Lecture 02
Semiconductor Physics

Prepared By

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ILOS

- **In this section, we will learn:**
  - The basic properties of semiconductors and, in particular, silicone – the material used to make most modern electronic circuits.
  - How doping a pure silicon crystal dramatically changes electrical conductivity – the fundamental idea in underlying the use of semiconductors in the implementation of electronic devices.
  - The two mechanisms by which current flows in semiconductors – drift and diffusion charge carriers.
  - The structure and operation of the *pn* junction – a basic semiconductor structure that implements the diode and plays a dominant role in semiconductors.

Agenda

- ❑ Introduction
- ❑ Intrinsic Semiconductors
- ❑ Extrinsic (Doped) Semiconductors
- ❑ Current Flow in Semiconductors
- ❑ The pn Junction with Open-Circuit Terminals (Equilibrium)
- ❑ The pn Junction with Applied Voltage
- ❑ Capacitive Effects in the pn Junction

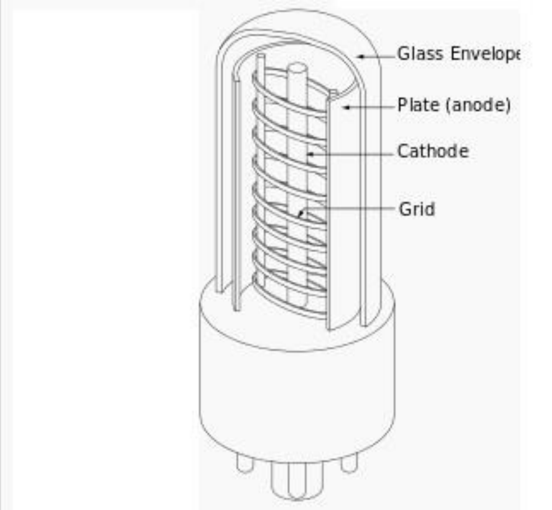
Solid state electronic devices

Solid-state electronics are those circuits or devices built entirely from solid materials and in which the electrons, or other charge carriers, are confined entirely within the solid material.

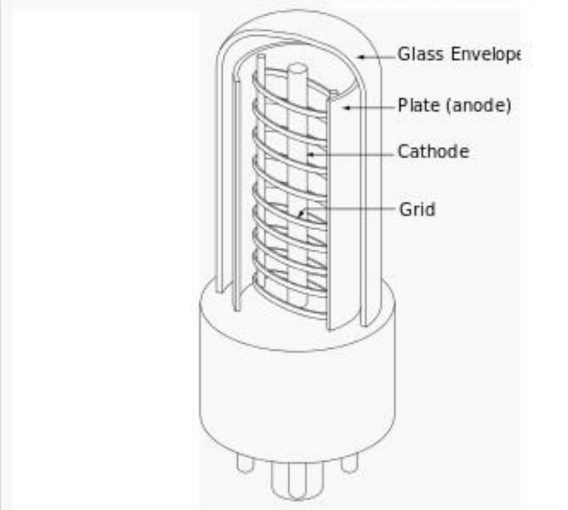
The term is often used to contrast with the earlier technologies of vacuum and gas-discharge tube devices, and it is also conventional to exclude electro-mechanical devices (relays, switches, hard drives and other devices with moving parts) from the term solid state.

Earlier Technologies

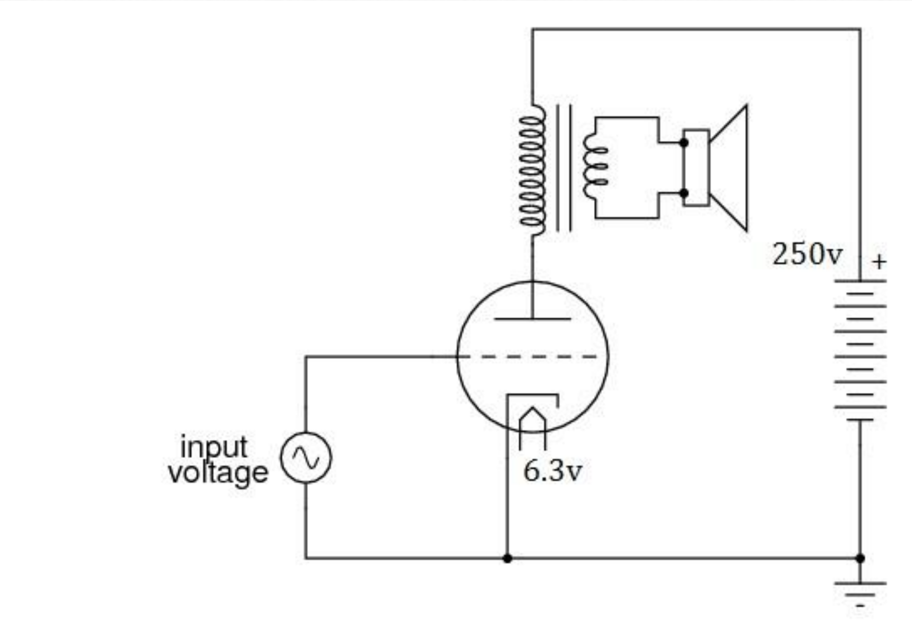
Vacuum Tubes

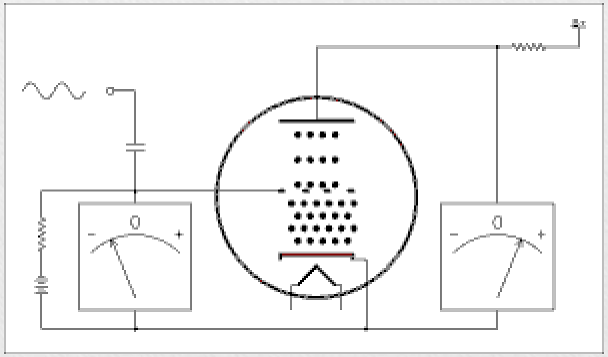


Earlier Technologies



Vacuum Tubes





First - BJTs

The transistor was probably the most important invention of the 20th Century, and the story behind the invention is one of clashing egos and top secret research.

Reference:

Bell Labs Museum

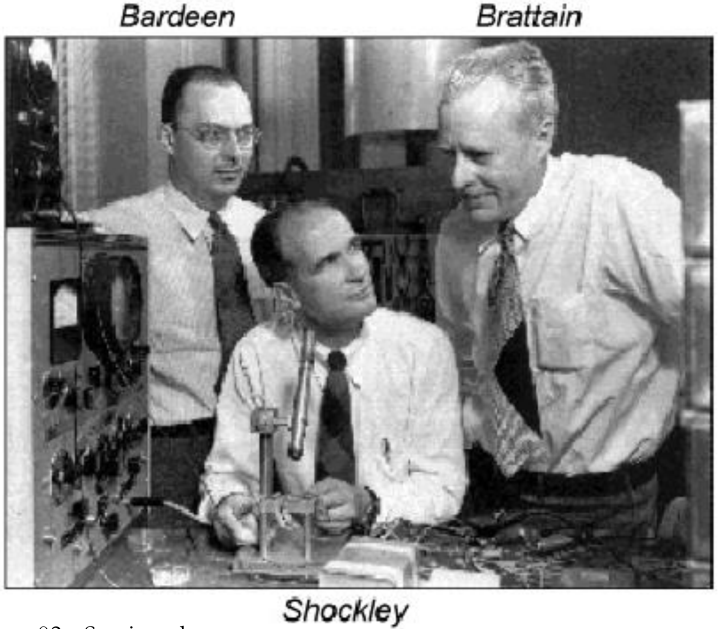
B. G. Streetman & S. Banerjee 'Solid State Electronic Devices', Prentice Hall 1999.

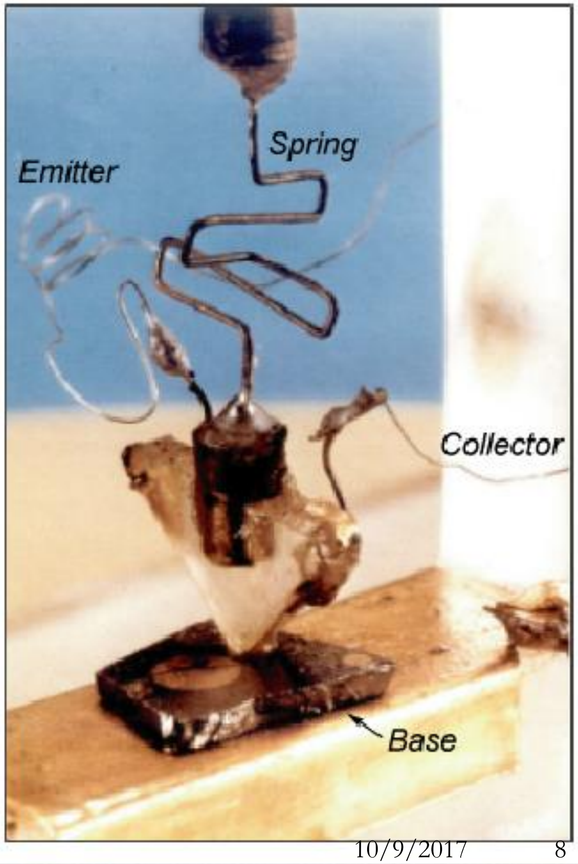
Point-Contact Transistor – first transistor ever made

The first transistor was a point-contact transistor

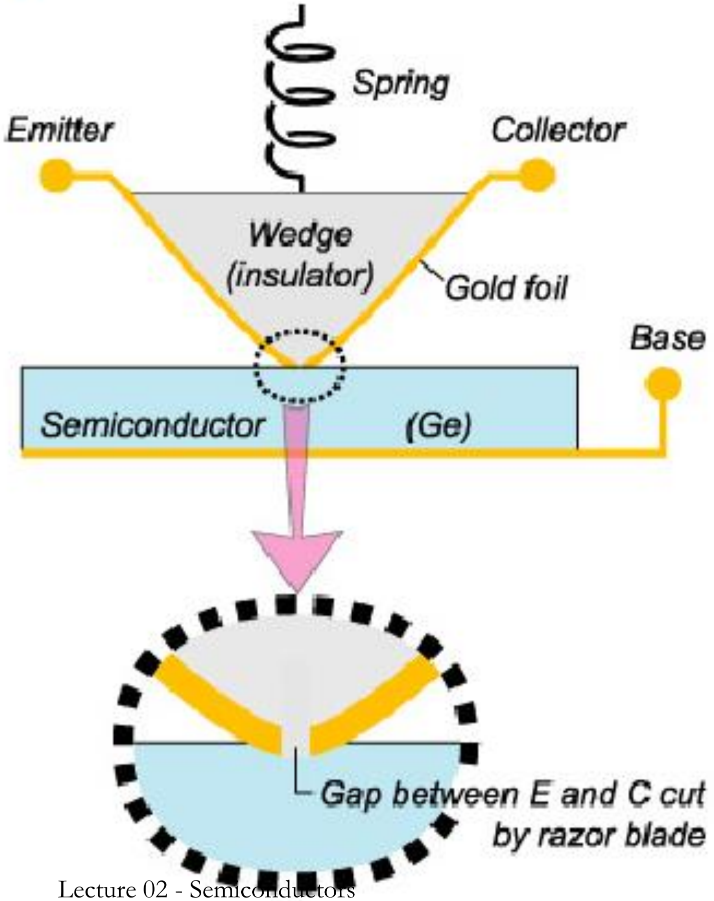
The first point-contact transistor

John Bardeen, Walter Brattain, and William Shockley
Bell Laboratories, Murray Hill, New Jersey (1947)

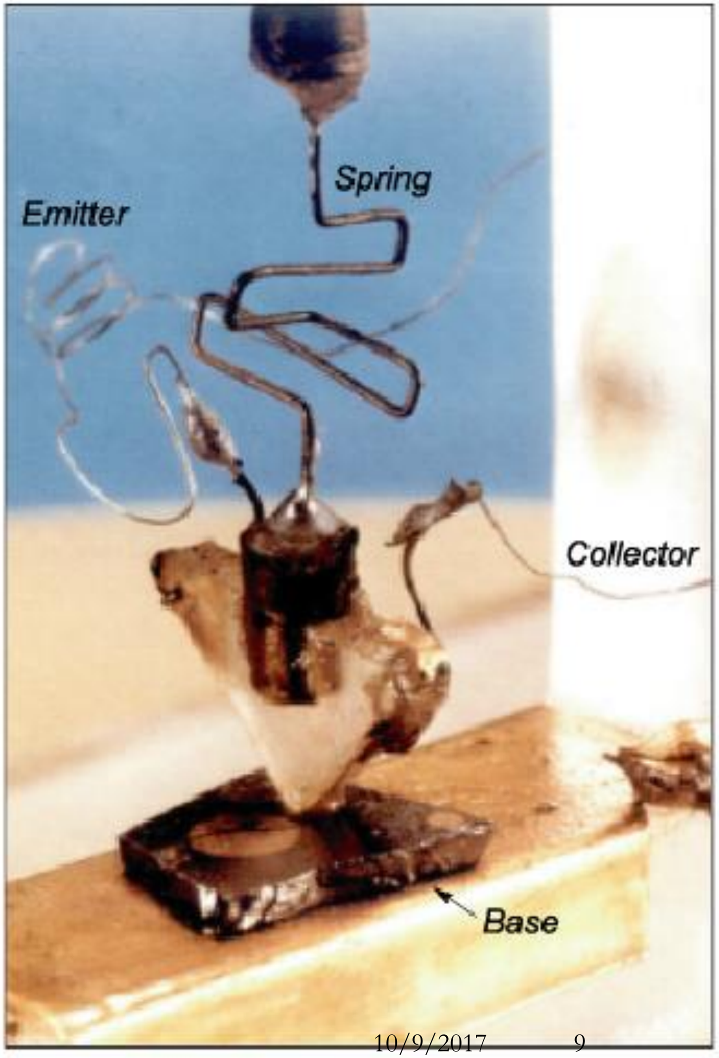




How did first point-contact transistor work?



Schematic of the first point-contact transistor



Qualitative basic operation of point-contact transistor

A gold foil was glued to a triangular insulating wedge.

A narrow gap was cut with a razor blade to form the E and C.

The gap was approximately 50 μm wide.

Under forward bias of the EB junction, minority carriers are injected into base (In case of point-contact transistor, strong forward bias is required).

Most minority carriers are collected by the reverse-biased BC junction.

Thus the base controls the current flow between E and C.

Problems with first transistor…

The point-contact transistor is a surface-effect device, *i. e.* important effects occur at the semiconductor surface.

