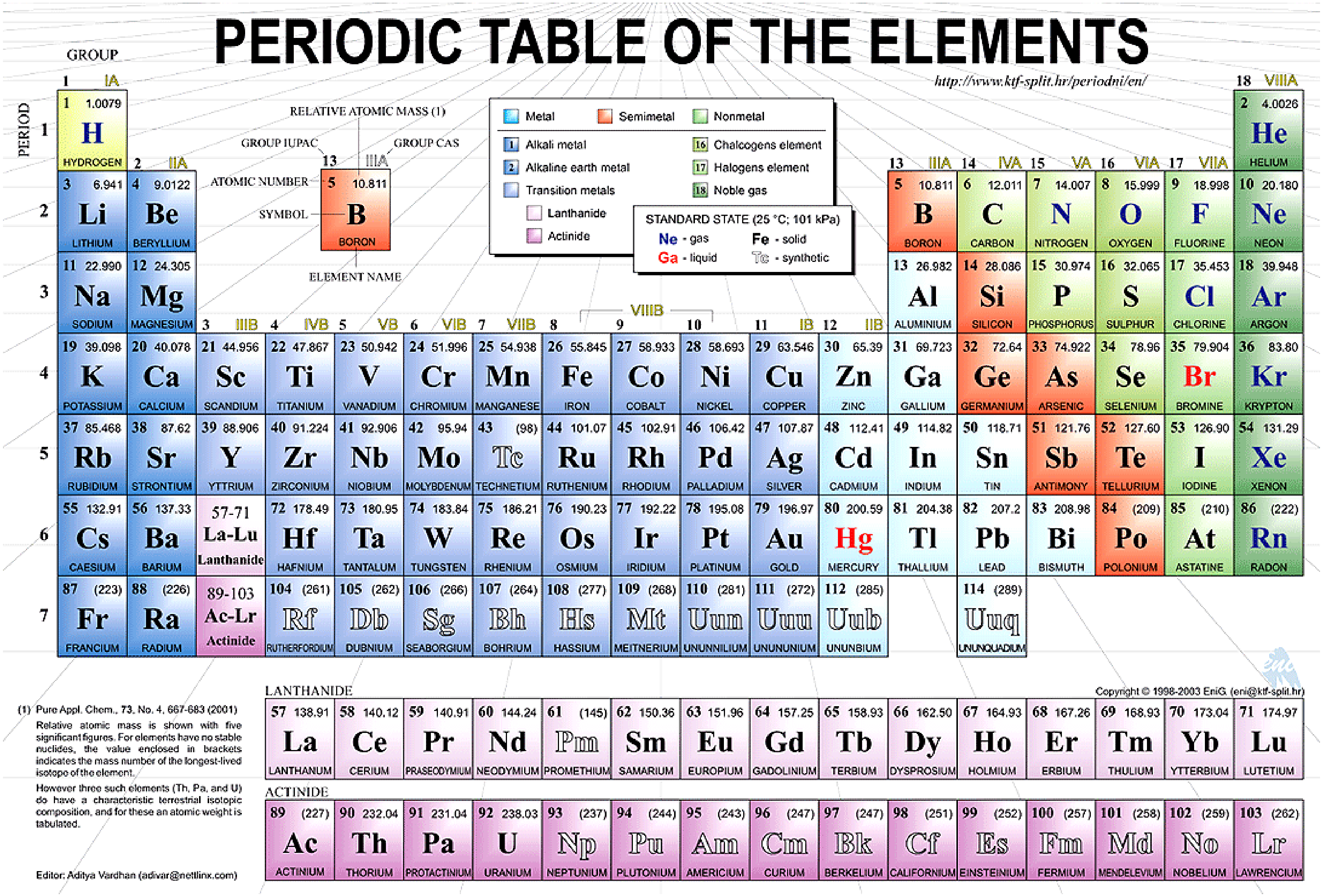
IV-VI

IV-IV



III A	IVA	V A	VIA
5 10.811 B BORON	6 12.011 C CARBON	7 14.007 N NITROGEN	8 15.999 O OXYGEN
13 26.982 Al ALUMINIUM	14 28.086 Si SILICON	15 30.974 P PHOSPHORUS	16 32.065 S SULPHUR
31 69.723 Ga GALLIUM	32 72.64 Ge GERMANIUM	33 74.922 As ARSENIC	34 78.96 Se SELENIUM
49 114.82 In INDIUM	50 118.71 Sn TIN	51 121.76 Sb ANTIMONY	52 127.60 Te TELLURIUM
81 204.38 Tl THALLIUM	82 207.2 Pb LEAD	83 208.98 Bi BISMUTH	84 (209) Po POLONIUM

