

# **Semiconductor Materials**

# Introduction to Semiconductors

Objective of the lecture:

1. Define a semiconductor - no. of electrons in outer shell, location on periodic table, most commonly used ones etc.
2. Know the crystal structure of silicon, the cause and result of defects.
3. Understand intrinsic and extrinsic semiconductor behaviour, know how to affect this behaviour through doping.
4. Explain in detail what depletion regions are and how they are formed.
5. P-N junction

# Why semiconductors?

- **SEMICONDUCTORS: They are here, there, and everywhere**
- Computers, palm pilots, Silicon (Si) MOSFETs, ICs, CMOS laptops, anything "intelligent"
- 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 GaN LEDs (green, blue)  
taillights InGaAsP LEDs (red, amber)
- Air bags Si MEMs, Si ICs
- and, they are important, especially to Elec.Eng.& Computer Sciences

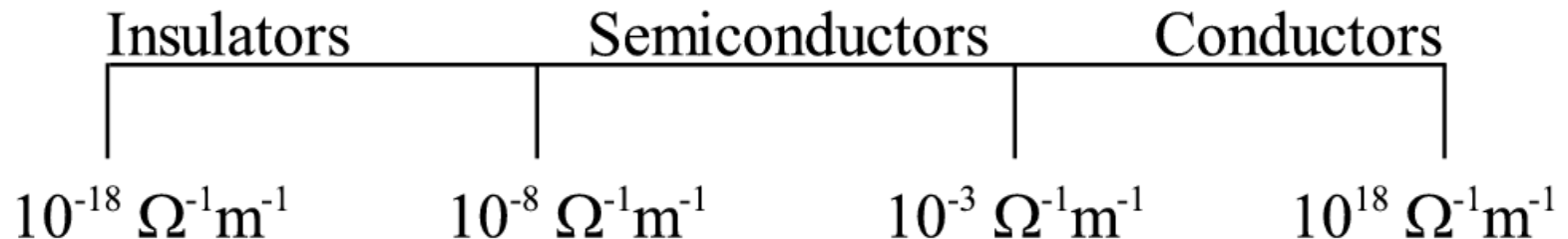
# Introduction

Semiconductors are materials whose electrical properties lie between Conductors and Insulators.

Ex : Silicon and Germanium

**Give the examples of Conductors and Insulators!**

Difference in conductivity



# Semiconductor Materials

- **Elemental semiconductors** - Si and Ge (column IV of periodic table) -compose of single species of atoms
- **Compound semiconductors** - 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)
- There are also three-element (**ternary**) compounds (GaAsP) and four-elements (**quaternary**) compounds such as InGaAsP.

(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
			GaSb	CdTe
			InP	
			InAs	
			InSb	

# Periodic Table of the Elements

# Periodic Table of the Elements

The periodic table displays elements organized by atomic number and chemical properties. The highlighted elements (B, C, N, O) are part of the p-block, specifically the second period. The red arrow points towards the elements in the lower right, which are typically semiconductors.

1A	1	H	2A	2	He	0																														
	3	Li	4	Be	5	B	6	C	7	N	8	O	9	F	10	Ne																				
	11	Na	12	Mg	13	Al	14	Si	15	P	16	S	17	Cl	18	Ar																				
	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
	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
	55	Cs	56	Ba	57	*La	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
	87	Fr	88	Ra	89	+Ac	104	Rf	105	Ha	106	Sg	107	Ns	108	Hs	109	Mt	110	111	112	113														

Semiconductor materials

\* Lanthanide Series

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

+ Actinide Series

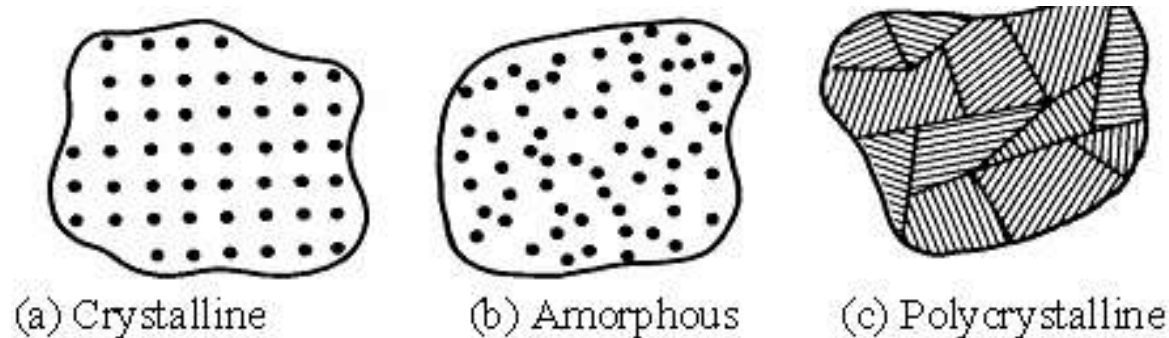
# Semiconductor Materials

- The wide variety of electronic and optical properties of these semiconductors provides the device engineer with great flexibility in the design of electronic and opto-electronic functions.
- **Ge** was widely used in the early days of semiconductor development for transistors and diodes.
- **Si** is now used for the majority of rectifiers, transistors and integrated circuits.
- **Compounds** are widely used in high-speed devices and devices requiring the emission or absorption of light.
- The electronic and optical properties of semiconductors are strongly affected by impurities, which may be added in precisely controlled amounts (e.g. an impurity concentration of one part per million can change a sample of Si from a poor conductor to a good conductor of electric current). This process called **doping**.



# 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 (Fig. 2); some have no periodic structure at all (*amorphous solids*), and other are composed of many small regions of single-crystal material (*polycrystalline solids*).



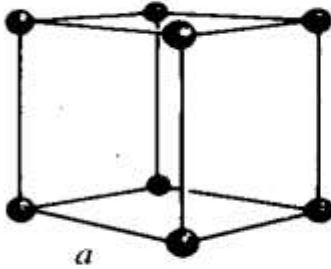
The periodic arrangement of atoms in crystal is called the *lattice*; the lattice contains a volume, called a *unit cell*, which is representative of the entire lattice and is regularly repeated throughout the crystal.



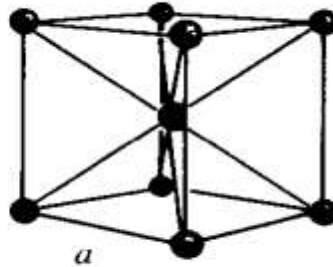
# Solid state structures

- Cubic lattices:

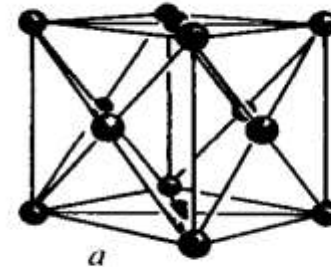
Unit cells for types of cubic lattice structure.



Simple cubic (sc)

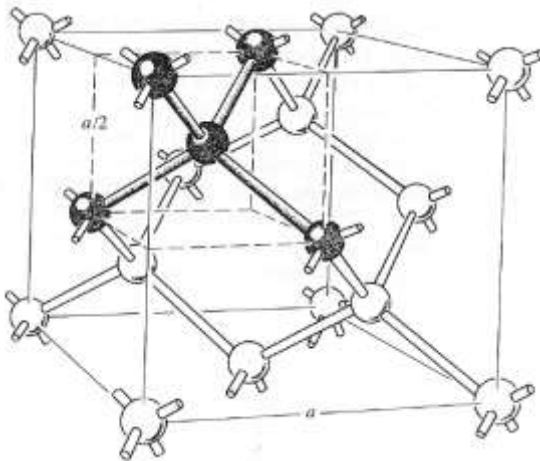


Body-centered cubic (bcc)



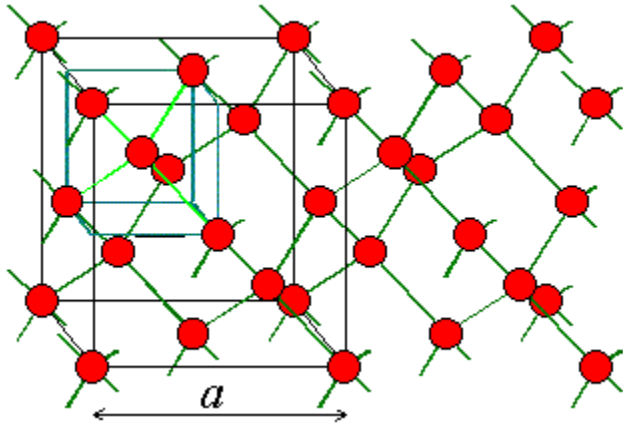
Face-centered cubic (fcc)

Diamond lattice unit cell, showing the four nearest neighbour structure

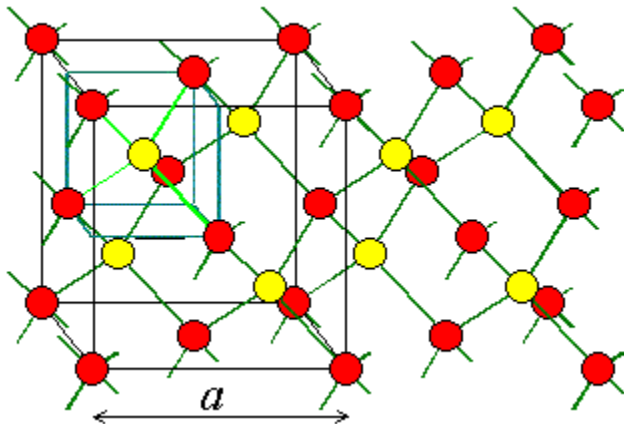


The basic lattice structure for many important semiconductors is the diamond lattice, which is characteristic of Si and Ge. In many compound semiconductors, atoms are arranged in a basic diamond structure but are different on alternating sites. This is called a *zincblende* lattice and is typical of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

# Solid state structures



The diamond lattice of silicon and germanium.