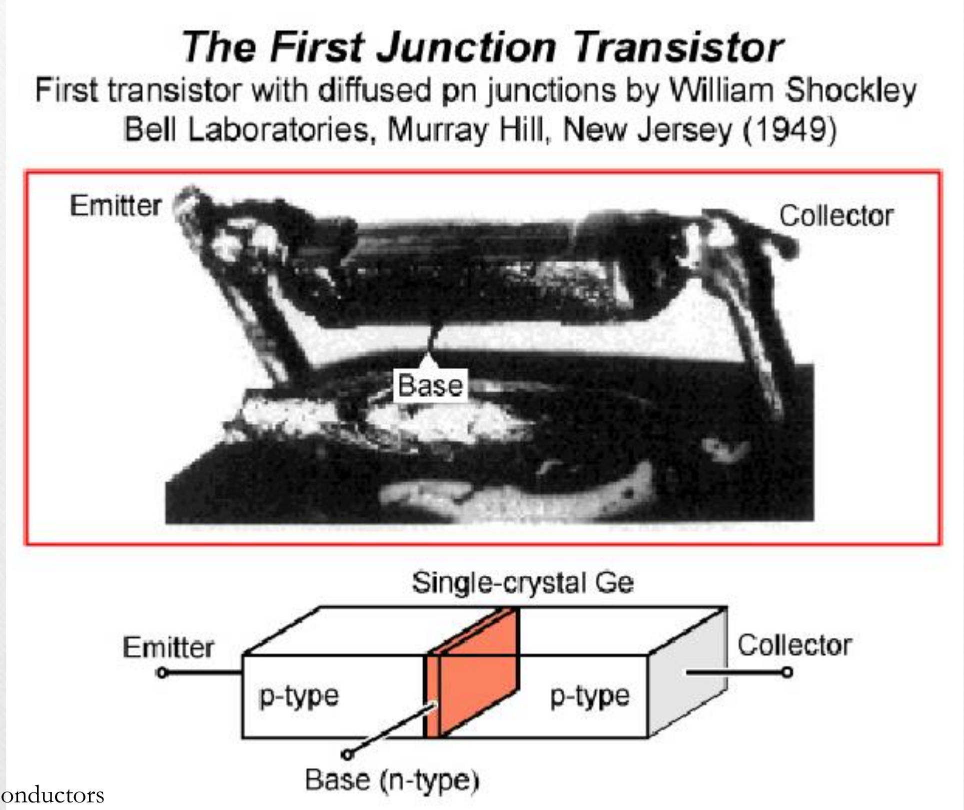
Surfaces are easily contaminated.

Surface-effect devices are unstable (*e. g.* mechanical vibrations).

First Bipolar Junction Transistors

W. Shockley invented the p-n junction transistor

The physically relevant region is moved to the bulk of the material



The First Junction Transistor

First transistor with diffused pn junctions by William Shockley

Bell Laboratories, Murray Hill, New Jersey (1949)

Why semiconductors?

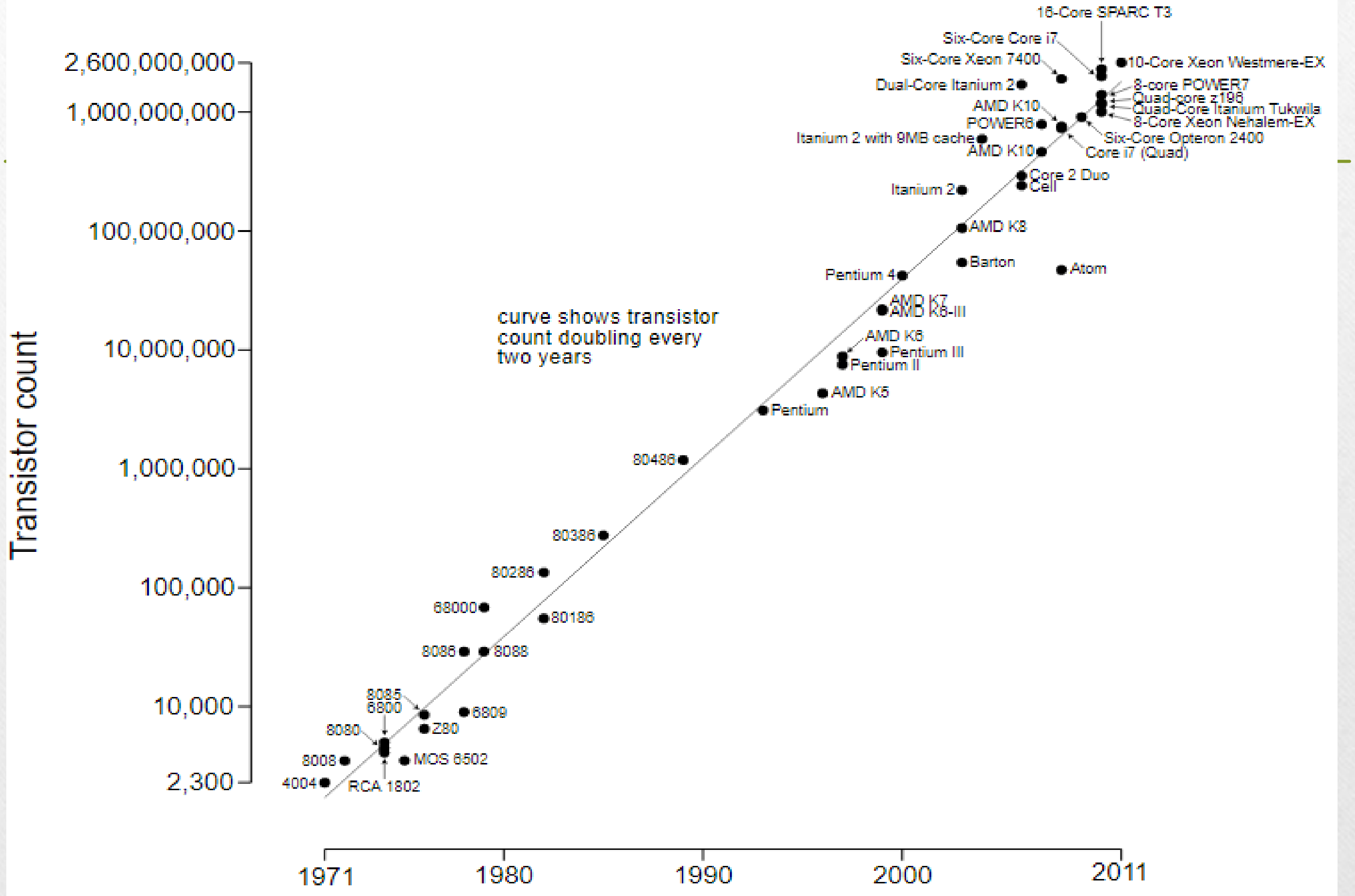
SEMICONDUCTORS: They are here, there, everywhere and in anything "intelligent"

Computers, laptops	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 (LEDs)
Satellite dishes	InGaAs MMICs (Monolithic Microwave ICs)
Fiber networks	InGaAsP laser diodes, pin photodiodes
Traffic signals, car taillights	GaN LEDs (**green**, **blue**)
	InGaAsP LEDs (**red**, **amber**)
Air bags	Si MEMs, Si ICs

Why semiconductors?

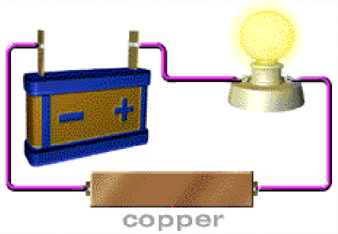
Semiconductor devices are **WIDELY** used

Why semiconductors?

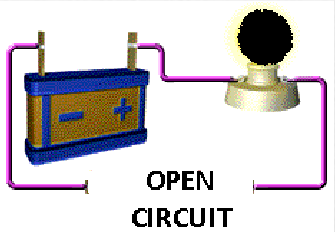


Solid Materials

- **Conductors:** Allow Electric current to flow through them



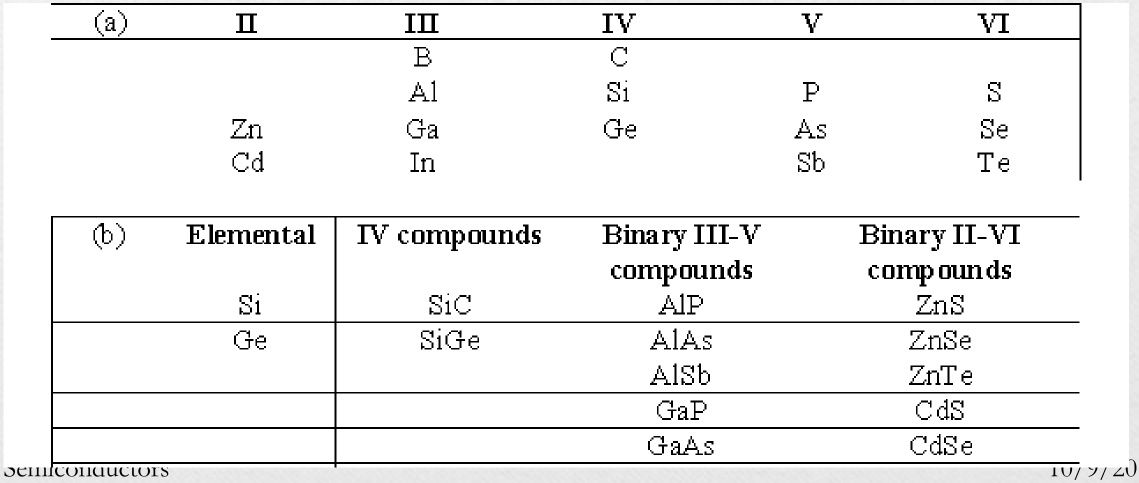
- **Insulators:** Do not Allow Electric current to flow through them



- **Semiconductors:** Materials whose conductivity lies in between that of Conductors (copper) and insulators (glass). They have conductivities in the range of 10^{-4} to 10^{+4} S/m.

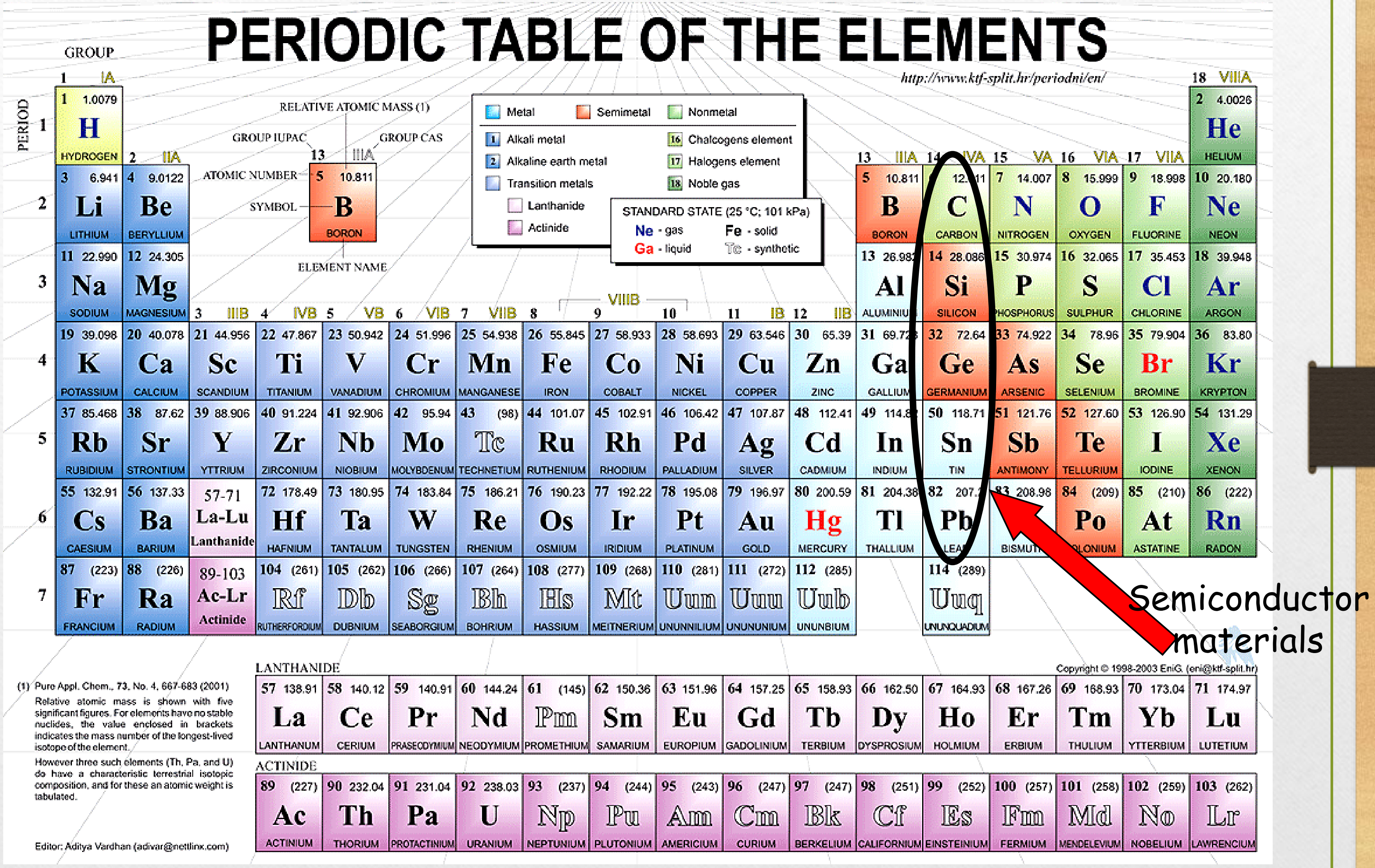
Semiconductors

- **single-element** – such as germanium and silicon. (column IV of periodic table) –compose of single species of atoms
- **compound** – such as gallium-arsenide. – combinations of atoms of column III and column V and some atoms from column II and VI. (combination of two atoms results in binary compounds).