- Compound SC may be binary, ternary or quatarnary SCs.
- III-V SCs - GaN (3.4eV), InN (0.7eV), AlN (6.2eV) , GaP, GaAs, InP, InAs, InSb
- II-VI SCs – ZnS(3.68eV), ZnSe, ZnTe, CdS(2.42eV) , CdSe, and CdTe
- IV –VI - PbS(0.41eV), PbSe (0.27eV), and PbTe (0.31eV) – Useful for infrared detectors and radiation sources



PERIODIC TABLE OF THE ELEMENTS

http://www.ktf-split.hr/periodni/en/

🟦 Metal 🟥 Semimetal 🟩 Nonmetal

1 Alkali metal

2 Alkaline earth metal

Transition metals

Lanthanide

Actinide

16 Chalcogens element

17 Halogens element

18 Noble gas

STANDARD STATE (25 °C; 101 kPa)

Ne - gas

Fe - solid

Ga - liquid

Tc - synthetic

PERIOD	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9	10	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	1 1.0079 H HYDROGEN																	2 4.0026 He HELIUM
2	3 6.941 Li LITHIUM	4 9.0122 Be BERYLLIUM											5 10.811 B BORON	6 12.011 C CARBON	7 14.007 N NITROGEN	8 15.999 O OXYGEN	9 18.998 F FLUORINE	10 20.180 Ne NEON
3	11 22.990 Na SODIUM	12 24.305 Mg MAGNESIUM											13 26.982 Al ALUMINIUM	14 28.086 Si SILICON	15 30.974 P PHOSPHORUS	16 32.065 S SULPHUR	17 35.453 Cl CHLORINE	18 39.948 Ar ARGON
4	19 39.098 K POTASSIUM	20 40.078 Ca CALCIUM	21 44.956 Sc SCANDIUM	22 47.867 Ti TITANIUM	23 50.942 V VANADIUM	24 51.996 Cr CHROMIUM	25 54.938 Mn MANGANESE	26 55.845 Fe IRON	27 58.933 Co COBALT	28 58.693 Ni NICKEL	29 63.546 Cu COPPER	30 65.39 Zn ZINC	31 69.723 Ga GALLIUM	32 72.64 Ge GERMANIUM	33 74.922 As ARSENIC	34 78.96 Se SELENIUM	35 79.904 Br BROMINE	36 83.80 Kr KRYPTON
5	37 85.468 Rb RUBIDIUM	38 87.62 Sr STRONTIUM	39 88.906 Y YTTRIUM	40 91.224 Zr ZIRCONIUM	41 92.906 Nb NIOBIUM	42 95.94 Mo MOLYBDENUM	43 (98) Tc TECHNETIUM	44 101.07 Ru RUTHENIUM	45 102.91 Rh RHODIUM	46 106.42 Pd PALLADIUM	47 107.87 Ag SILVER	48 112.41 Cd CADMIUM	49 114.82 In INDIUM	50 118.71 Sn TIN	51 121.76 Sb ANTIMONY	52 127.60 Te TELLURIUM	53 126.90 I IODINE	54 131.29 Xe XENON
6	55 132.91 Cs CAESIUM	56 137.33 Ba BARIUM	57-71 La-Lu Lanthanide	72 178.49 Hf HAFNIUM	73 180.95 Ta TANTALUM	74 183.84 W TUNGSTEN	75 186.21 Re RHENIUM	76 190.23 Os OSMIUM	77 192.22 Ir IRIDIUM	78 195.08 Pt PLATINUM	79 196.97 Au GOLD	80 200.59 Hg MERCURY	81 204.38 Tl THALLIUM	82 207.2 Pb LEAD	83 208.98 Bi BISMUTH	84 (209) Po POLONIUM	85 (210) At ASTATINE	86 (222) Rn RADON
7	87 (223) Fr FRANCIUM	88 (226) Ra RADIUM	89-103 Ac-Lr Actinide	104 (261) Rf RUTHERFORDIUM	105 (262) Db DUBNIUM	106 (266) Sg SEABORGIUM	107 (264) Bh BOHRIUM	108 (277) Hs HASSIUM	109 (268) Mt MEITNERIUM	110 (281) Uun UNUNNILIUM	111 (272) Uuu UNUNUNIUM	112 (285) Uub UNUNBIUM		114 (289) Uuq UNUNQUADIUM				