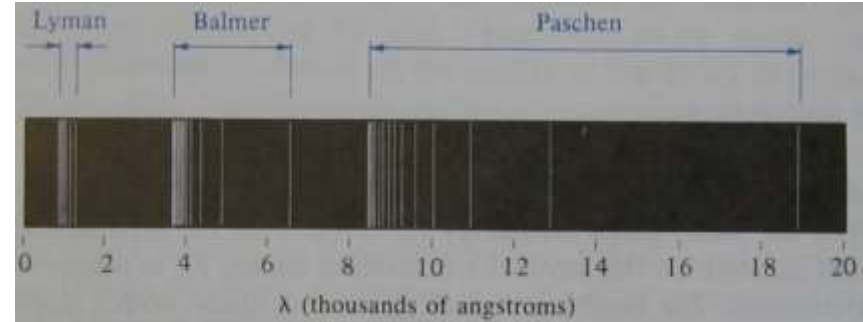


The zinc-blende crystal structure of GaAs and InP

Each atom in the diamond lattice has a covalent bond with four adjacent atoms, which together form a tetrahedron. This lattice can also be formed from two fcc-cubic lattices, which are displaced along the body diagonal of the larger cube in Figure by one quarter of that body diagonal. The diamond lattice therefore is a fcc-cubic lattice with a basis containing two identical atoms.

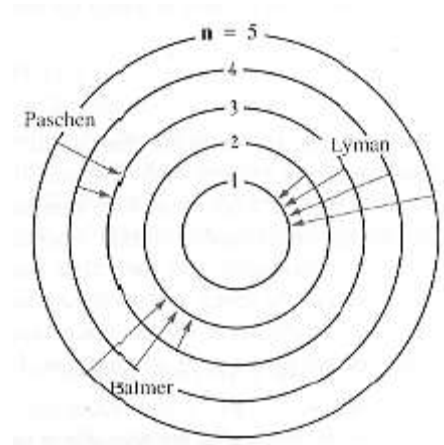
# Atoms and electrons

We shall investigate some of the important properties of electrons, with special emphasis on two points: (1) the electronic structure of atoms and (2) the interaction of atoms and electrons with excitation, such as the absorption and emission of light. By studying electron energies in an atom, we lay the foundation for understanding the influence of the lattice on electrons participating in current flow through a solid.



One of the most valuable experiments of modern physics is the analysis of absorption and emission of light by atoms. For example, an electric discharge can be created in a gas, so that the atoms begin to emit light with wavelengths characteristic of the gas.

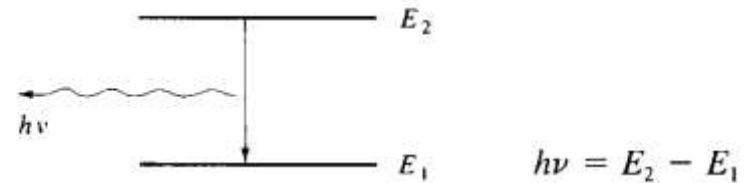
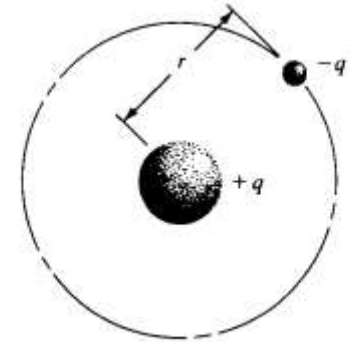
The result of emission spectra experiments led Niels Bohr to construct a model for the hydrogen atom, based on the mathematics of planetary systems. If the electron in the hydrogen atom has a series of planetary-type orbits available to it, it can be excited to an outer orbit and then can fall to any one of the inner orbits, giving off energy corresponding to one of the lines seen in a spectrum.



# The Bohr model

To develop the model, Bohr made several postulates:

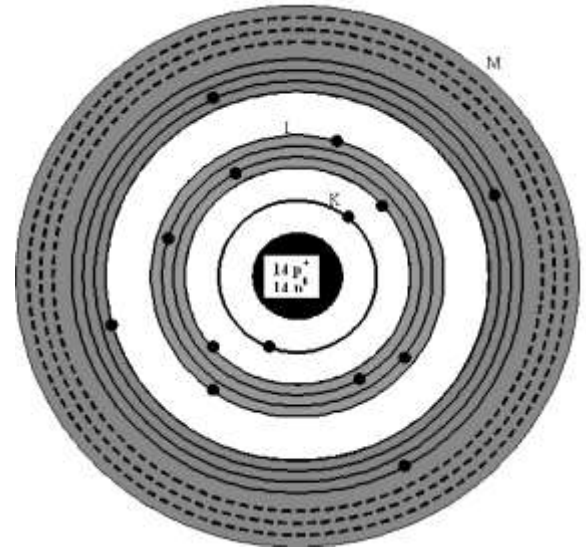
1. Electrons exist in certain stable, circular orbits about the nucleus.
2. The electron may shift to an orbit of higher or lower energy, thereby gaining or losing energy equal to the difference in the energy levels (by absorption or emission of a photon of energy  $h\nu$ ).



However, the simple Bohr model, which accurately described the gross features of the hydrogen spectrum, did not include many fine features. These features were described later by principles of quantum mechanics.

# 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).



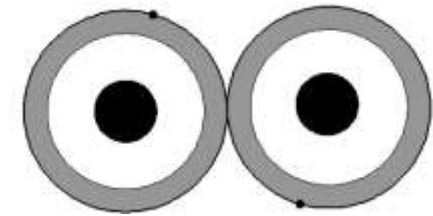
Silicon, Si, is a group IV material having an atomic number of 14. Consequently it has 14 positively charged protons and 14 neutrons in its nucleus. It has 14 orbiting negatively charged electrons: 2 in a full K shell; 8 in a full L shell and 4 in a half-full M sub-shell. With a half full outer sub-shell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

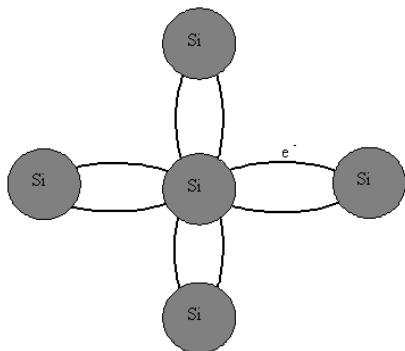
# The Silicon Atom

A **covalent bond** can be formed between two atoms which have only one electron in an outer orbit or energy level. In this case the individual electrons from the separate atoms at the same energy level orbit both atoms jointly as shown in figures.

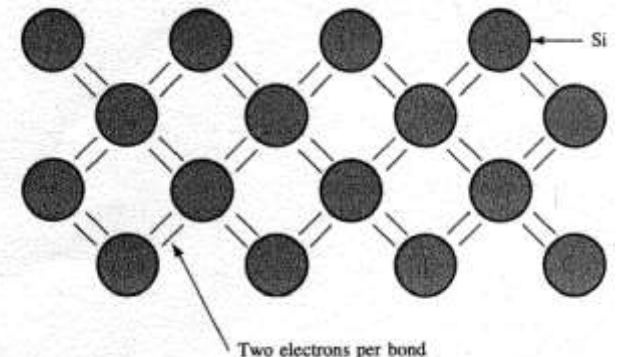


Both atoms essentially share the pair of electrons at the given energy level in the outer sub-shell, with the two electrons having opposite spins. This forms a bonding attraction between the two atoms which is not extremely strong but is nonetheless powerful and maintains a high degree of stability in the material.

In the case of Silicon, each of the 4 outer electrons enters into a covalent bond with a neighbouring atom.