(a)	II	III	IV	V	VI
		B	C		
		Al	Si	P	S
	Zn	Ga	Ge	As	Se
	Cd	In		Sb	Te

(b)	Elemental	IV compounds	Binary III-V compounds	Binary II-VI compounds
	Si	SiC	AlP	ZnS
	Ge	SiGe	AlAs	ZnSe
			AlSb	ZnTe
			GaP	CdS
			GaAs	CdSe



PERIODIC TABLE OF THE ELEMENTS

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

GROUP / PERIOD

PERIOD	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8	9 VIIIB	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	12. 11 **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 26.98 **Al** ALUMINIU	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 69.72 **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	49 114.8 **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. **Pb** LEA	3 208.98 BISMUT	84 (209) **Po** LONIUM	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				

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

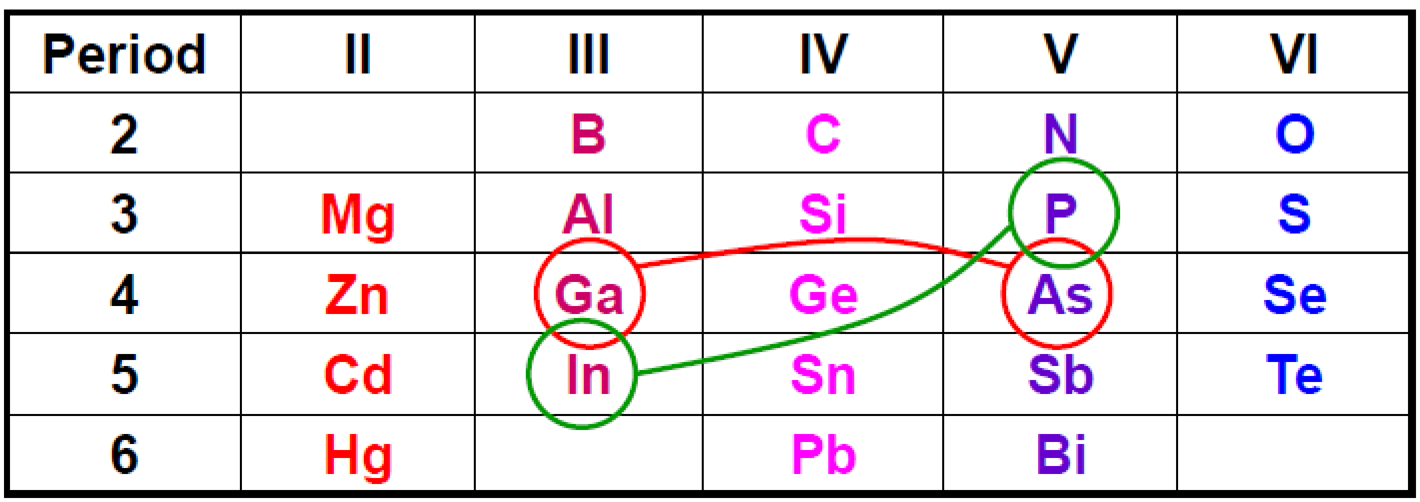
- 🟦 Metal
- 🟥 Semimetal
- 🟩 Nonmetal
- 1 Alkali metal
- 2 Alkaline earth metal
- Transition metals
- Lanthanide
- Actinide
- 16 Chalcogens element
- 17 Halogens element
- 18 Noble gas

STANDARD STATE (25 °C; 101 kPa)
Ne - gas
Fe - solid
Ga - liquid
Tc - synthetic

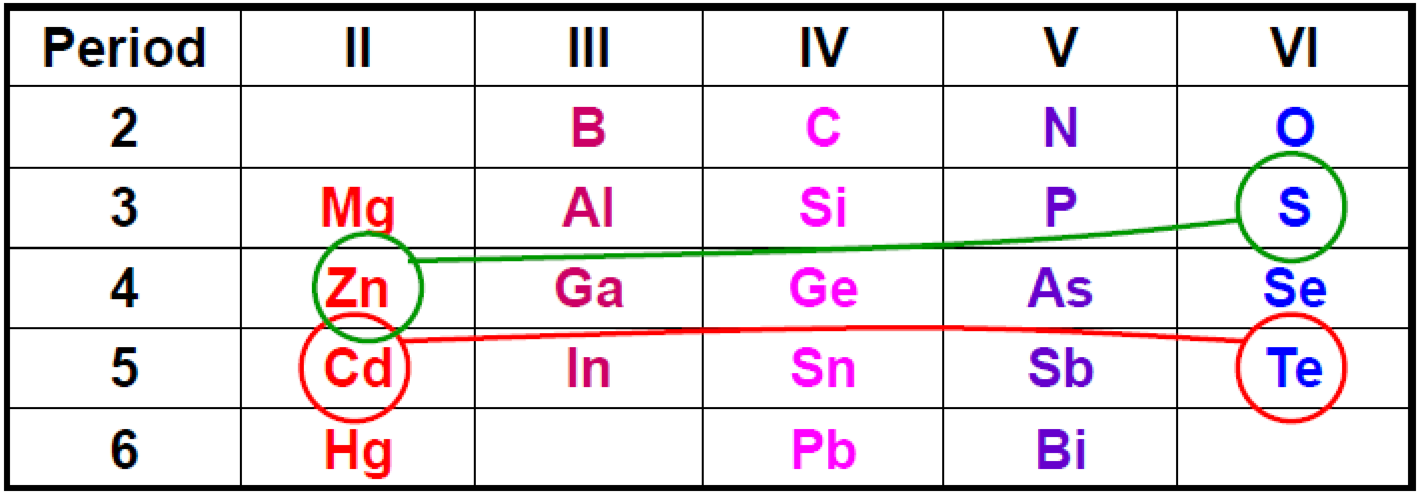
(1) Pure Appl. Chem., 73, No. 4, 667-683 (2001)
Relative atomic mass is shown with five significant figures. For elements have no stable nuclides, the value enclosed in brackets indicates the mass number of the longest-lived isotope of the element.
However three such elements (Th, Pa, and U) do have a characteristic terrestrial isotopic composition, and for these an atomic weight is tabulated.

Editor: Aditya Vardhan (adivar@netlinx.com)

Semiconductor materials



Period	II	III	IV	V	VI
2		B	C	N	O
3	Mg	Al	Si	P	S
4	Zn	Ga	Ge	As	Se
5	Cd	In	Sn	Sb	Te
6	Hg		Pb	Bi	



Period	II	III	IV	V	VI
2		B	C	N	O
3	Mg	Al	Si	P	S
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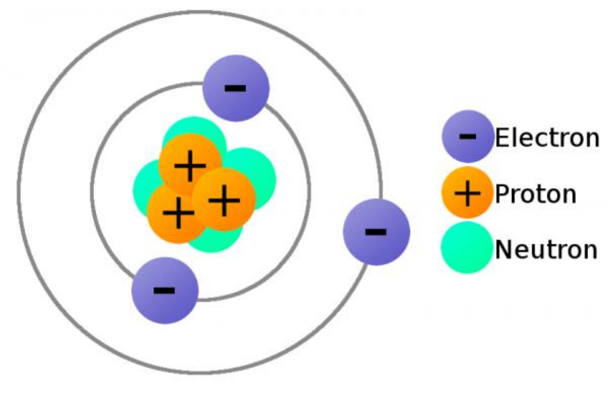
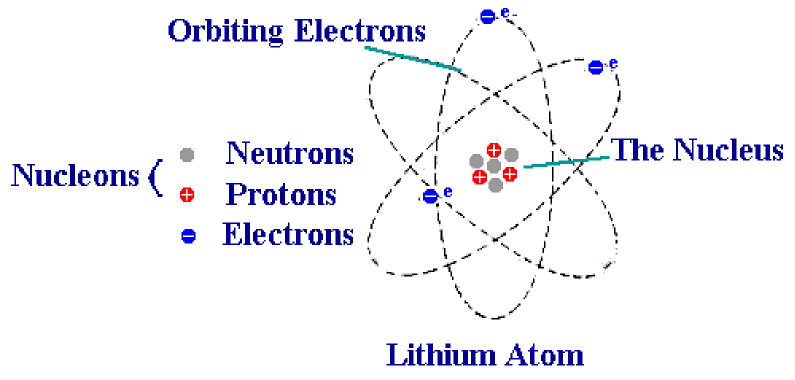
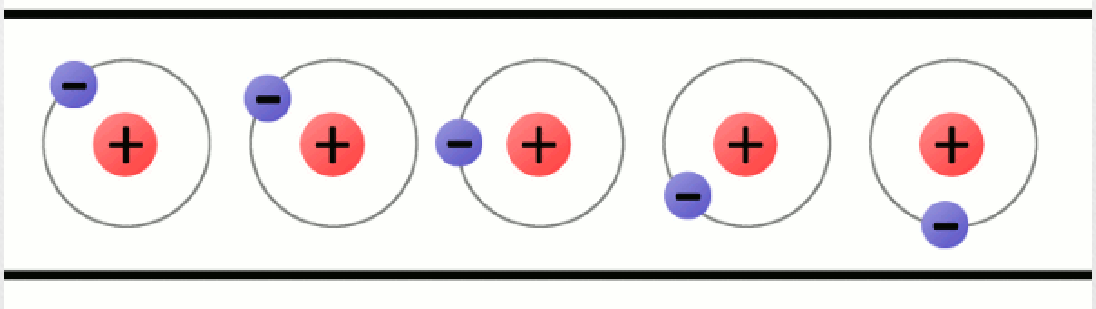
Atomic Structure



A lithium atom



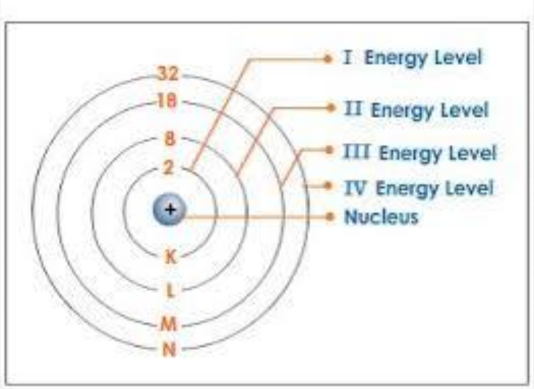


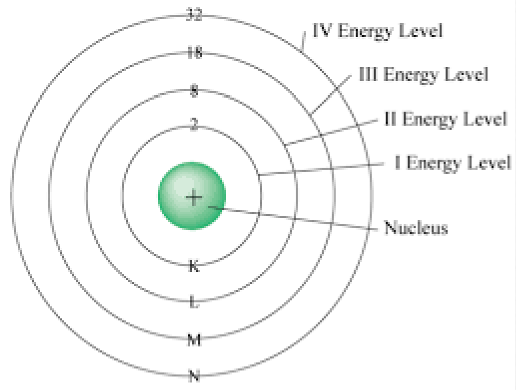
Electric Current Flow in conductors

Atomic Structure

Electron shells and sub-shells

shell n	K 1	L 2		M 3			N 4			
sub-shell l	s 0	s 0	p 1	s 0	p 1	d 2	s 0	p 1	d 2	f 3
electron number	2	2	6	2	6	10	2	6	10	14
	2	8		18			32			





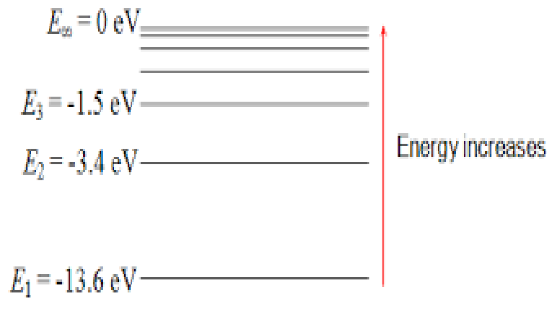


Figure 2 Energy Levels of an Atom

The octet rule

Atoms are most stable if they have a filled or empty outer layer of electrons.

Except for H and He, a filled layer contains 8 electrons – an octet

Atoms will

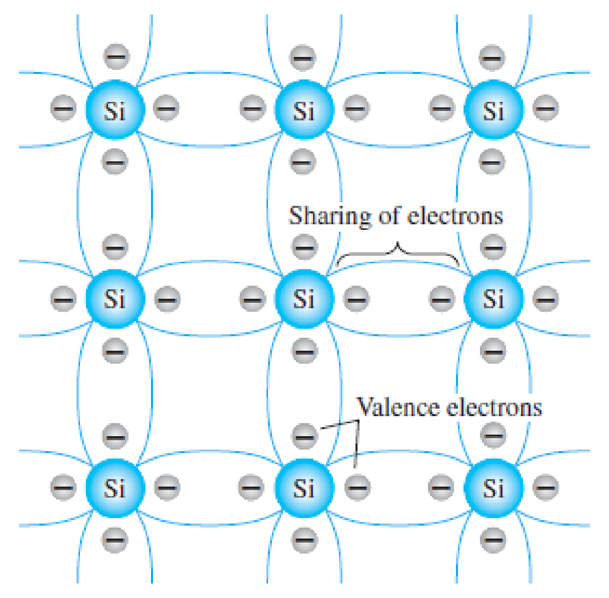
gain or lose	(ionic compounds)
share	(covalent compounds)

Electrons to make a filler or empty outer layer.

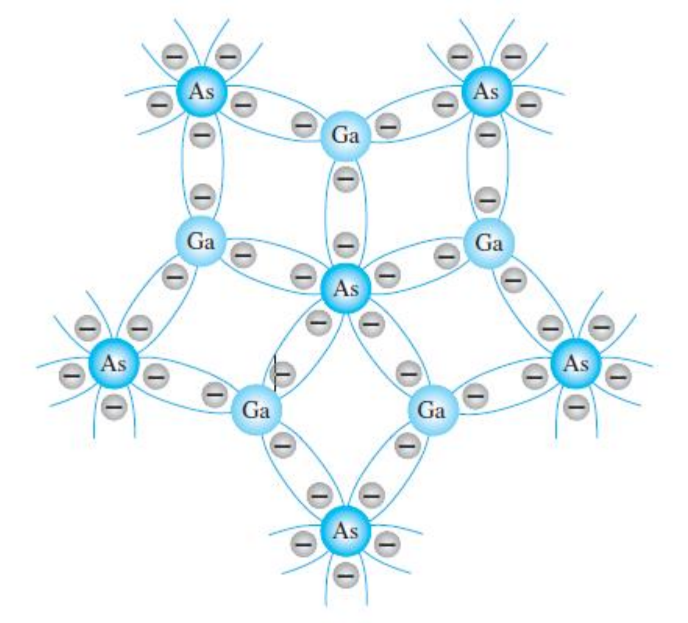
Atomic Structure

- **valence electron** – is an electron that participates in the formation of chemical bonds. It can exist only in the outermost electron shell.
  - Atoms with one or two valence electrons more than are needed for a "closed" shell are highly reactive because the extra electrons are easily removed to form positive ions.
- **covalent bond** – is a form of chemical bond in which two atoms share a pair of atoms.

Covalent Bonding And Intrinsic Materials



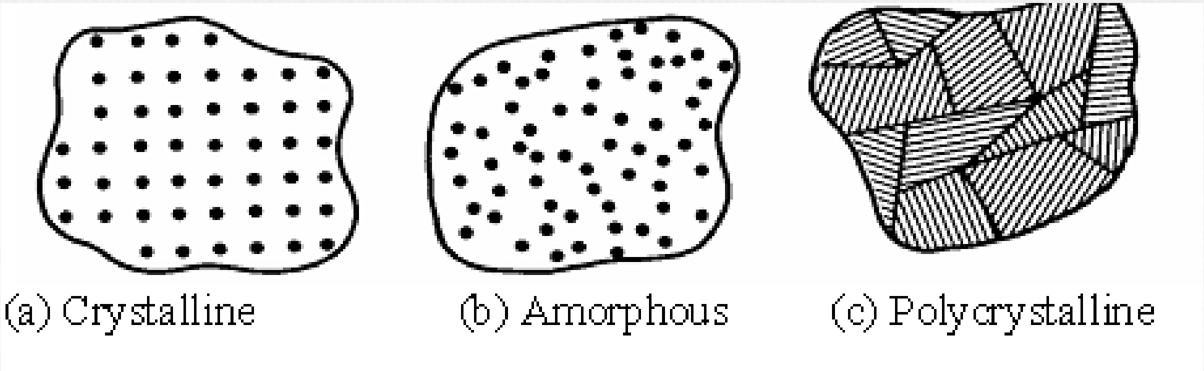
Covalent bonding of the silicon atom.



Covalent bonding of the GaAs crystal.