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LANTHANIDE

57 138.91 La LANTHANUM	58 140.12 Ce CERIUM	59 140.91 Pr PRASEODYMIUM	60 144.24 Nd NEODYMIUM	61 (145) Pm PROMETHIUM	62 150.36 Sm SAMARIUM	63 151.96 Eu EUROPIUM	64 157.25 Gd GADOLINIUM	65 158.93 Tb TERBIUM	66 162.50 Dy DYSPROSIUM	67 164.93 Ho HOLMIUM	68 167.26 Er ERBIUM	69 168.93 Tm THULIUM	70 173.04 Yb YTTERBIUM	71 174.97 Lu LUTETIUM

ACTINIDE

89 (227) Ac ACTINIUM	90 232.04 Th THORIUM	91 231.04 Pa PROTACTINIUM	92 238.03 U URANIUM	93 (237) Np NEPTUNIUM	94 (244) Pu PLUTONIUM	95 (243) Am AMERICIUM	96 (247) Cm CURIUM	97 (247) Bk BERKELIUM	98 (251) Cf CALIFORNIUM	99 (252) Es EINSTEINIUM	100 (257) Fm FERMIUM	101 (258) Md MENDELEVIUM	102 (259) No NOBELIUM	103 (262) Lr LAWRENCIUM

(1) Pure Appl. Chem., 73, No. 4, 667-683 (2001)
Relative atomic mass is shown with five significant figures. For elements have no stable nuclides, the value enclosed in brackets indicates the mass number of the longest-lived isotope of the element.

However three such elements (Th, Pa, and U) do have a characteristic terrestrial isotopic composition, and for these an atomic weight is tabulated.

Editor: Aditya Vardhan (adivar@nettlinx.com)

Additional Semiconductors: Wurzite III-V's and II-VI's□ Lead Salts (IV-VI's), Column IV□

Material	Semiconductor		Crystal Lattice		Energy Band	
System	Name	Symbol	Structure	Period(A)	Gap(eV)	Type
III-V	Aluminum Nitride	AlN	W	a = , c =	6.2	i
(nitrides)	Gallium Nitride	GaN	W	a = 3.189, c = 5.185	3.36	d
	Indium Nitride	InN	W	a = , c =	0.7	d
II-VI	Zinc Sulfide	ZnS	W	a = 3.82, c = 6.28	3.68	d
(wurtzite)	Cadmium Sulfide	CdS	W	a = 4.16, c = 6.756	2.42	d
IV-VI	Lead Sulfide	PbS	R	5.9362	0.41	d
	Lead Selenide	PbSe	R	6.128	0.27	d
	Lead Telluride	PbTe	R	6.4620	0.31	d
IV	Diamond	C	D	3.56683	5.47	i
	Silicon	Si□	D	5.43095	1.124	i
	Germanium	Ge□	D	5.64613	0.66	i
	Grey Tin	Sn□	D	6.48920	0.08	d
IV-IV	Silicon Carbide	SiC	W	a = 3.086, c = 15.117	2.996	i
	Silicon-Germanium	Si_xGe_{1-x}	Z	vary with x (i.e. an alloy)		i

Key: Z = zinc blende, W = wurtzite, R = rock salt; i = indirect gap, d = direct gap