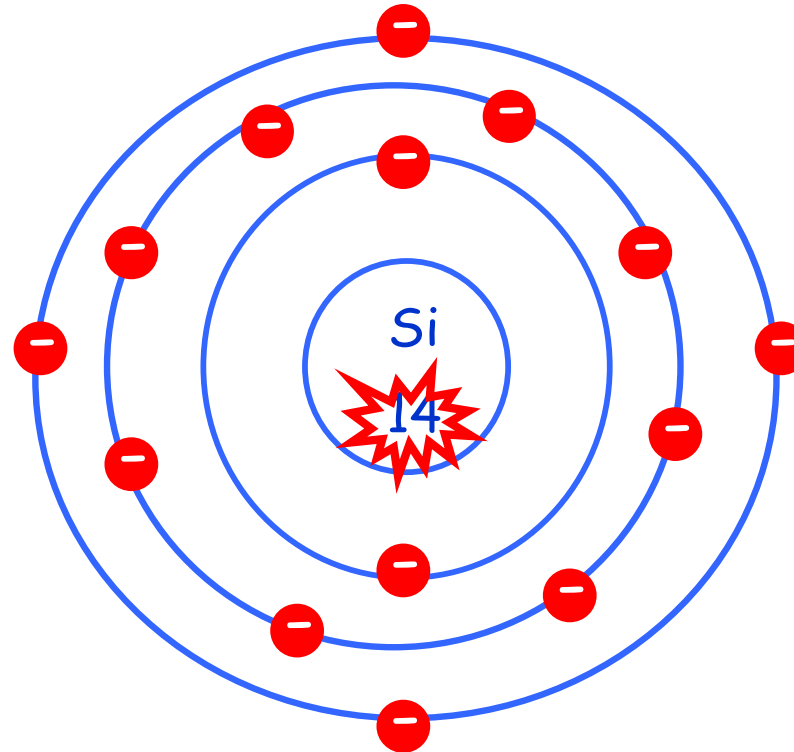


**A Covalent Bond Formed by the Sharing of Electrons in an Outer Energy Level**





# The Silicon Atomic Structure



**Silicon: our primary example and focus**

Atomic no. 14

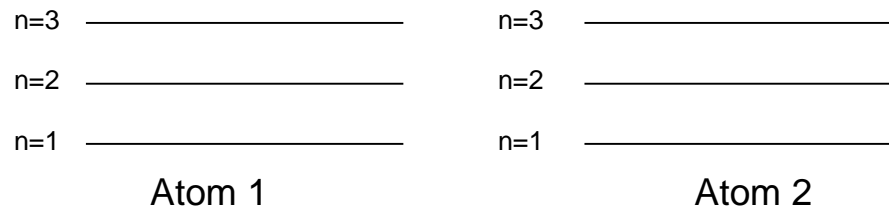
14 electrons in three shells: 2 ) 8 ) 4  
i.e., 4 electrons in the outer "bonding"  
shell

Silicon forms strong covalent bonds with  
4 neighbors

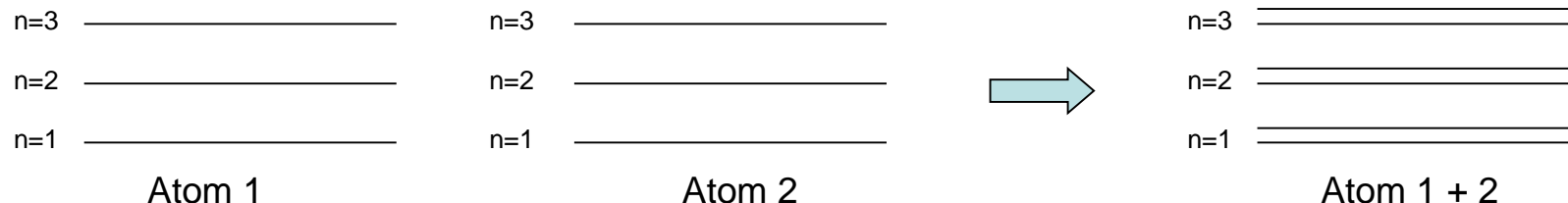
However, like all  
other elements it  
would prefer to have  
8 electrons in its  
outer shell

# Band theory of a solid

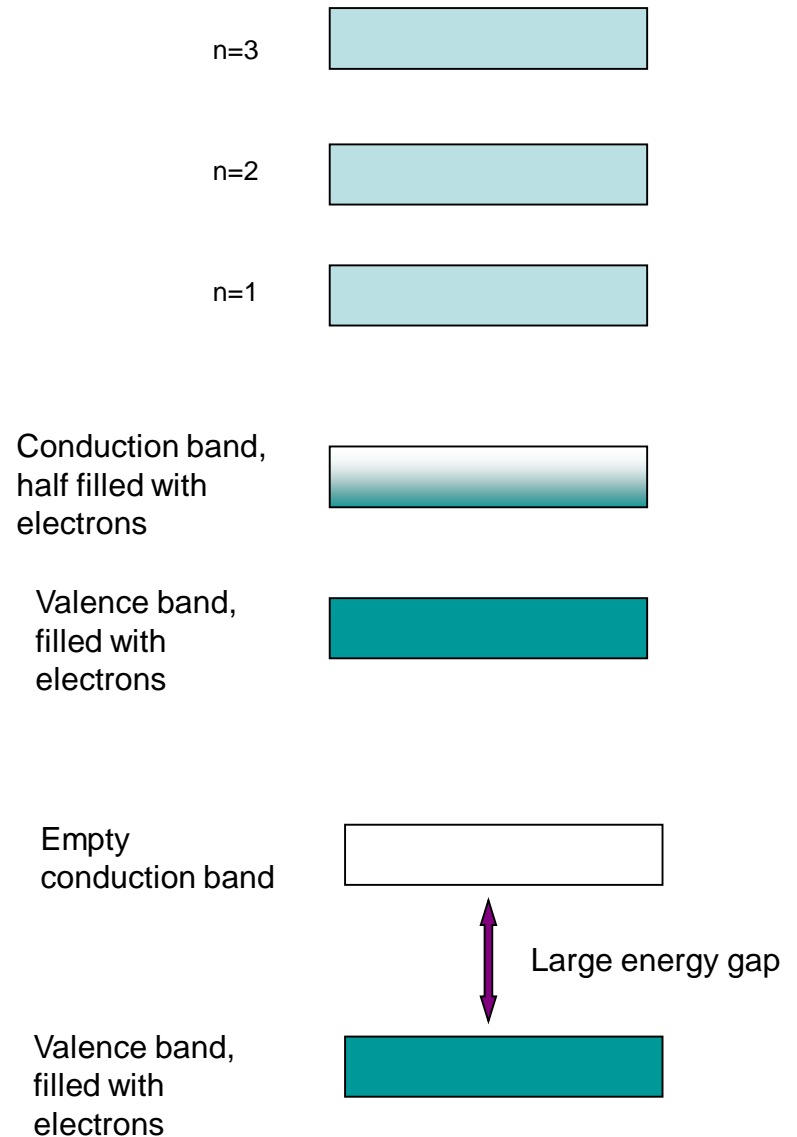
- A solid is formed by bringing together isolated single atoms.
- Consider the combination of two atoms. If the atoms are far apart there is no interaction between them and the energy levels are the same for each atom. The numbers of levels at a particular energy is simply doubled



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

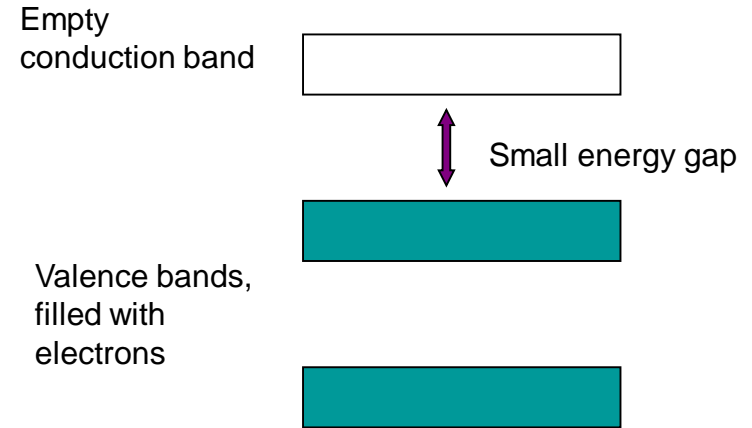


- A solid will have millions of atoms close together in a lattice so these energy levels will create bands each separated by a gap.
- **Conductors:**
  - If we have used up all the electrons available and a band is still only half filled, the solid is said to be a good conductor. The half filled band is known as the conduction band.
- **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.



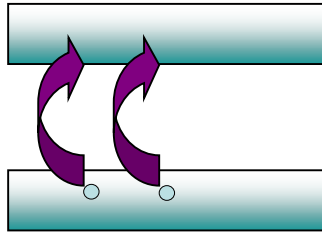
## Semiconductors:

- Some materials have a filled valence band just like insulators but a small 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**.



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 ?