Solid state structures

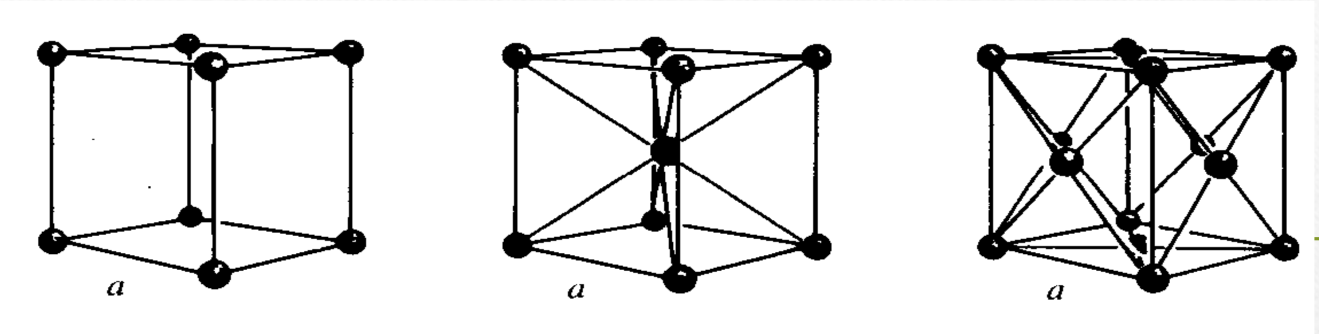
A crystalline solid is distinguished by the fact that atoms making the crystal are arranged in a periodic fashion. That is, there is some basic arrangement of atoms that is repeated throughout the entire solid. Thus the crystal appears exactly the same at one point as it does at a series of other equivalent points, once the basic periodicity is discovered. However, not all solids are crystals; some have no periodic structure at all (*amorphous* solids), and other are composed of many small regions of single-crystal material (*polycrystalline* solids).



The periodic arrangement of atoms in crystal is called the *lattice;* the lattice contains a volume, called a *unit cell*, which is representative of the entire lattice and is regularly repeated throughout the crystal.

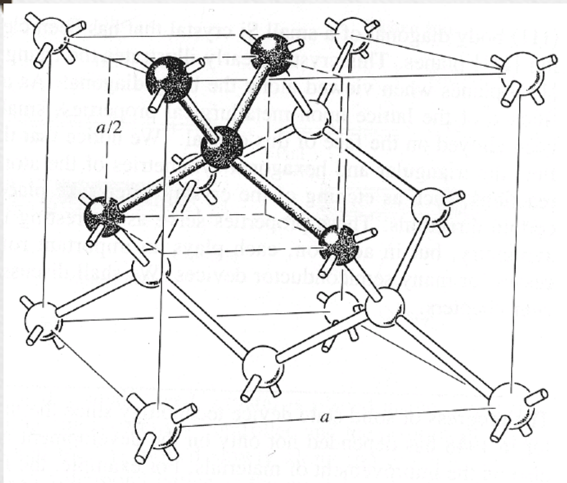
Solid state structures

- **Cubic lattices:** Unit cells for types of cubic lattice structure.



Simple cubic (sc) Body-centered cubic (bcc) Face-centered cubic (fcc)

Diamond lattice unit cell, showing the four nearest neighbour structure

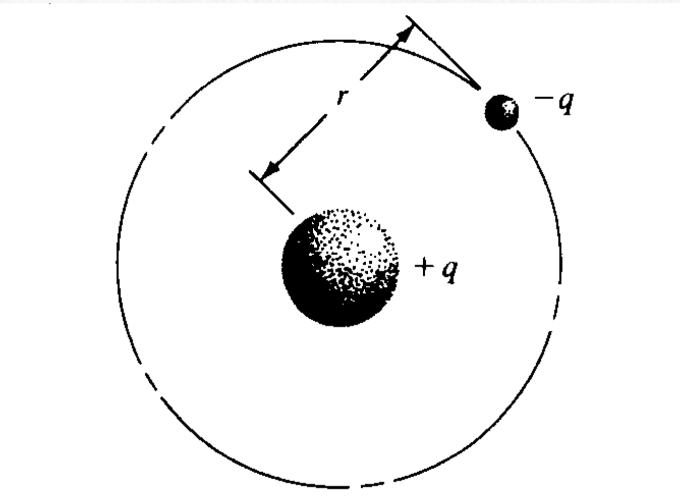


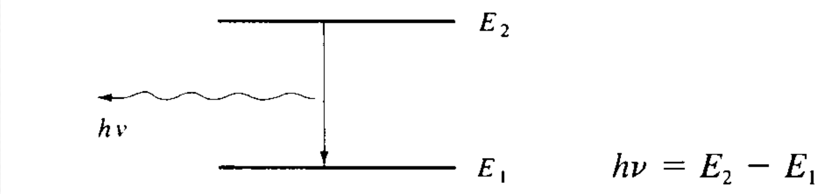
The basic lattice structure for many important semiconductors is the diamond lattice, which is characteristic of Si and Ge. In many compound semiconductors, atoms are arranged in a basic diamond structure but are different on alternating sites. This is called a *zincblende* lattice and is typical of the III-V compounds. The diamond lattice can be thought of as an *fcc* structure with an extra atom placed at **a**/4+**b**/4+**c**/4 from each of the *fcc* atoms.

The Bohr model

To develop the atom model, Bohr made several postulates:

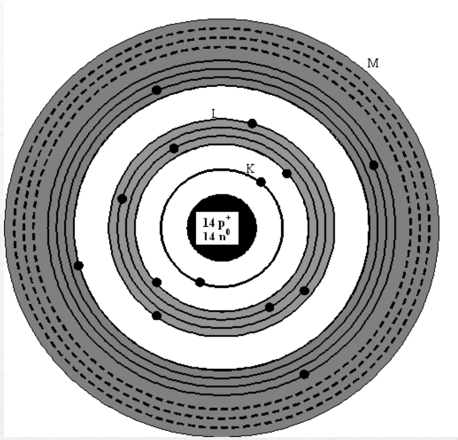
1. Electrons exist in certain stable, circular orbits about the nucleus.
2. The electron may shift to an orbit of higher or lower energy, thereby gaining or losing energy equal to the difference in the energy levels (by absorption or emission of a photon of energy *hv*).





The Silicon Atom

Finally, the work of Bohr, Boltzmann, Plank, Einstein and others has developed an understanding of the atomic structure which shows that electrons circle the nucleus in orbits having different associated energies. The electrons also spin on their own axes. The energy of electrons is quantised in that only certain discrete levels of energy can be possessed by electrons and no values in between these discrete levels are allowed. The levels exist in groups which are referred to as shells and there are sub-shells (l) within main shells (n).

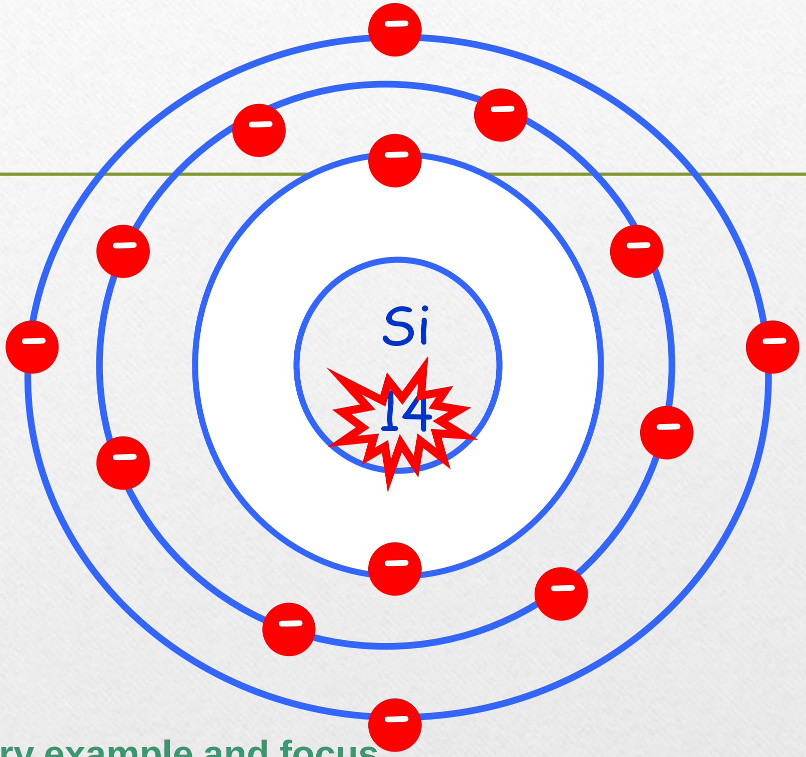


Silicon, Si, is a group IV material having an atomic number of 14. Consequently it has 14 positively charged protons and 14 neutrons in its nucleus. It has 14 orbiting negatively charged electrons: 2 in a full K shell; 8 in a full L shell and 4 in a half-full M sub-shell. With a half full outer sub-shell the atom has an affinity for 4 additional electrons to try to complete the outer sub-shell.

The Pauli’s Exclusion Principle

states that no two electrons in an atom or molecule can share the exact same quantum specification. In practice, this means that no more than two electrons can share precisely the same orbit or energy level and the two must have opposite spins.

The Silicon Atomic Structure



Silicon: our primary example and focus

Atomic no. 14

14 electrons in three shells: 2) 8) 4

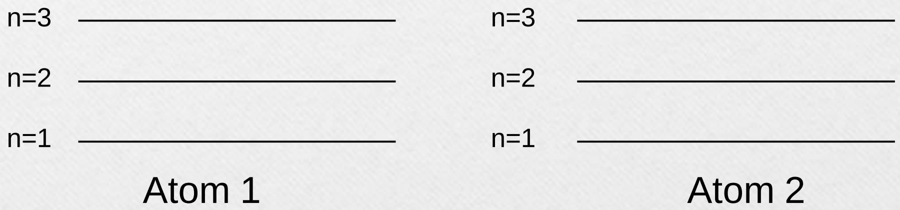
i.e., 4 electrons in the outer "bonding" shell

Silicon forms strong covalent bonds with 4 neighbors

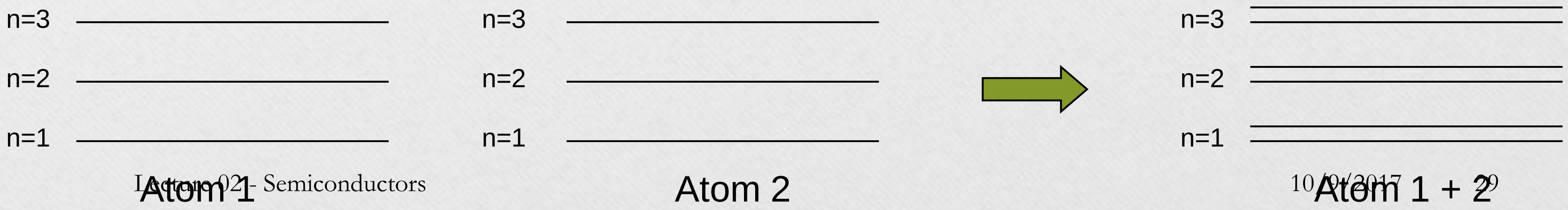
However, like all other elements it would prefer to have 8 electrons in its outer shell

Band theory of a solid

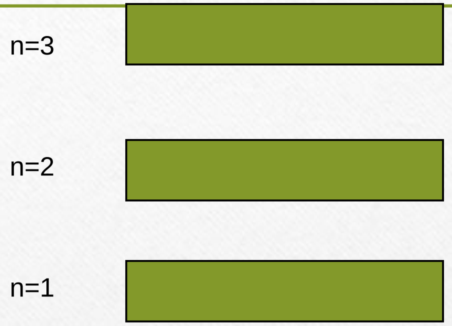
- A solid is formed by bringing together isolated single atoms.
- Consider the combination of two atoms. If the atoms are far apart there is no interaction between them and the energy levels are the same for each atom. The numbers of levels at a particular energy is simply doubled



- If the atoms are close together the electron wave functions will overlap and the energy levels are shifted with respect to each other.

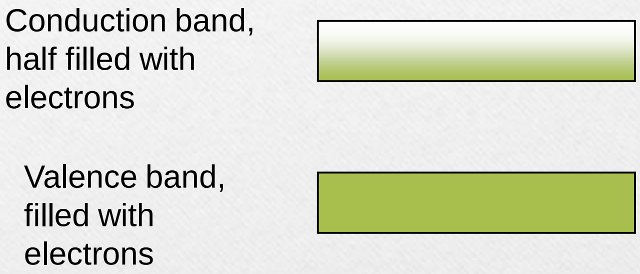


- A solid will have millions of atoms close together in a lattice so these energy levels will creates bands each separated by a gap.



- Conductors:

  If we have used up all the electrons available and a band is still only half filled, the solid is said to be a good conductor. The half filled band is known as the conduction band.

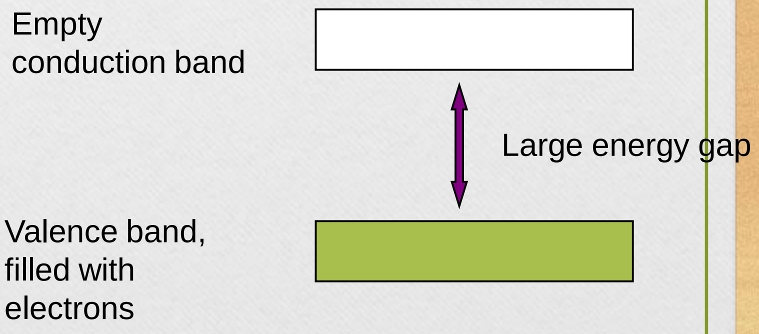


Conduction band, half filled with electrons

Valence band, filled with electrons

- Insulators:

  If, when we have used up all the electrons the highest band is full and the next one is empty with a large gap between the two bands, the material is said to be a good insulator. The highest filled band is known as the valence band while the empty next band is known as the conduction band.



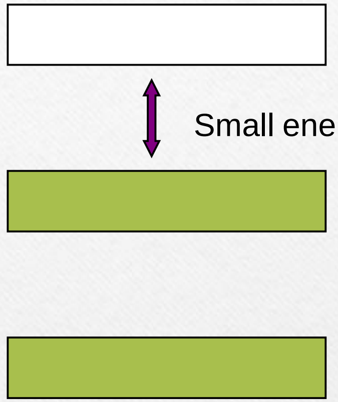
Empty conduction band

Large energy gap

Valence band, filled with electrons

Semiconductors:

- Some materials have a filled valence band just like insulators but a <u>small</u> gap to the conduction band.
- At zero Kelvin the material behave just like an insulator but at room temperature, it is possible for some electrons to acquire the energy to jump up to the conduction band. The electrons move easily through this conduction band under the application of an electric field. This is an intrinsic semiconductor.