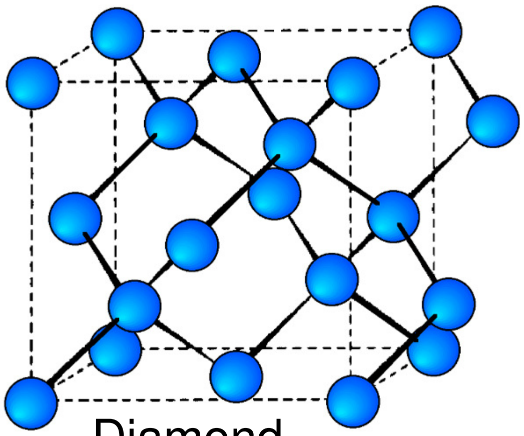
Taken from SMA-5111 – Prof. Fonstad

Crystal Structure of Si (IV elements)

The diamond cubic structure consists of two interpenetrating face-centered cubic lattices, with one offset $^{1}/_{4}$ of a cube along the cube diagonal.

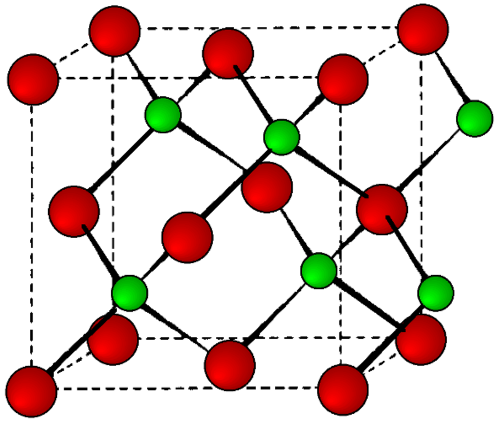
Each of the atoms (e.g., C) is four coordinate, and the shortest interatomic distance (C-C) may be determined from the unit cell parameter (*a*).

$C\text{-}C = a(3)^{0.5} \; / \; 4 \; = 0.422a$



Diamond

C, Si, Ge, Sn, ...



Zinc Blende

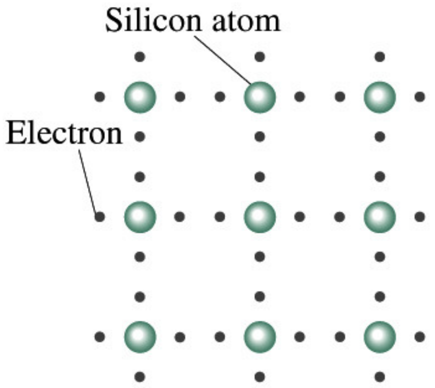
GaAs, InP,..etc...

Intrinsic semiconductors

- In pure state semiconductor is called intrinsic semiconductor.

- At room temperature a few electrons have sufficient energy to overcome the bandgap and contribute to the current.

- $n.p = n_i^2$ also valid for extrinsic SC



Intrinsic Si

Extrinsic semiconductors (doped intrinsic semiconductor)

- The incorporation of impurity elements (dopants) in an intrinsic semiconductor by a controlled way is called doping.

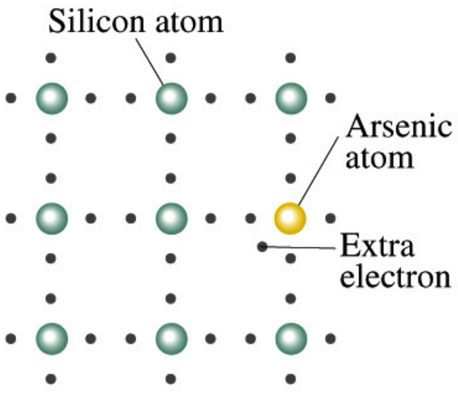
- The objective of doping is to increases the conductivity of a semiconductor.

- The main dopants are from column V (for n-type semiconductor) and Column III elements (for p-type semiconductor).

Extrinsic semiconductors (doped intrinsic semiconductor)

n-type semiconductor

- Silicon samples doped with a pentavalent atom such as arsenic is known as an n-type semiconductor because conduction is due to negative charges (electrons).
- Since each pentavalent atom essentially 'donates' an electron to the lattice, it is called a donor atom.