# Periodic Table of the Elements

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1A	1	H	2A	2	He	0																														
1	3	Li	4	Be	5	B	6	C	7	N	8	O	9	F	10	Ne																				
2	11	Na	12	Mg	13	Al	14	Si	15	P	16	S	17	Cl	18	Ar																				
3	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
4	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
5	55	Cs	56	Ba	57	*La	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
6	87	Fr	88	Ra	89	+Ac	104	Rf	105	Ha	106	Sg	107	Ns	108	Hs	109	Mt	110	110	111	111	112	112	113	113	113	113	113	113	113	113	113	113	113	
7	113	113	113	113	113	113	113	113	113	113	113	113	113	113	113	113	113	113	113	113	113	113	113	113	113	113	113	113	113	113	113	113	113	113	113	

Semiconductor materials

\* Lanthanide Series

+ Actinide Series

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

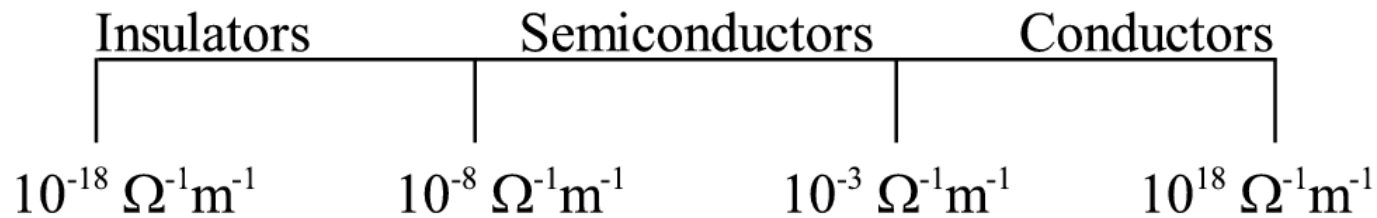
# Possible Semiconductor Materials

Carbon	C	6	<ul style="list-style-type: none"><li>1. Very Expensive</li><li>2. Band Gap Large: 6eV</li><li>3. Difficult to produce without high contamination</li></ul>
Silicon	Si	14	<ul style="list-style-type: none"><li>1. Cheap</li><li>2. Ultra High Purity</li><li>3. Oxide is amazingly perfect for IC applications</li></ul>
Germanium	Ge	32	<ul style="list-style-type: none"><li>1. High Mobility</li><li>2. High Purity Material</li><li>3. Oxide is porous to water/hydrogen (problematic)</li></ul>
Tin	Sn	50	<ul style="list-style-type: none"><li>1. Only "White Tin" is semiconductor</li><li>2. Converts to metallic form under moderate heat</li></ul>
Lead	Pb	82	<ul style="list-style-type: none"><li>1. Only "White Lead" is semiconductor</li><li>2. Converts to metallic form under moderate heat</li></ul>

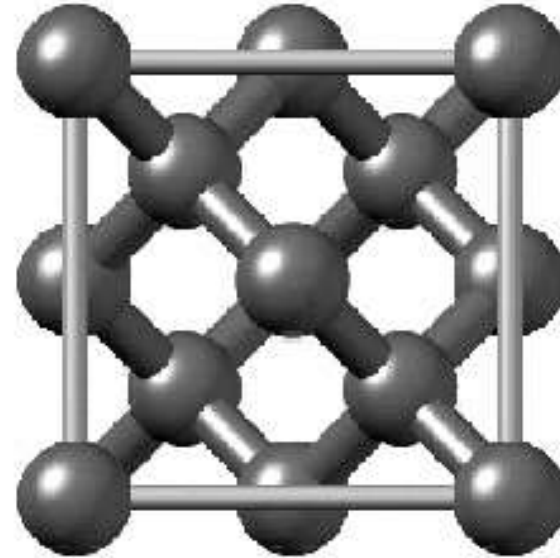
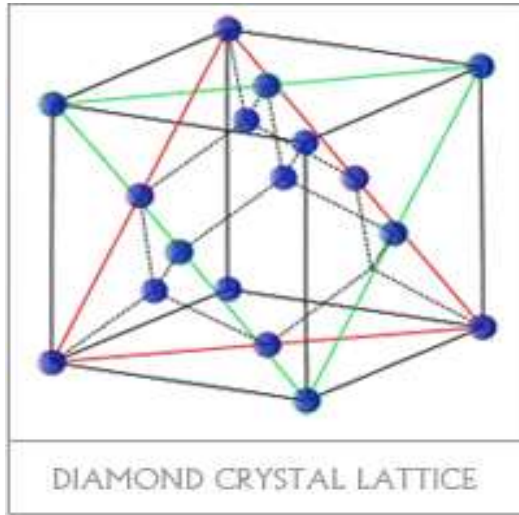


## Brief introduction to Semiconductors

(conductivity for Si depends on doping, Cu  $\sim 6 \times 10^7 \Omega^{-1}\text{m}^{-1}$ )  
Think of a crystal matrix of silicon atoms (Si has 4 valence electrons).



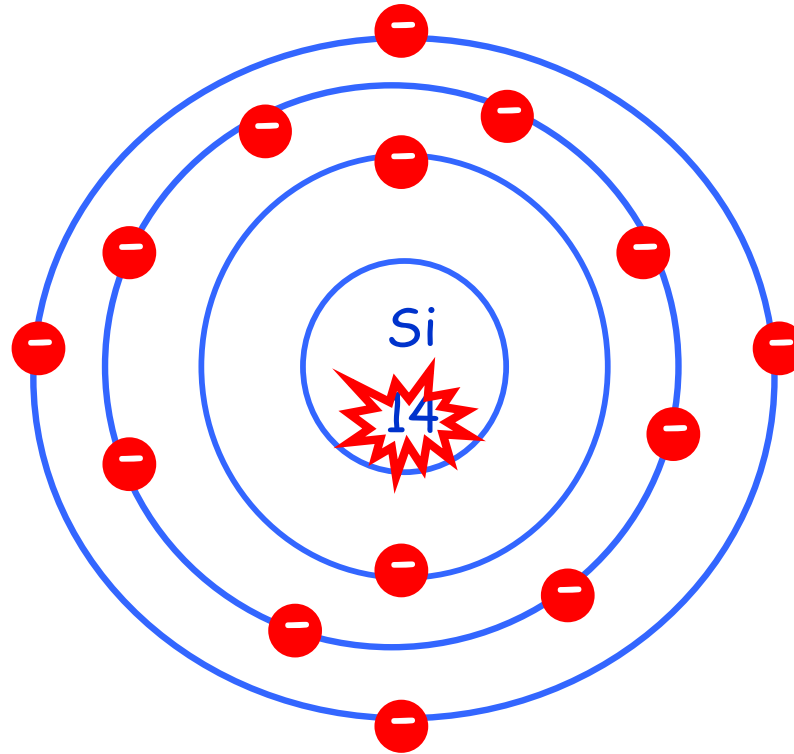
# Diamond lattice structure



The diamond lattice can be thought of as an *fcc* structure with an extra atom placed at  $\mathbf{a}/4 + \mathbf{b}/4 + \mathbf{c}/4$  from each of the *fcc* atoms.

Diamond lattice - [http://en.wikipedia.org/wiki/File:Diamond\\_cubic\\_animation.gif](http://en.wikipedia.org/wiki/File:Diamond_cubic_animation.gif)