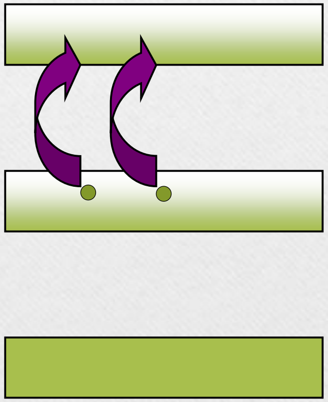


Empty conduction band

Small energy gap

Valence bands, filled with electrons

At zero Kelvin – no conduction



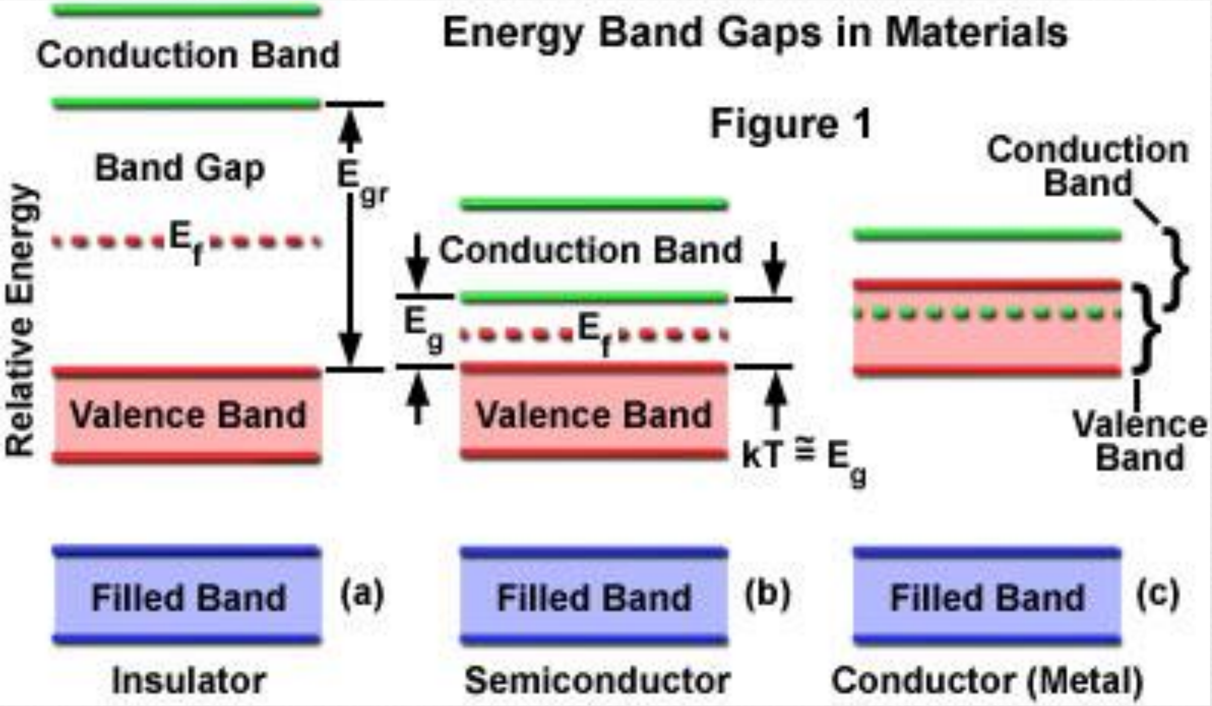
Conduction band, with some electrons

Top valence band now missing some electrons

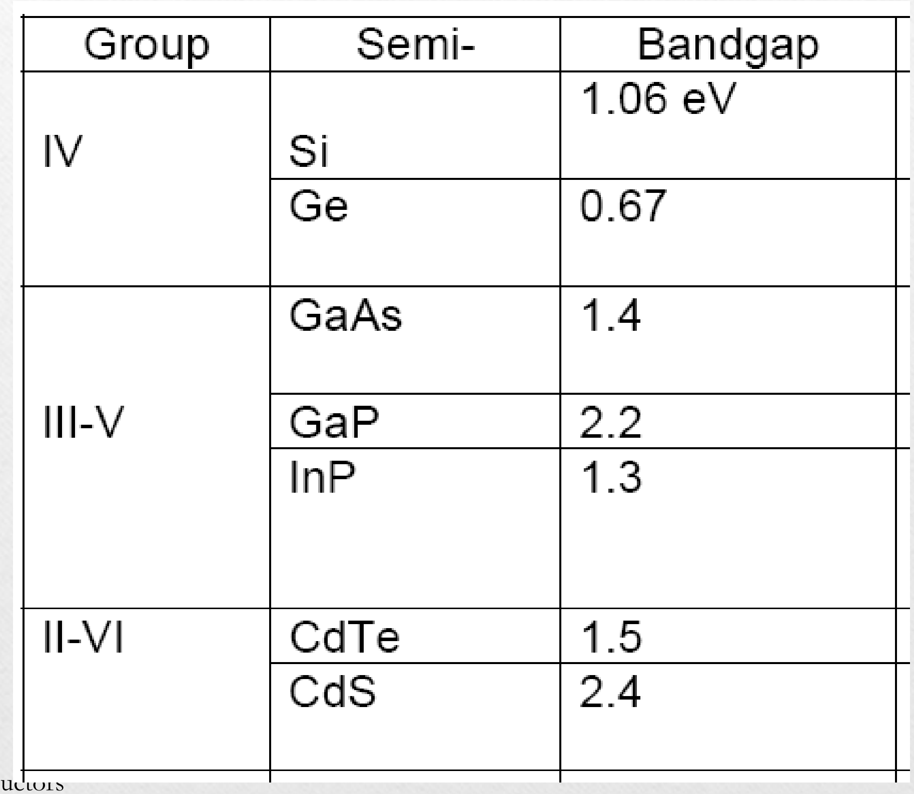
At room temperature – some conduction

So where are all these materials to be found in the periodic table ?

Semiconductors



Semiconductors

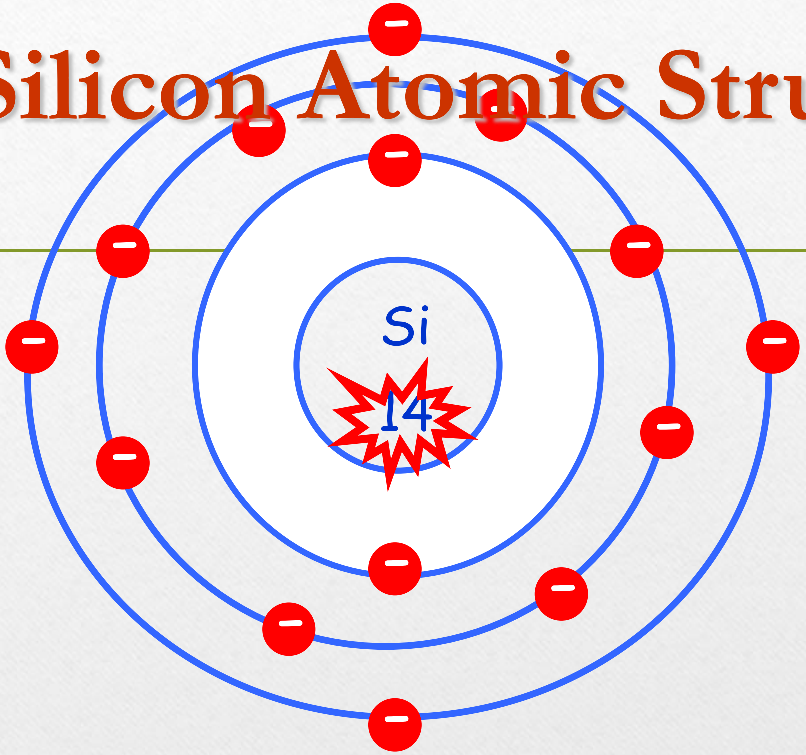


Group	Semi-	Bandgap
IV	Si	1.06 eV
	Ge	0.67
III-V	GaAs	1.4
	GaP	2.2
	InP	1.3
II-VI	CdTe	1.5
	CdS	2.4

Possible Semiconductor Materials

Carbon	**C**	**6**	1. Very Expensive 2. Band Gap Large: 6eV 3. Difficult to produce without high contamination
Silicon	**Si**	**14**	1. Cheap 2. Ultra High Purity 3. Oxide is amazingly perfect for IC applications
Germanium	**Ge**	**32**	1. High Mobility 2. High Purity Material 3. Oxide is porous to water/hydrogen (problematic)
Gallium arsenide	**GaAs**		1. High Mobility 2. High speed switching

The Silicon Atomic Structure

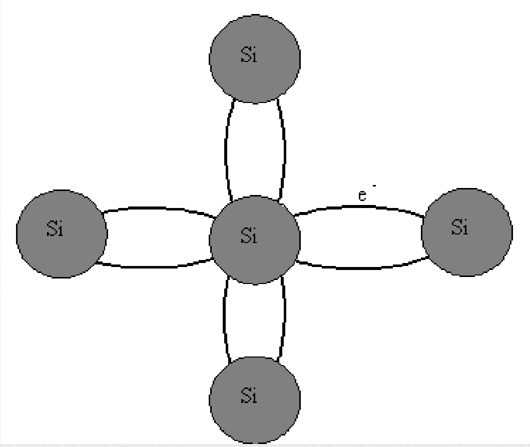


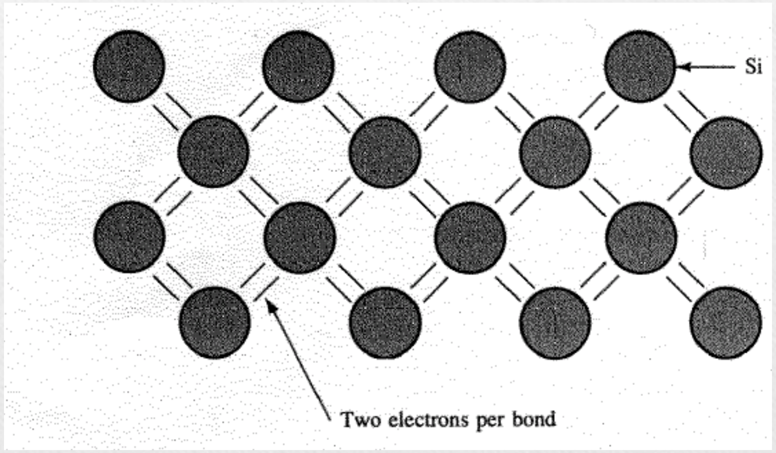
Silicon : It's a Group 4 element which means it has 4 electrons in outer shell

However, like all other elements it would prefer to have 8 electrons in its outer shell

Bonding of Si atoms

This results in the covalent bonding of Si atoms in the crystal matrix

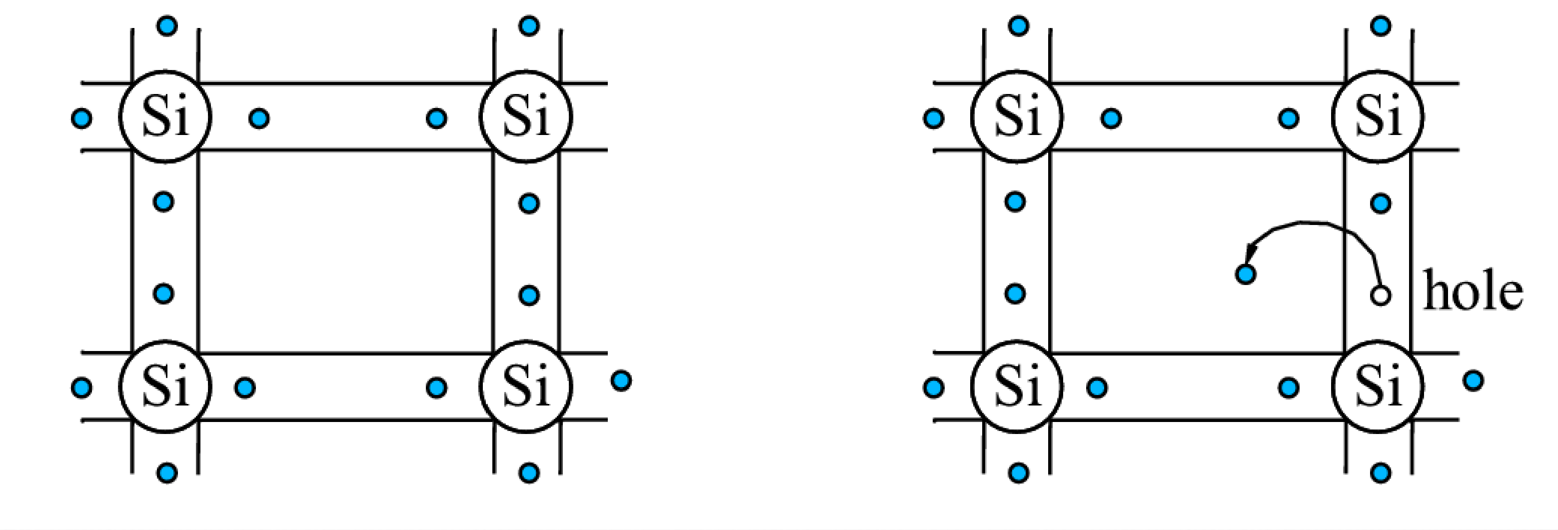




A Covalent Bond Formed by the Sharing of Electrons in an Outer Energy Level

Electrons and Holes

Si and Ge are tetravalent elements – each atom of Si (Ge) has 4 valence electrons in crystal matrix



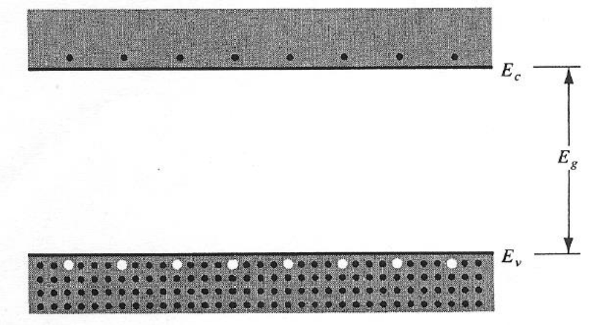
T=0 all electrons are bound in covalent bonds

no carriers available for conduction.

For T> 0 thermal fluctuations can break electrons free creating electron-hole pairs

Both can move throughout the lattice and therefore conduct current.

Electrons and Holes



Electron-hole pairs in a semiconductor. The bottom of the conduction band denotes as E_c and the top of the valence band denotes as E_v.