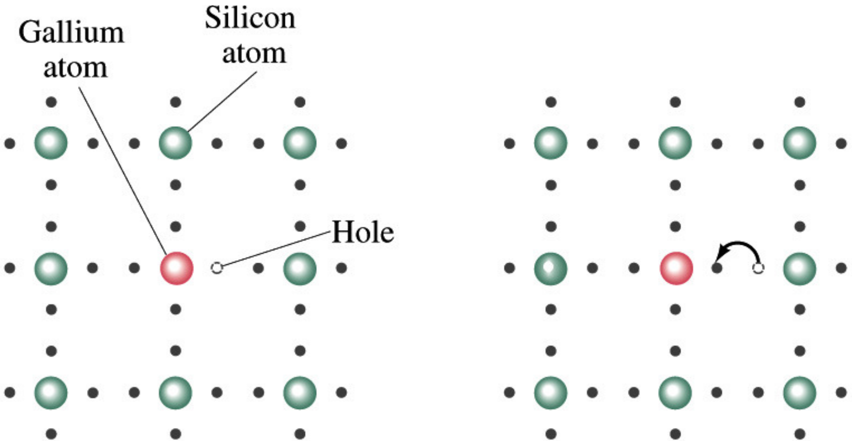


n-type Si

p-type semiconductor

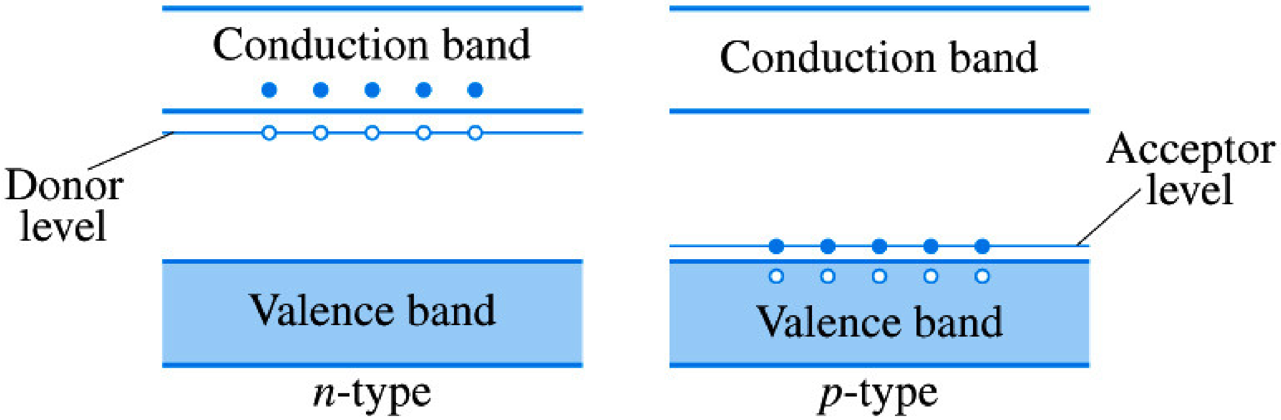
- Silicon samples doped with trivalent atoms such as gallium are known as p-type semiconductors because conduction is due to positive holes.

➢ Note that both n-type and p-type semiconductors are electrically neutral.



p-type Si

n and p-type Semiconductors



- In n-type semiconductors the ‘impurity’ energy level lies very close to the conduction band. Electrons are readily promoted to the conduction band from the ‘impurity‘ level which is, therefore, known as the donor level. Majority carriers concentration **$n = N_d$** and minority carriers $p = n_i^2 / n$
- In p-type semiconductors the ‘impurity’ level lies just above the valence band. Electrons are readily accepted from the valence band leaving holes behind. The ‘impurity’ levels are therefore known as acceptor levels. Majority carriers concentration **$p = N_a$** and minority carriers $n = n_i^2 / p$

Main dopants and their ionization energies

Ionization energies for dopants in Si & Ge (eV)			
Type	Element	Si	Ge
n-type	P	0.044	0.012
	As	0.049	0.013
	Sb	0.039	0.010
p-type	B	0.045	0.010
	Al	0.057	0.010
	Ga	0.065	0.011
	In	0.16	0.011