# The Silicon Atomic Structure

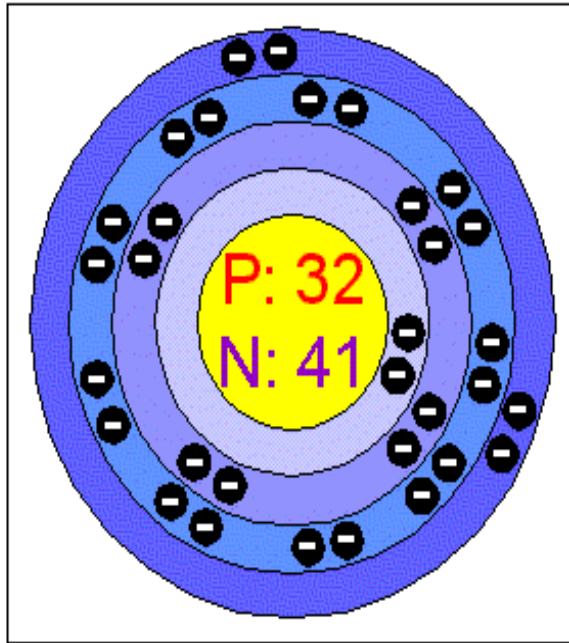


Silicon : It's a Group 4 element which means it has 4 electrons in outer shell

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

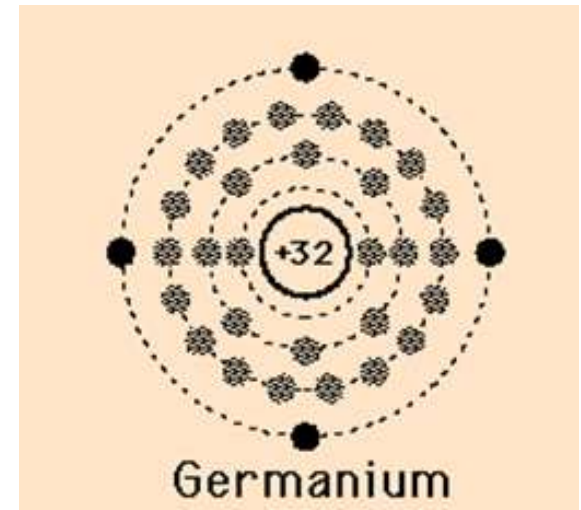
# The Germanium Atomic Structure

## Atomic Structure



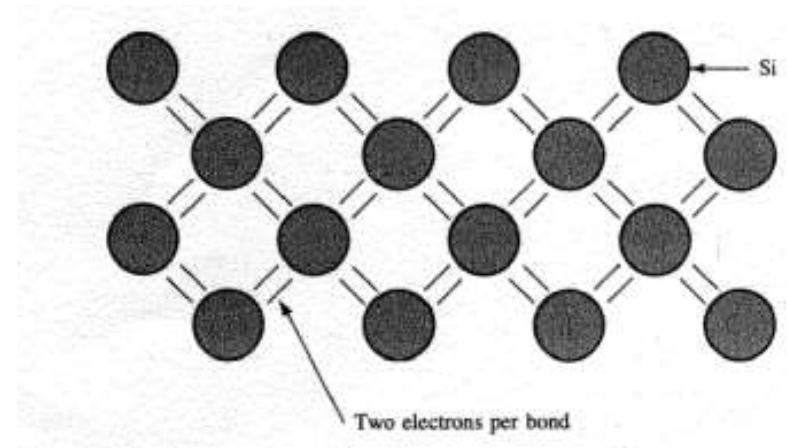
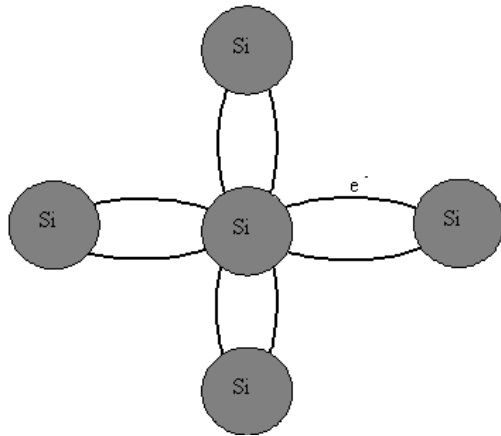
Number of Energy Levels: 4

First Energy Level: 2  
Second Energy Level: 8  
Third Energy Level: 18  
Fourth Energy Level: 4



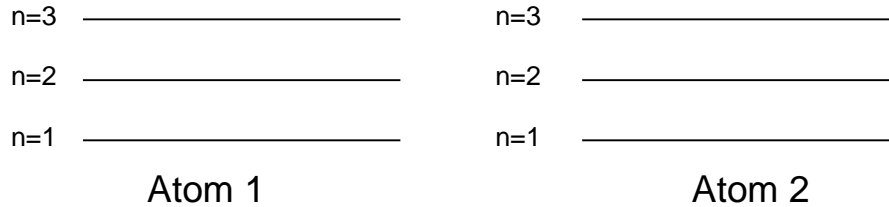
# Bonding of Si atoms

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

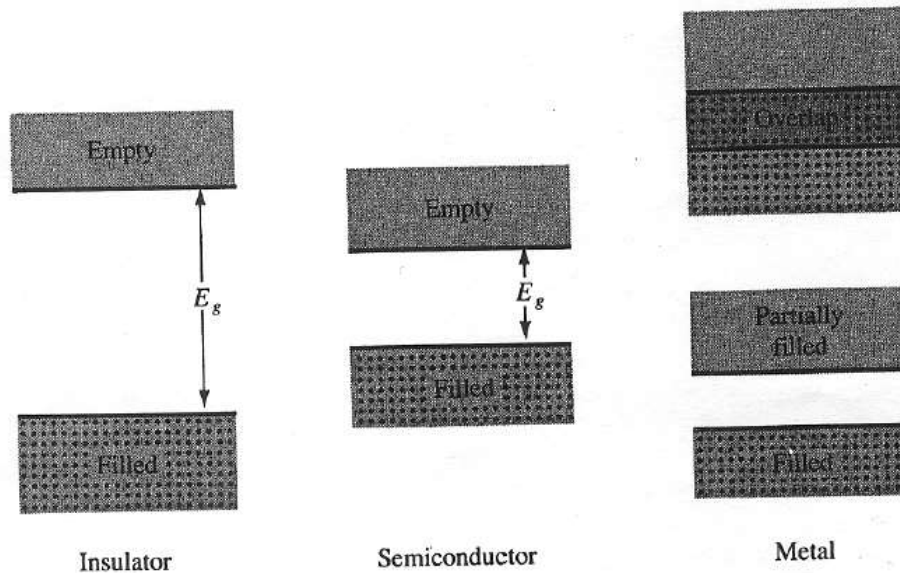


**A Covalent Bond Formed by the Sharing of Electrons in an Outer Energy Level**

# Band Gap Energy



Discrete energy levels for 2 atoms separated by a large distance.



Typical continuous band pictures at 0 K for different solid materials.

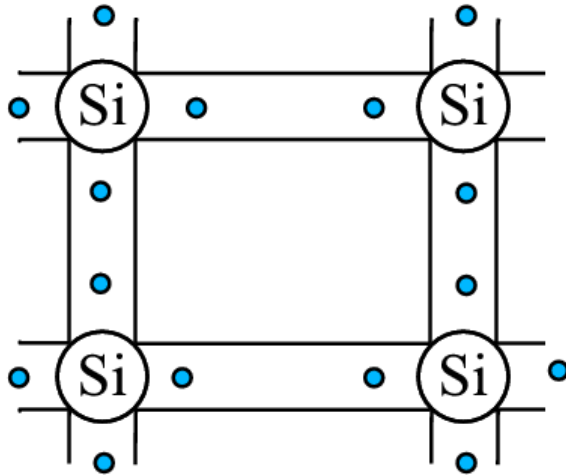
Group	Semi-	Bandgap
IV	Si	1.06 eV
	Ge	0.67
III-V	GaAs	1.4
	GaP	2.2
	InP	1.3
II-VI	CdTe	1.5
	CdS	2.4

Note that the band gap energy,  $E_g$  for insulators is  $\sim 10$  eV, while for metals it is close to 0 eV ( $1\text{eV}=1.6\times 10^{-19}$  J).



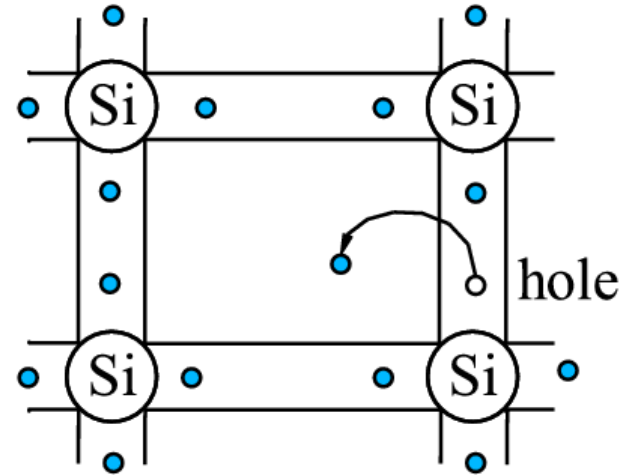
# Electrons and Holes

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

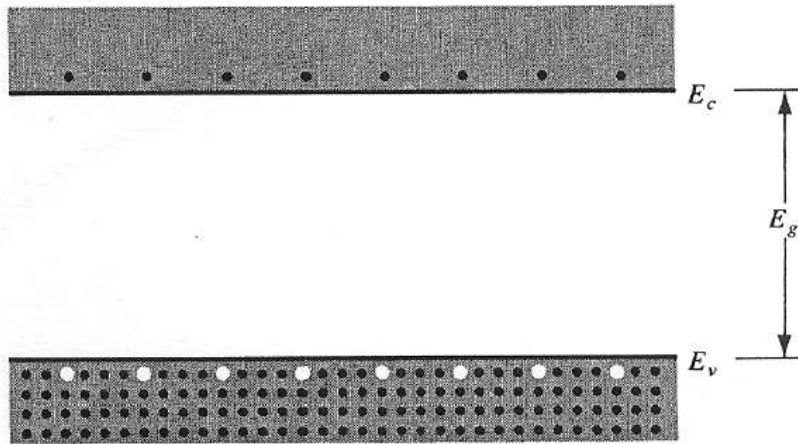
For  $T > 0$

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**.