For T>0

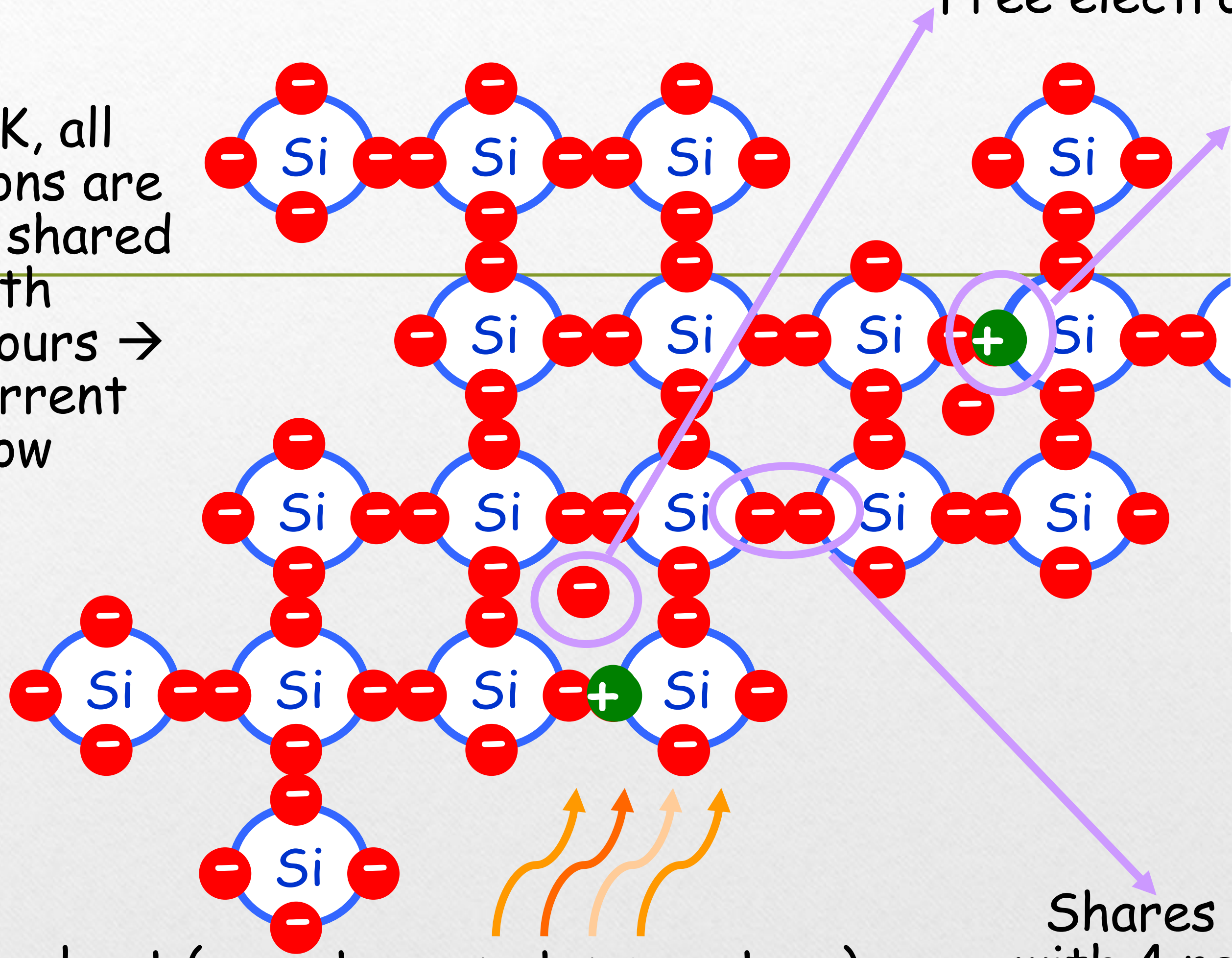
some electrons in the valence band receive enough thermal energy to be excited across the band gap to the conduction band.

The result is a material with some electrons in an otherwise empty conduction band and some unoccupied states in an otherwise filled valence band.

An empty state in the valence band is referred to as a ***hole***.

If the conduction band electron and the hole are created by the excitation of a valence band electron to the conduction band, they are called an ***electron-hole pair*** (EHP).

Silicon Lattice Structure



Free electron

At 0K, all electrons are tightly shared with neighbours → no current flow

Vacancy left by electron. Overall charge on silicon is zero → this "hole" must be positive

Adding heat (even to room temperature) allows some bonds to break, and electrons can flow

Shares electrons with 4 neighbouring atoms → 8 electrons in outer shell

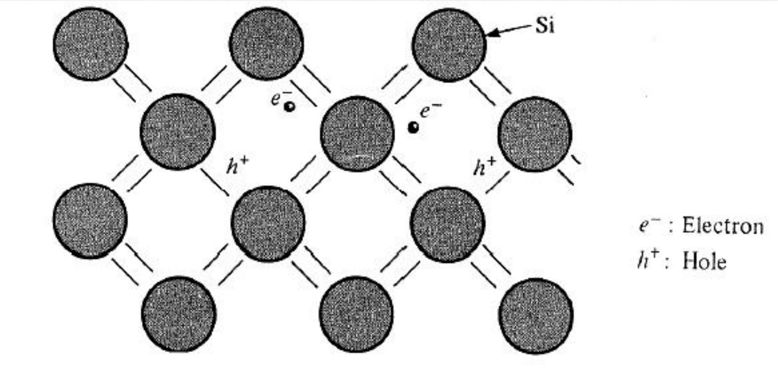
Intrinsic Material

A perfect semiconductor crystal with no impurities or lattice defects is called an ***intrinsic*** semiconductor.

At T=0 K –
No charge carriers
Valence band is filled with electrons
Conduction band is empty

At T>0
Electron-hole pairs are generated

EHPs are the only charge carriers in *intrinsic material*



Electron-hole pairs in the covalent bonding model in the Si crystal.

Since electron and holes are created in pairs – the electron concentration in conduction band, n (electron/cm^3) is equal to the concentration of holes in the valence band, p (holes/cm^3).

Each of these intrinsic carrier concentrations is denoted n_i.

Thus for intrinsic materials
$n=p=n_i$

Intrinsic Material

- At a given temperature there is a certain concentration of electron-hole pairs n_i. If a steady state carrier concentration is maintained, there must be *recombination* of EHPs at the same rate at which they are generated. Recombination occurs when an electron in the conduction band makes a transition to an empty state (hole) in the valence band, thus annihilating the pair. If we denote the generation rate of EHPs as g_i (EHP/cm^3·s) and the recombination rate as r_i, equilibrium requires that

$$r_i = g_i$$

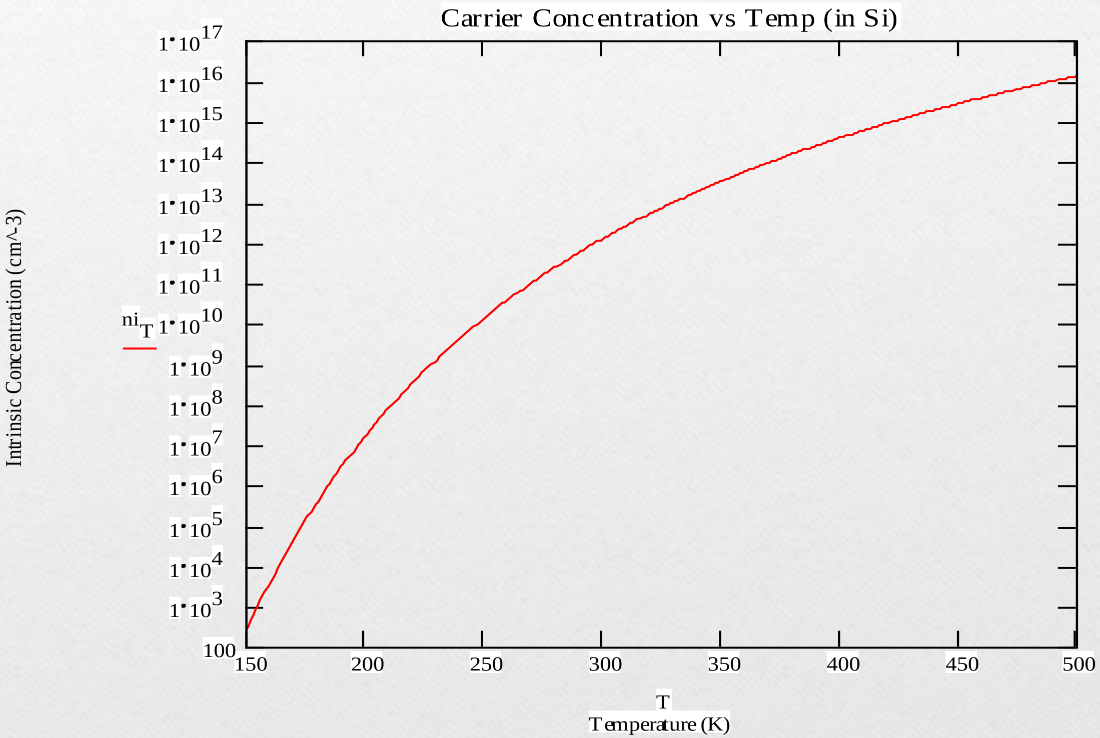
- Each of these rates is temperature dependent. For example, $g_i(T)$ increases when the temperature is raised, and a new carrier concentration n_i is established such that the higher recombination rate $r_i(T)$ just balances generation. At any temperature, we can predict that the rate of recombination of electrons and holes r_i, is proportional to the equilibrium concentration of electrons n_0 and the concentration of holes p_0:

$$r_i = \alpha_r n_o p_o = \alpha_r n_i^2 = g_i$$

- The factor α_r is a constant of proportionality which depends on the particular mechanism by which recombination takes place.

Increasing conductivity by temperature

As temperature increases, the number of free electrons and holes created increases exponentially.



Therefore the conductivity of a semiconductor is influenced by temperature

The process of freeing electrons, creating holes, and filling them **facilitates current flow…**

Intrinsic Semiconductors

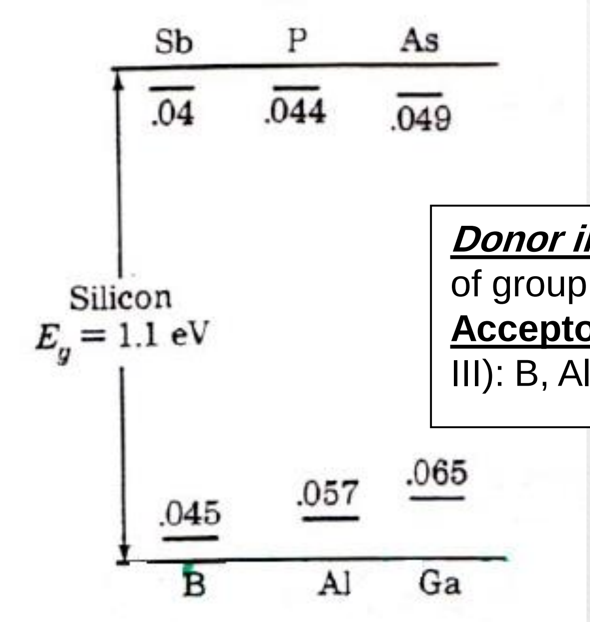
- silicon at low temps
  - all covalent bonds – are intact
  - no electrons – are available for conduction
  - conducitivity – is zero
- silicon at room temp
  - some covalent bonds – break, freeing an electron and cre hole, due to thermal energy
  - some electrons – will wander from their parent a ming available for conduction
  - conductivity – is greater than zero

Increasing conductivity

- The conductivity of the semiconductor material increases when the temperature increases.
- This is because the application of heat makes it possible for some electrons in the valence band to move to the conduction band.
- Obviously the more heat applied the higher the number of electrons that can gain the required energy to make the conduction band transition and become available as charge carriers.
- This is how temperature affects the carrier concentration.
- Another way to increase the number of charge carriers is to add them in from an external source.
- Doping or implant is the term given to a process whereby one element is injected with atoms of another element in order to change its properties.
- Semiconductors (Si or Ge) are typically doped with elements such as Boron, Arsenic and Phosphorous to change and enhance their electrical properties.

Extrinsic Material

By doping, a crystal can be altered so that it has a predominance of either electrons or holes. Thus there are two types of doped semiconductors, n-type (mostly electrons) and p-type (mostly holes). When a crystal is doped such that the equilibrium carrier concentrations n_0 and p_o are different from the intrinsic carrier concentration n_i, the material is said to be *extrinsic*.



Donor impurities (elements of group V): P, Sb, As
Acceptor elements (group III): B, Al, Ga, In

When impurities or lattice defects are introduced, additional levels are created in the energy bands structure, usually within the band gap.

The valence and conduction bands of silicon with additional impurity energy levels within the energy gap.

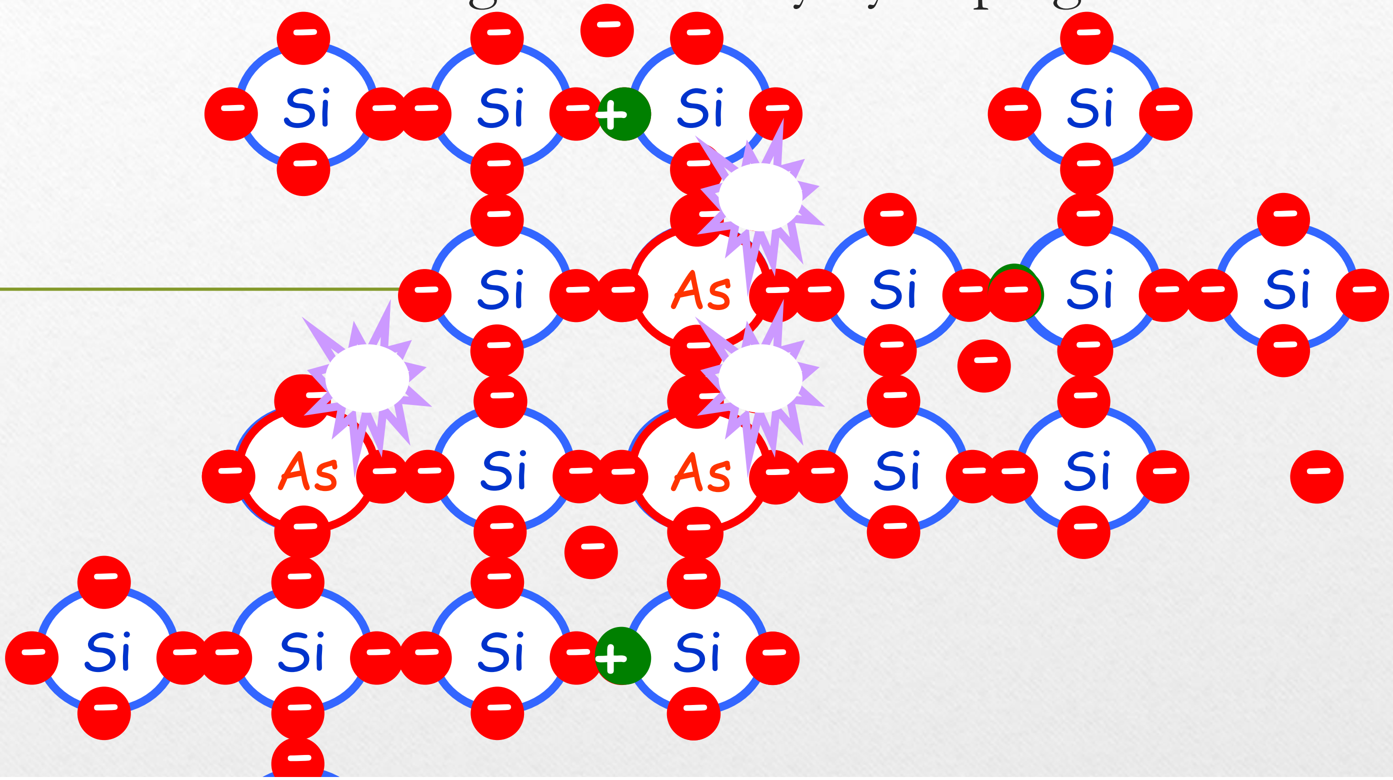
Total number of electrons

III – Al – 13

IV – Si – 14

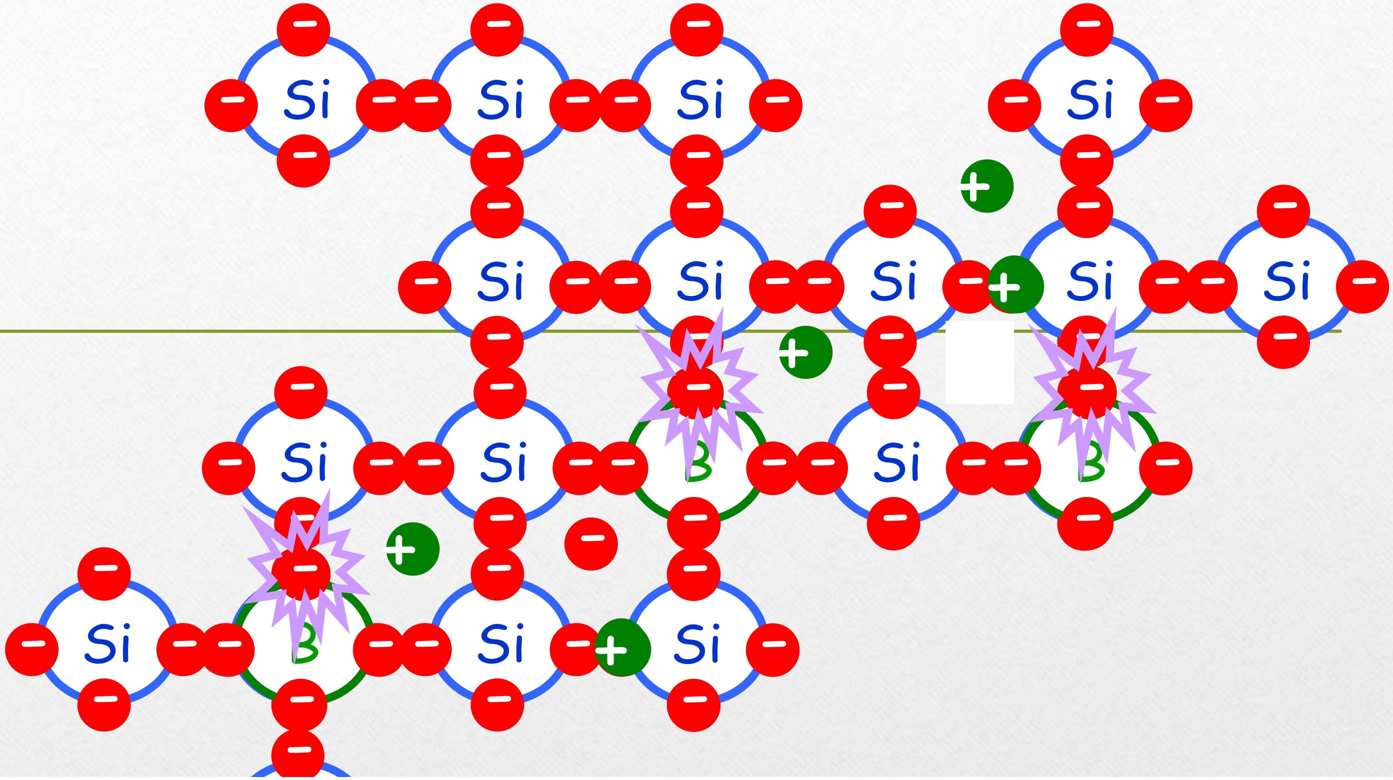
V - P - 15

Increasing conductivity by doping



- Inject Arsenic into the crystal with an implant step.
- Arsenic is Group5 element with 5 electrons in its outer shell, (one more than silicon).
- This introduces extra electrons into the lattice which can be released through the application of heat and so produces and electron current
- The result here is an N-type semiconductor (n for negative current carrier).

Increasing conductivity by doping



- Inject Boron into the crystal with an implant step.
- Boron is Group3 element is has 3 electrons in its outer shell (one less than silicon)
- This introduces holes into the lattice which can be made mobile by applying heat. This gives us a hole current
- The result is a P-type semiconductor (p for positive current carrier)

The Fermi – Dirac distribution function

- The density of electrons in a semiconductor is related to the density of available states and the probability that each of these states is occupied.
- The density of occupied states per unit volume and energy is simply the product of the *density of states* and the Fermi-Dirac probability function (also called the *Fermi function*):

The Fermi – Dirac distribution function

Electrons in solids obey Fermi - Dirac distribution given by:

$$\boxed{F(E) = \frac{1}{1 + e^{[(E - E_F)/kT]}}} \qquad (2.1)$$

where k is Boltzmann's constant ➔ $k = 1.38 \times 10^{-23}$ J/K.

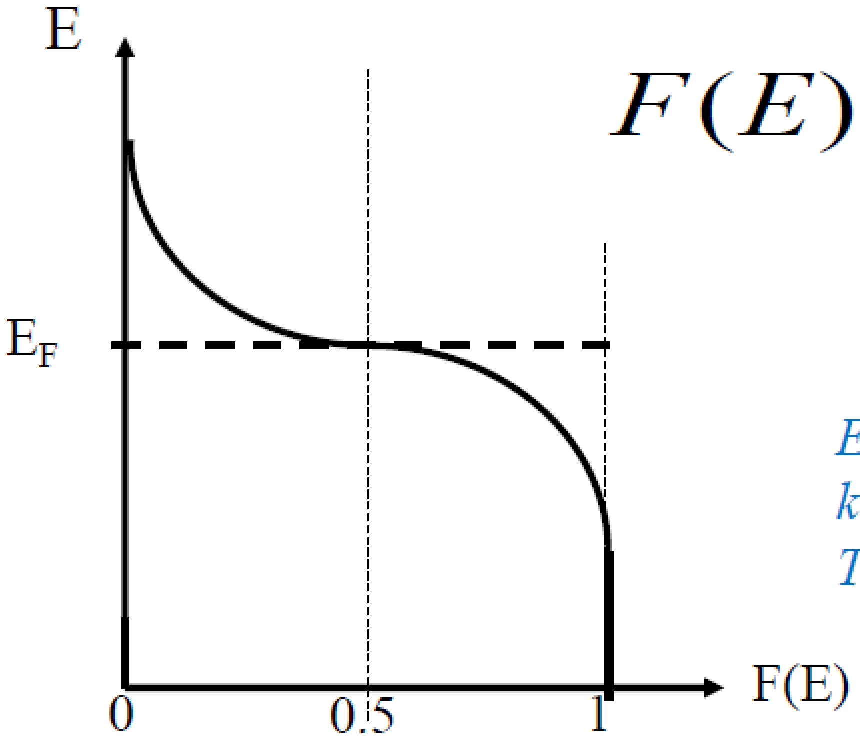
T is the temperature in kelvin

The function ***F*(E)** called ***the Fermi-Dirac distribution function*** which gives the probability that an electron occupies an electronic state with energy E.

The quantity E_F is called ***the Fermi level***, and it represents the energy level at which the probability to find an electron is 50%. For an energy $E = E_F$ the occupation probability is

$$\boxed{F(E_F) = \left[1 + e^{[(E_F - E_F)/kT]}\right]^{-1} = \frac{1}{1+1} = \frac{1}{2}}$$

This is the probability for electrons to occupy the Fermi level.



$$F(E) = \frac{1}{e^{(E-E_F)/kT} + 1}$$

E_F	Fermi level
k	Boltzmann's constant
T	temperature in kelvins

The Fermi – Dirac distribution function

Approximations in Fermi distribution function

$$F(E) = \frac{1}{1 + e^{[(E-E_F)/kT]}}$$

$$\text{for } (E - E_F) > 3kT \qquad \text{(high E)}$$

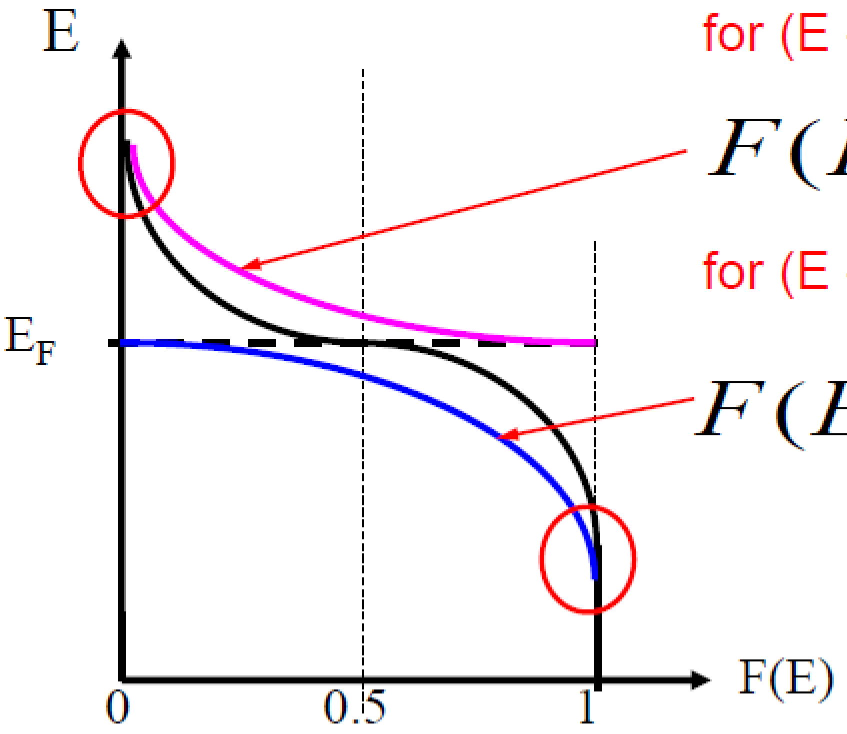
$$F(E) \cong e^{-[(E-E_F)/kT]}$$

$$\Rightarrow \text{distribution of electrons in the C.B}$$

$$\text{for } (E - E_F) < 3kT \qquad \text{(low E)}$$

$$F(E) \cong 1 - e^{-[(E_F-E)/kT]}$$

$$\Rightarrow \text{distribution of holes in the V.B}$$



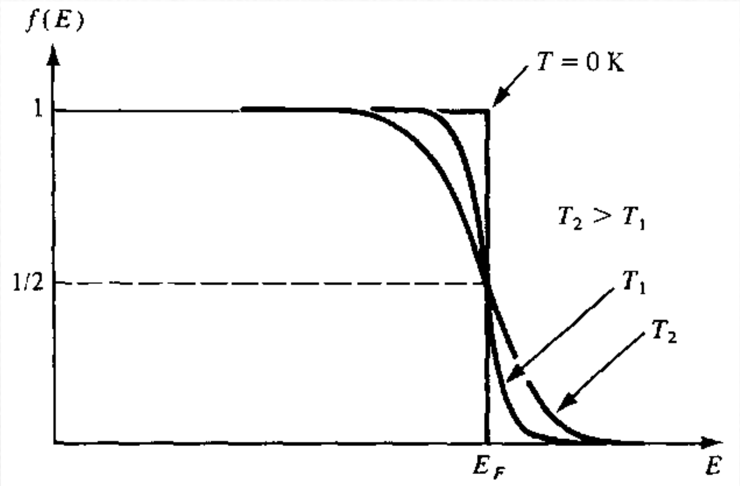
for $(E - E_F) > 3kT$

$$F(E) \cong e^{-(E-E_F)/kT}$$

for $(E - E_F) < 3kT$

$$F(E) \cong 1 - e^{-(E-E_F)/kT}$$

The Fermi – Dirac distribution function



The Fermi – Dirac distribution function for different temperatures

At T=0 K, *F*(E) has rectangular shape

the denominator of the exponent is

1/(1+0)=1 when ($E<E_f$), exp. negative

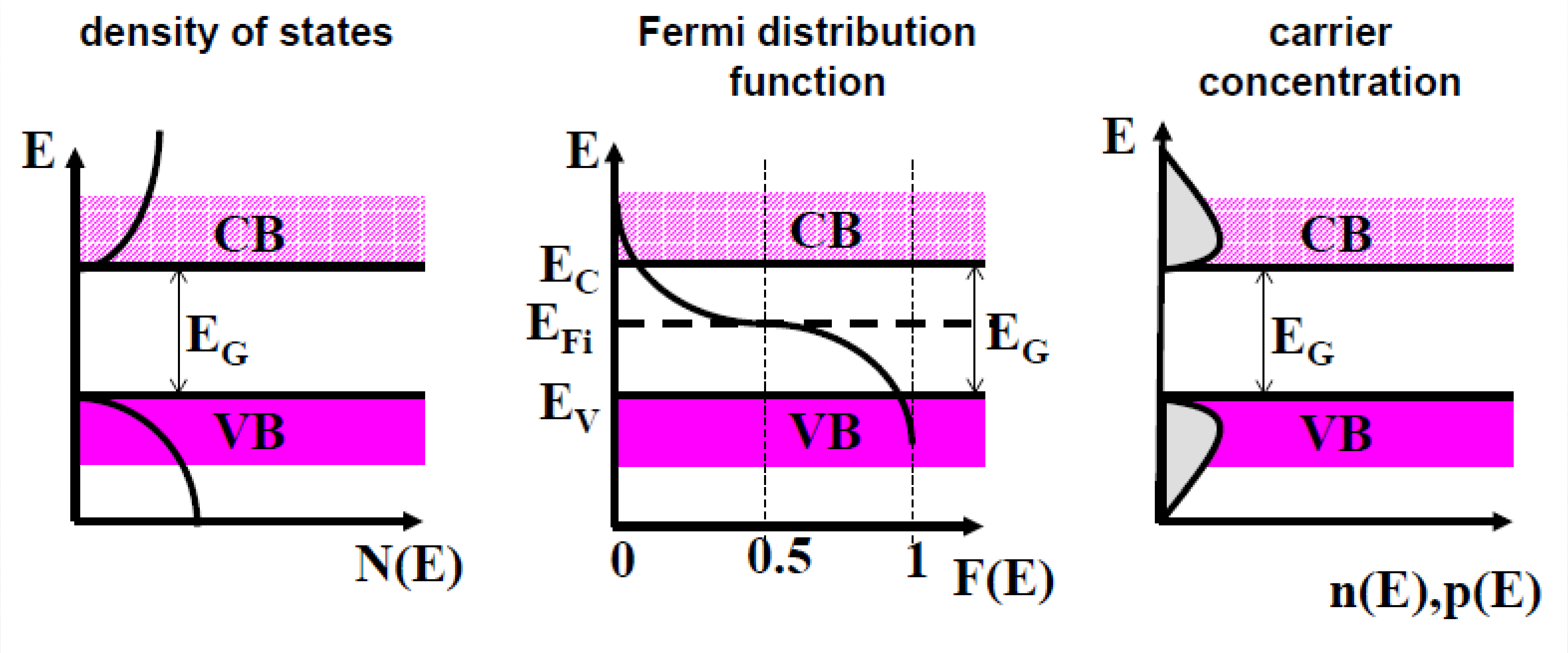
1/(1+∞)-0 when ($E>E_f$), exp. positive

At 0 K every available energy state up to E_F is filled with electrons, and all states above E_F are empty.