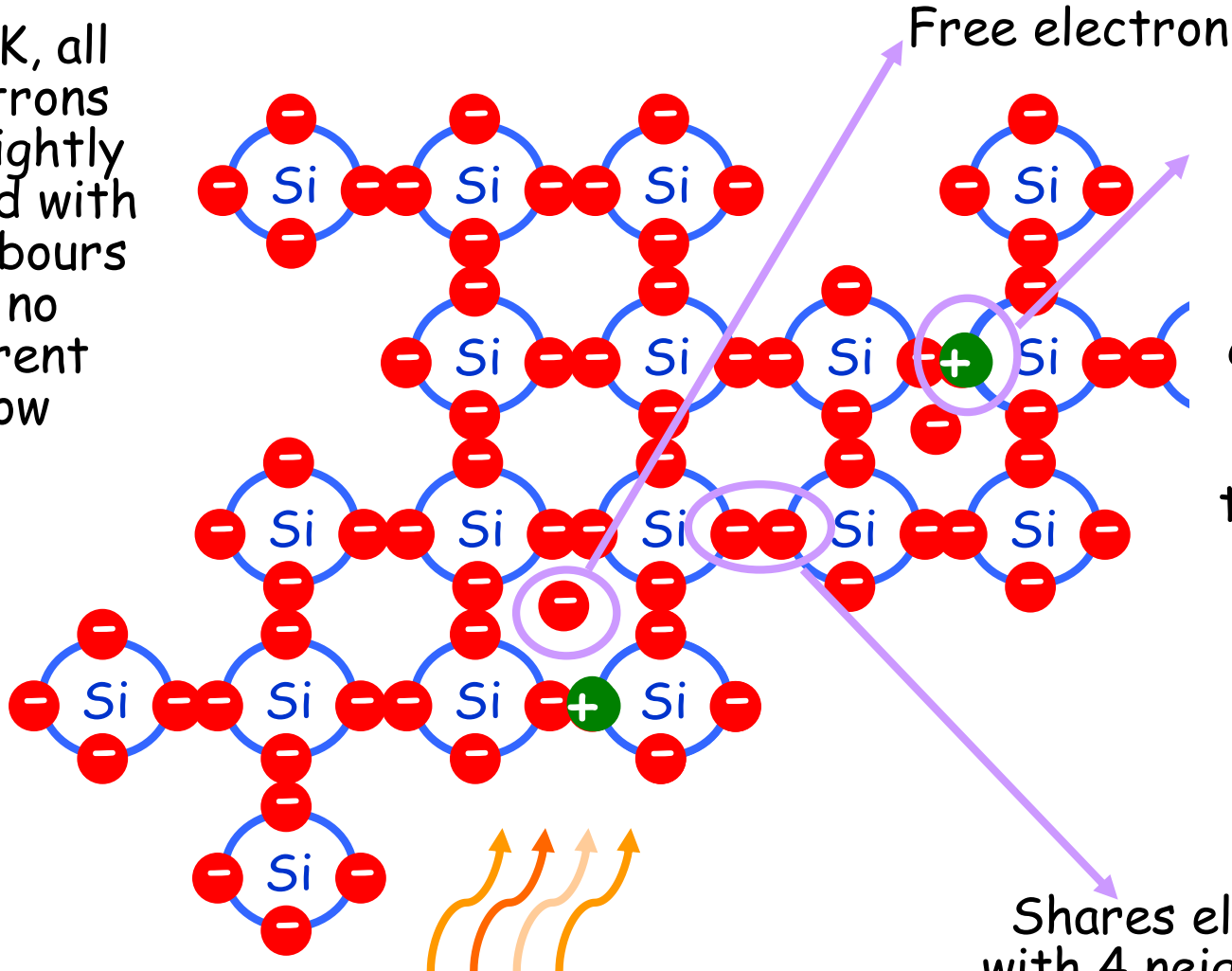
If the conduction band electron and the hole are created by the excitation of a valence band electron to the conduction band, they are called an **electron-hole pair** (EHP).



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  $E_v$ .

# Silicon Lattice Structure

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

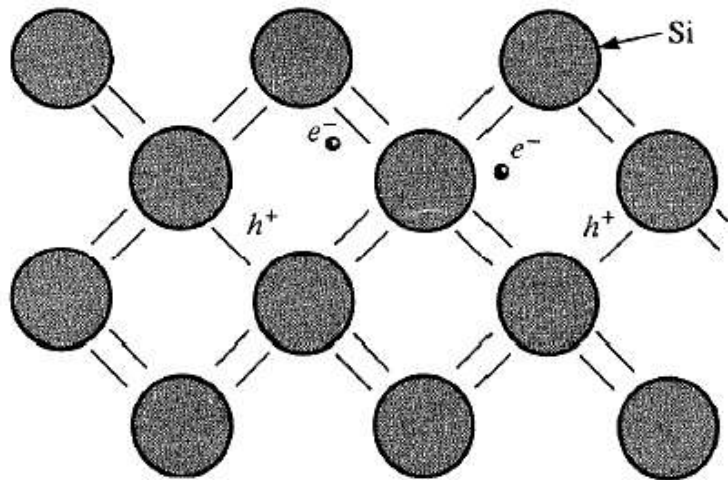
Valence band is filled with electrons

Conduction band is empty

At  $T>0$

Electron-hole pairs are generated

EHPs are the only charge carriers in ***intrinsic material***



$e^-$  : Electron

$h^+$  : Hole

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

Each of these intrinsic carrier concentrations is denoted  $n_i$ .

**Thus for intrinsic materials  $n=p=n_i$**

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

# 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<sup>3</sup>·s) and the recombination rate as  $r_i$ , equilibrium requires that

$$r_i = g_i$$

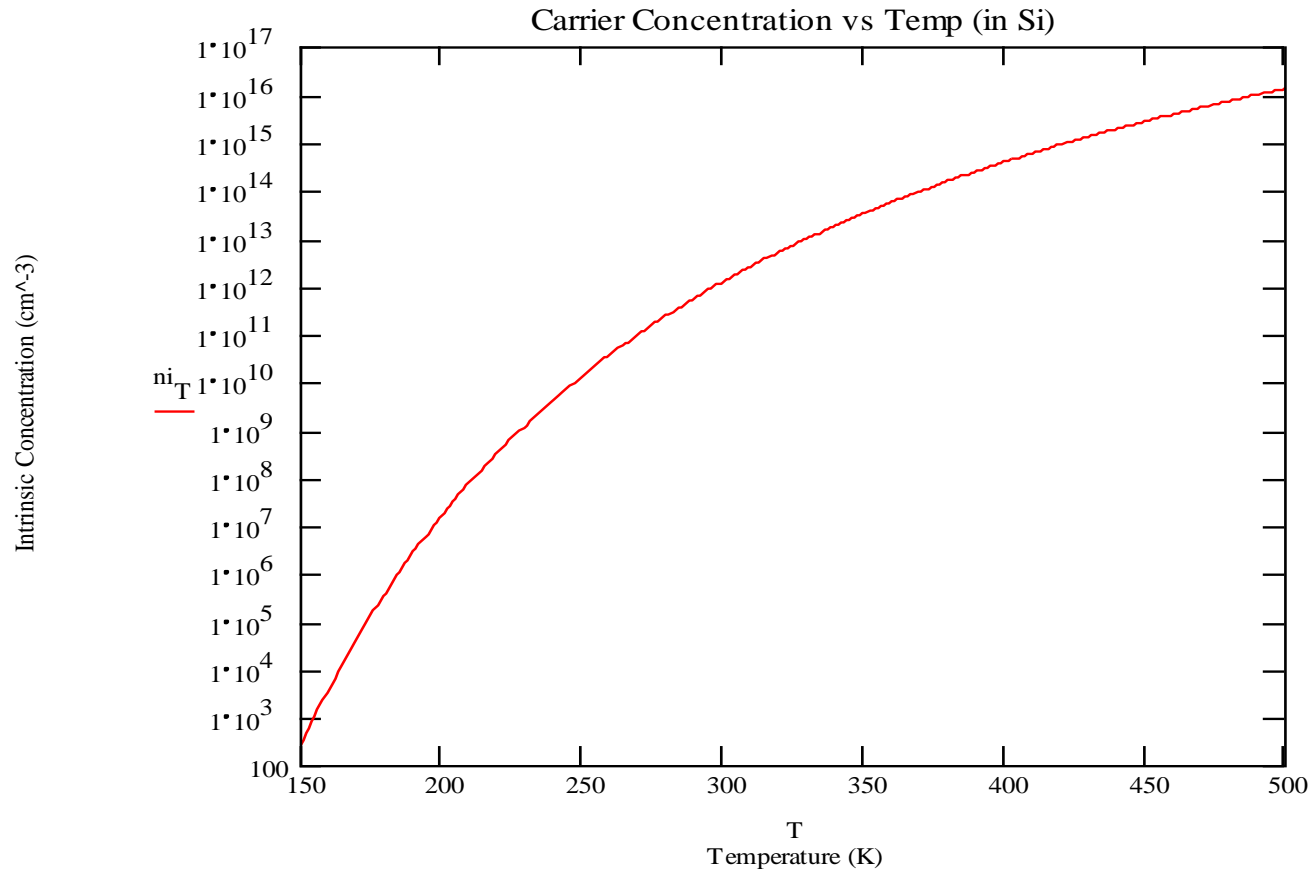
- Each of these rates is temperature dependent. For example,  $g_i(T)$  increases when the temperature is raised, and a new carrier concentration  $n_i$  is established such that the higher recombination rate  $r_i(T)$  just balances generation. At any temperature, we can predict that the rate of recombination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