At temperatures higher than 0 K, some probability ***F*(E)** exists for states above the Fermi level to be filled with electrons and there is a corresponding probability **[1 - *F*(E)]** that states below E_F are empty.

The Fermi function is symmetrical about E_F for all temperatures.

carrier concentration



$$n = p = n_i = \int_{E_c}^{\infty} F(E)S(E)dE$$

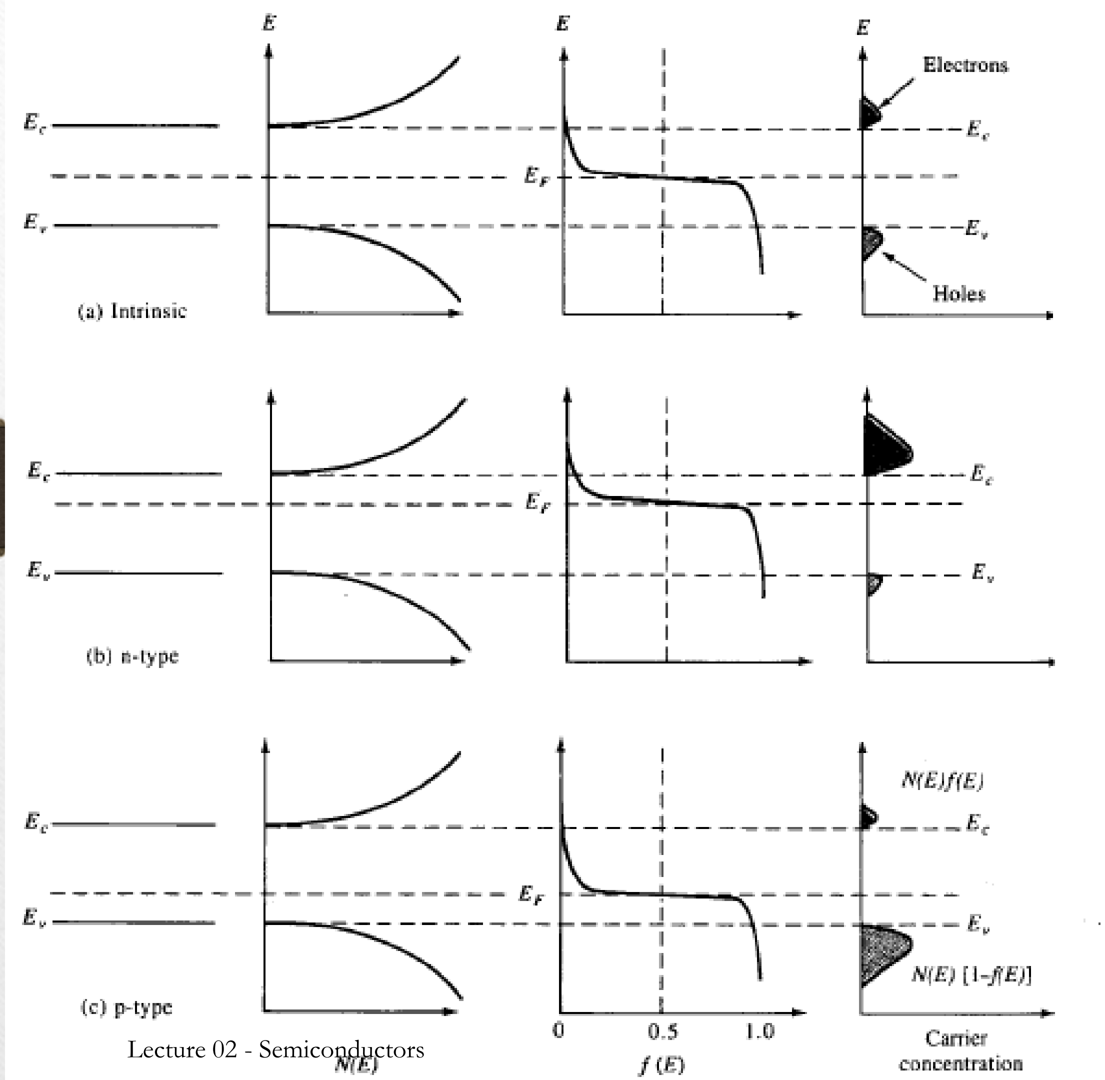
Electron and Hole Concentrations at Equilibrium

The Fermi distribution function can be used to calculate the concentrations of electrons and holes in a semiconductor if the densities of available states in the valence and conduction bands are known. The concentration of electrons in the conduction band is

$$n = \int_{E_c}^{\infty} F(E)S(E)dE \qquad (2.2)$$

where ***S(E)dE*** is the density of states (cm^{-3}) in the energy range ***dE***. The subscript o used for the electron and hole concentration symbols (n_o, p_o) indicates equilibrium conditions.

Band diagram, density of states, Fermi-Dirac distribution, and the carrier concentrations at thermal equilibrium



Intrinsic semiconductor

n-type semiconductor

p-type semiconductor

Carrier Concentration in Intrinsic Semiconductor

- When a suitable form of Energy is supplied to a Semiconductor then electrons take transition from Valence band to Conduction band.
- Hence a free electron in Conduction band and simultaneously free hole in Valence band is formed. This phenomenon is known as Electron - Hole pair generation.
- In Intrinsic Semiconductor the Number of Conduction electrons will be equal to the Number of Vacant sites or holes in the valence band.

Calculation of Density of Electrons

Let ‘dn’ be the Number of Electrons available between energy interval ‘E and E+ dE’ in the Conduction band

$$dn = F(E)S(E)dE$$

$$n_o = \int_{E_c}^{\infty} F(E)S(E)dE$$

Where S(E) dE is the Density of states in the energy interval E and E + dE and F(E) is the Probability of Electron occupancy.

Number of electrons in an energy level (E) in the conduction band is given by

$$n_o(E) = S_C(E)F(E)$$

Number of holes in an energy level (E) in the valence band is given by

$$p_o(E) = S_v(E)\left[1 - F(E)\right]$$

Where S_c and S_v are the density of energy states and given by:

$$S_C(E) = \frac{4\pi}{h^3}(2m_e)^{3/2}\sqrt{E - E_c}$$

$$S_v(E) = \frac{4\pi}{h^3}(2m_h)^{3/2}\sqrt{E_v - E}$$

Where:
h: Planck's constant,
m_e: effective mass of electron,
m_h: effective mass of hole

Hence, the carrier densities can be given by

$$n_o = \int n_o(E)dE$$

$$p_o = \int p_o(E)dE$$

$$n_o = \int_{E_c}^{\infty} F(E) S_C(E)\, dE = N_C e^{-(E_C - E_{Fi})/kT}$$

$$p_o = \int_{-\infty}^{E_v} [1 - F(E)] S_v(E)\, dE = N_v e^{-(E_{Fi} - E_V)/kT}$$

$N_c$and N_v are the effective density of states in the conduction band and the valence band, respectively

$$N_c = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2} = \frac{4\sqrt{2}}{h^3}(\pi m_n^* kT)^{3/2}$$

$$N_v = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2} = \frac{4\sqrt{2}}{h^3}(\pi m_h^* kT)^{3/2}$$

The product of n_o and p_o at equilibrium is a constant for a particular material and temperature (what is called the mass action law), even if the doping is varied:

$$n_o p_o = (N_c e^{\left[-(E_c - E_F)/kT\right]})(N_v e^{\left[-(E_F - E_v)/kT\right]})$$

$$= N_c N_v e^{\left[-(E_c - E_v)/kT\right]} = N_c N_v e^{\left[-E_g/kT\right]}$$

For intrinsic semiconductors:

$$n_i p_i = (N_c e^{\left[-(E_c - E_i)/kT\right]})(N_v e^{\left[-(E_i - E_v)/kT\right]})$$

$$n_i^{\,2} = N_c N_v e^{\left[-E_g/kT\right]}$$

$$\therefore n_i = \sqrt{N_c N_v}\, e^{\left[-E_g/2kT\right]}$$

The intrinsic electron and hole concentrations are equal (since the carriers are created in pairs), $\boldsymbol{n_i = p_i}$; thus the intrinsic concentration is

$$n_i = \sqrt{N_c N_v} e^{(-E_g/2kT)}$$

The constant product of electron and hole concentrations can be written conveniently as

$$\boxed{n_o p_o = n_i^2}$$

This is an important relation, and we shall use it extensively in later calculations. The intrinsic concentration for Si at room temperature is approximately $\boldsymbol{n_i}$ = 1.5 x 10^{10} cm^{-3}.

From $n_o = N_C e^{-(E_C - E_{Fi})/kT}$ and $p_o = N_v e^{-(E_{Fi} - E_V)/kT}$

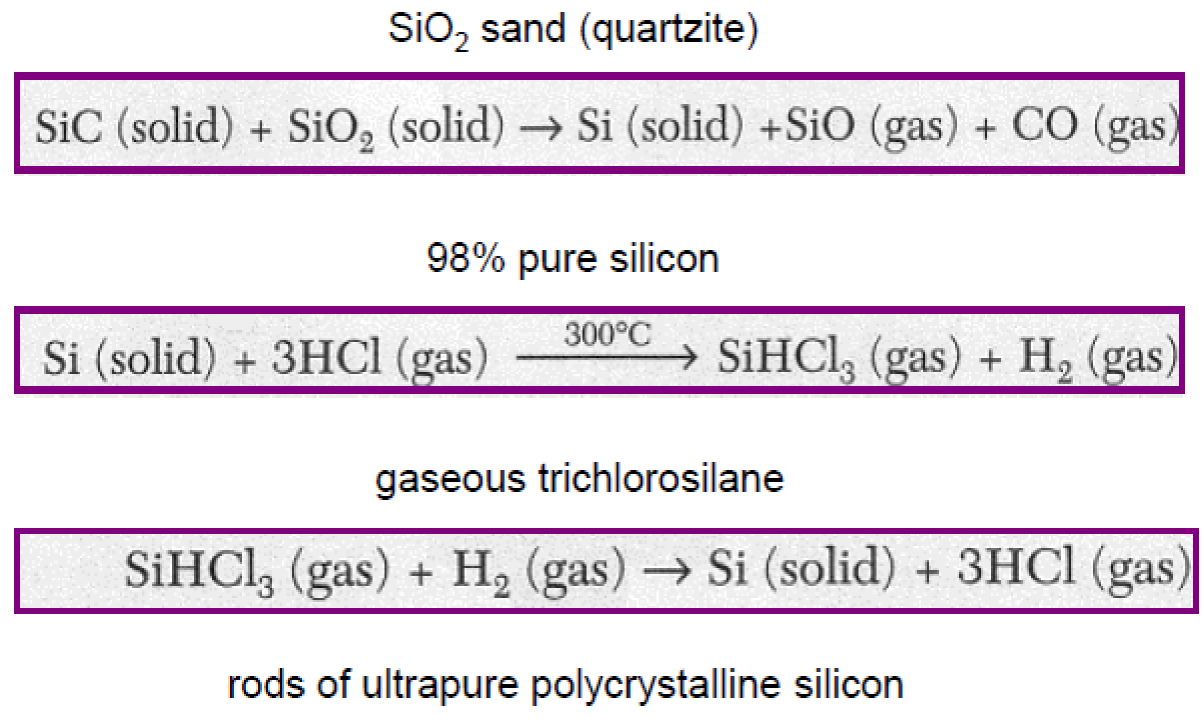
$$E_{Fi} = \frac{E_C + E_V}{2} + \frac{kT}{2} \ln \frac{N_V}{N_C}$$

$$\boxed{n_0 = n_i e^{\left[(E_F - E_i)/kT\right]}}$$

$$\boxed{p_0 = n_i e^{\left[(E_i - E_F)/kT\right]}}$$

Production steps of silicon

“95% of materials used by the electronic industry is silicon”



SiO_2 sand (quartzite)

$$\boxed{SiC\ (solid) + SiO_2\ (solid) \rightarrow Si\ (solid) + SiO\ (gas) + CO\ (gas)}$$

98% pure silicon

$$\boxed{Si\ (solid) + 3HCl\ (gas) \xrightarrow{300°C} SiHCl_3\ (gas) + H_2\ (gas)}$$

gaseous trichlorosilane

$$\boxed{SiHCl_3\ (gas) + H_2\ (gas) \rightarrow Si\ (solid) + 3HCl\ (gas)}$$

rods of ultrapure polycrystalline silicon

Czochralski technique

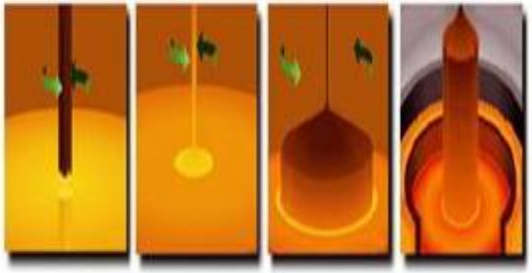
Raw material of Silicon (pure sand SiO_2)

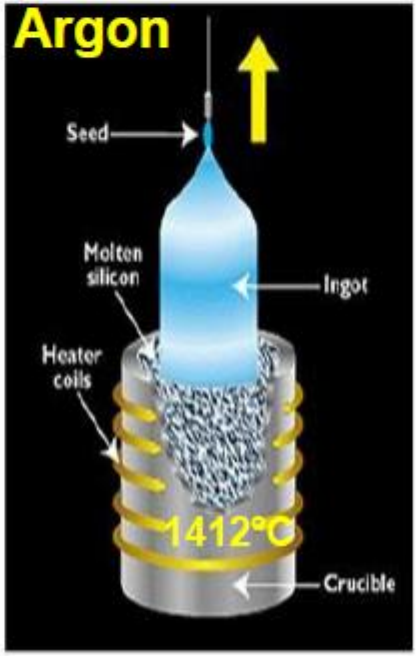
Step 1: Preparing the Molten Silicon Bath

The sand (SiO_2)is put into a rotating crucible and is heated above its melting point. The molten sand will become the source of the silicon that will form the wafer.

Step 2: Making the Ingot

A pure silicon seed crystal is now placed into the molten sand bath. This crystal will be pulled out slowly as it is rotated.





Silicon ingot

Photo: http://cnfolio.com/ELMnotes15

Summary (1)

- Today's microelectronics technology is almost entirely based on the semiconductor silicon. If a circuit is to be fabricated as a monolithic integrated circuit (IC), it is made using a single silicon crystal, no matter how large the circuit is.
- In a crystal of intrinsic or pure silicon, the atoms are held in position by covalent bonds. At very low temperatures, all the bonds are intact; No charge carriers are available to conduct current. As such, at these low temperatures, silicone acts as an insulator.

Summary (2)

- At room temperature, thermal energy causes some of the covalent bonds to break, thus generating free electrons and holes that become available to conduct electricity.
- Current in semiconductors is carried by free electrons and holes. Their numbers are equal and relatively small in intrinsic silicon.
- The conductivity of silicon may be increased drastically by introducing small amounts of appropriate impurity materials into the silicon crystal – via process called doping.

Summary (3)

- There are two kinds of doped semiconductor: *n*-type in which electrons are abundant, *p*-type in which holes are abundant.