$$r_i = \alpha_r n_0 p_0 = \alpha_r n_i^2 = g_i$$

- The factor  $\alpha_r$  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

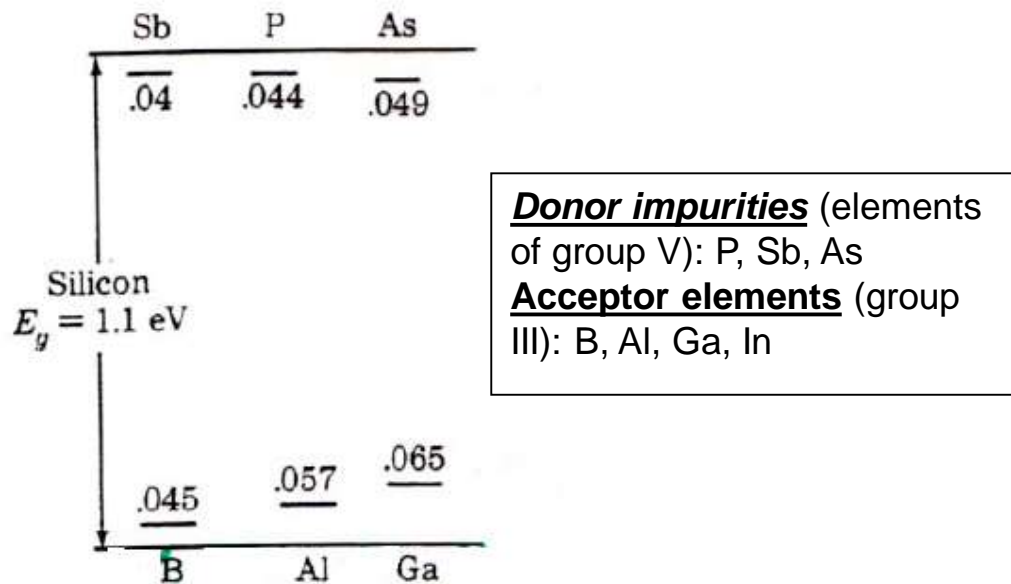


# Increasing conductivity

- 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  $p_0$  are different from the intrinsic carrier concentration  $n_i$ , the material is said to be *extrinsic*.



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

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

Total number of electrons

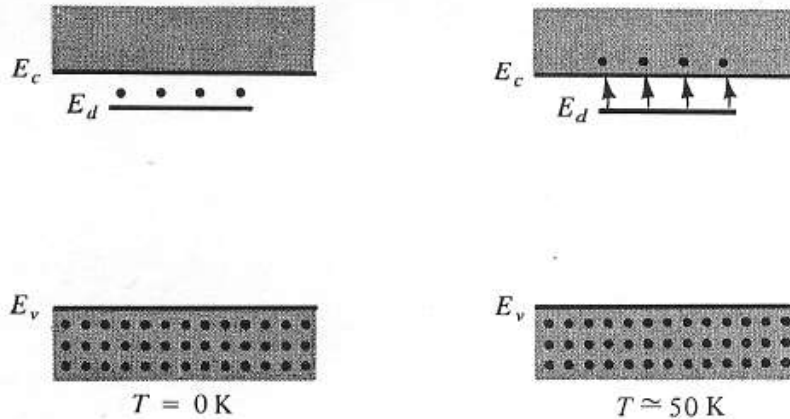
III – Al – 13

IV – Si – 14

V - P - 15

# Extrinsic Material – donation of electrons

## n-type material

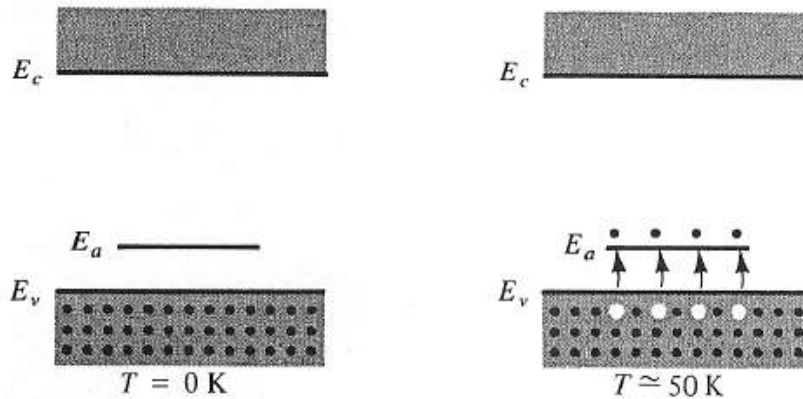


Donation of electrons from a donor level to the conduction band

An impurity from column V introduces an energy level very near the conduction band in Ge or Si. This level is filled with electrons at 0 K, and very little thermal energy is required to excite these electrons to the conduction band. Thus, at about 50-100 K nearly all of the electrons in the impurity level are "donated" to the conduction band. Such an impurity level is called a **donor** level, and the column V impurities in Ge or Si are called donor impurities. From figure we note that the material doped with donor impurities can have a considerable concentration of electrons in the conduction band, even when the temperature is too low for the intrinsic EHP concentration to be appreciable. Thus semiconductors doped with a significant number of donor atoms will have  $n_0 \gg (n_i, p_0)$  at room temperature. This is **n-type** material.

# Extrinsic Material – acceptance of electrons

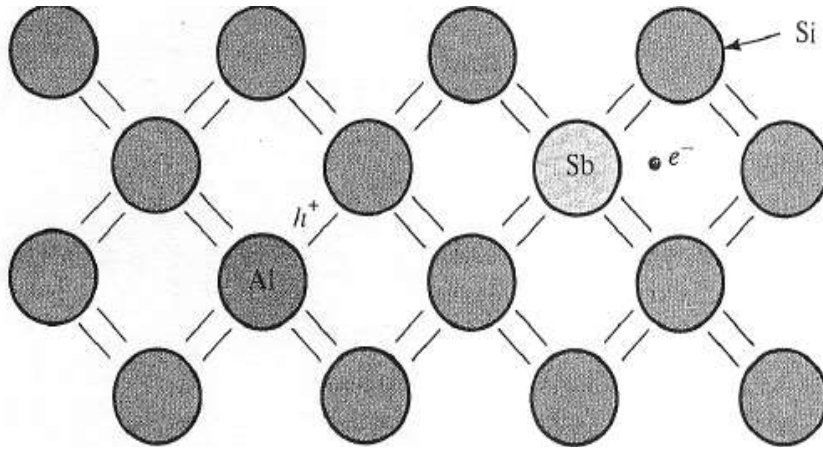
## P-type material



Acceptance of valence band electrons by an acceptor level, and the resulting creation of holes.

Atoms from column III (B, Al, Ga, and In) introduce impurity levels in Ge or Si near the valence band. These levels are empty of electrons at 0 K. At low temperatures, enough thermal energy is available to excite electrons from the valence band into the impurity level, leaving behind holes in the valence band. Since this type of impurity level "accepts" electrons from the valence band, it is called an acceptor level, and the column III impurities are acceptor impurities in Ge and Si. As figure indicates, doping with acceptor impurities can create a semiconductor with a hole concentration  $p_0$  much greater than the conduction band electron concentration  $n_0$  (**this is p-type material**).

# Donor and acceptors in covalent bonding model

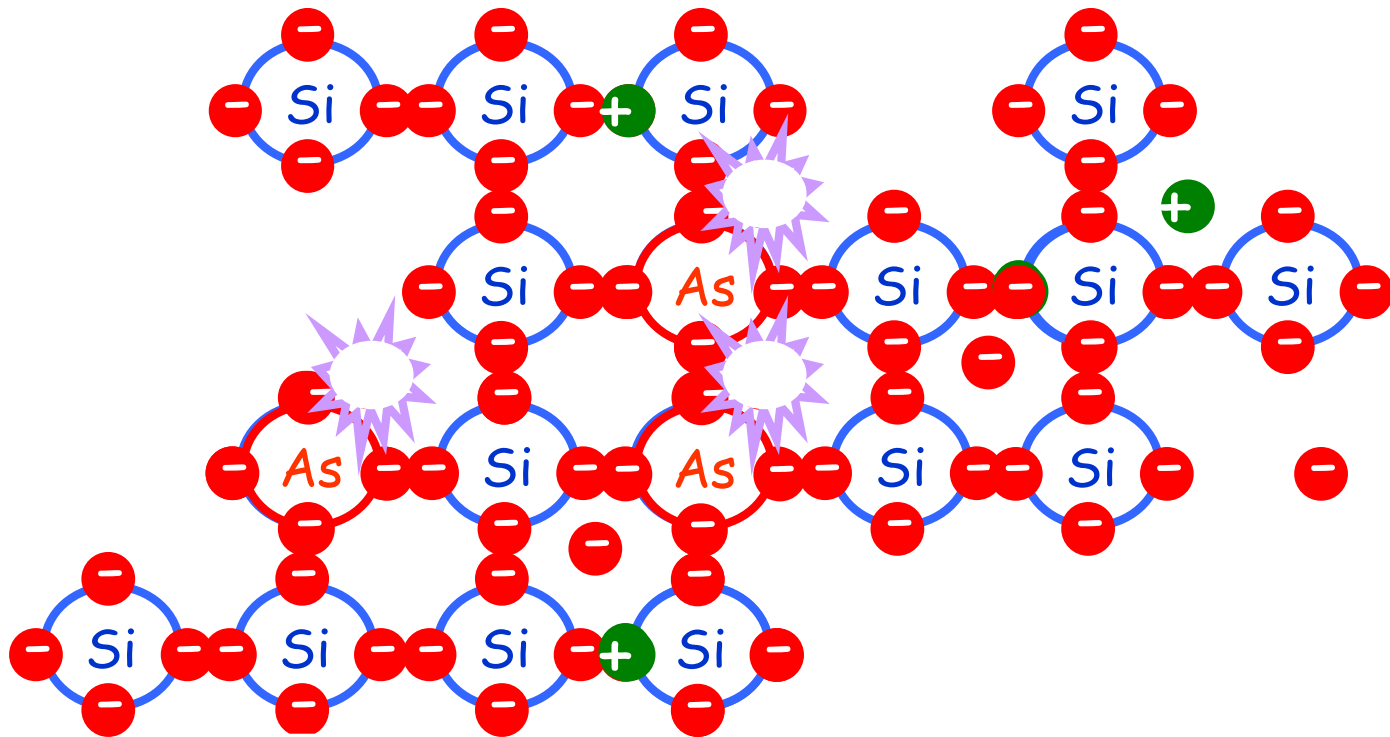


Donor and acceptor atoms in the covalent bonding model of a Si crystal.

In the covalent bonding model, donor and acceptor atoms can be visualized as shown in the Figure. An Sb atom (column V) in the Si lattice has the four necessary valence electrons to complete the covalent bonds with the neighboring Si atoms, plus one extra electron. This fifth electron does not fit into the bonding structure of the lattice and is therefore loosely bound to the Sb atom. A small amount of thermal energy enables this extra electron to overcome its coulombic binding to the impurity atom and be donated to the lattice as a whole. Thus it is free to participate in current conduction. This process is a qualitative model of the excitation of electrons out of a donor level and into the conduction band.

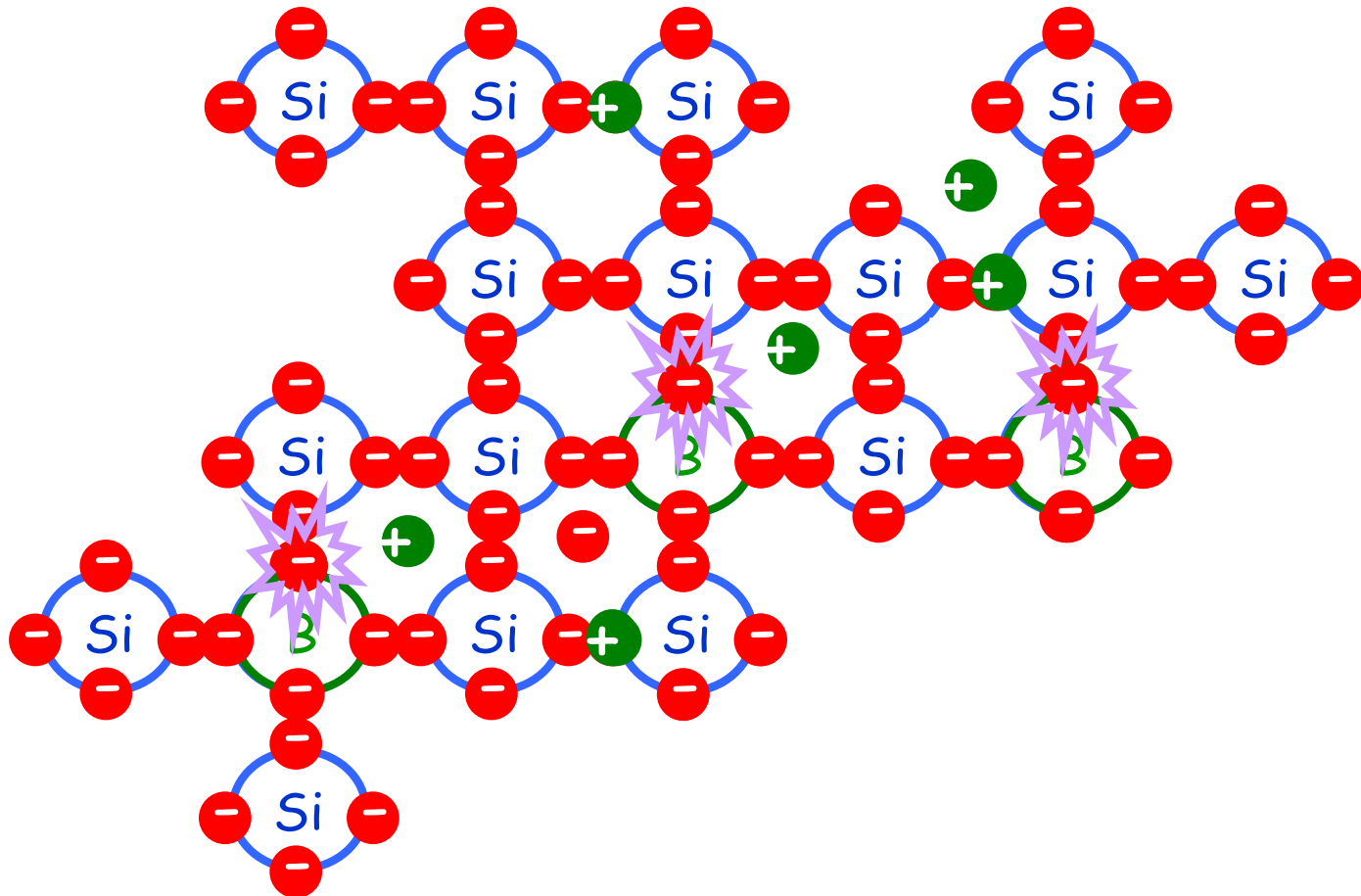
Similarly, the column III impurity Al has only three valence electrons to contribute to the covalent bonding, thereby leaving one bond incomplete. With a small amount of thermal energy, this incomplete bond can be transferred to other atoms as the bonding electrons exchange positions.

# Increasing conductivity by doping



- Inject Arsenic into the crystal with an implant step.
- Arsenic is Group 5 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 an 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 Group 3 element and 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)



# Calculation of binding energy

We can calculate rather simply the approximate energy required to excite the fifth electron of a donor atom into the conduction band (the donor binding energy) based on the Bohr model results:

$$E = \frac{m_n^* q^4}{2K^2 \hbar^2}$$

where  $m_n^*$  is the effective mass typical of semiconductors ( $m_n^* = 0.12m_0$ ),  $m_0 = 9.11 \times 10^{-31}$  kg is the electronic rest mass),  $\hbar = h / 2\pi$  is a reduced Planck's constant and

$$K = 4\pi\epsilon_0\epsilon_r$$

where  $\epsilon_r$  is the relative dielectric constant of the semiconductor material and  $\epsilon_0 = 8.85 \times 10^{-12}$  F/m is the permittivity of free space.

# The Fermi level

Electrons in solids obey Fermi - Dirac statistics:

The following consideration are used in the development of this statistics:

$$f(E) = \frac{1}{1 + \exp[(E - E_F)/kT]} \quad (4.6)$$

where  $k$  is Boltzmann's constant

$$k = 8.62 \cdot 10^{-5} \text{ eV/K} = 1.38 \cdot 10^{-23} \text{ J/K}.$$

1. **indistinguishability of the electrons,**
2. **electron wave nature,**
3. **the Pauli exclusion principle.**

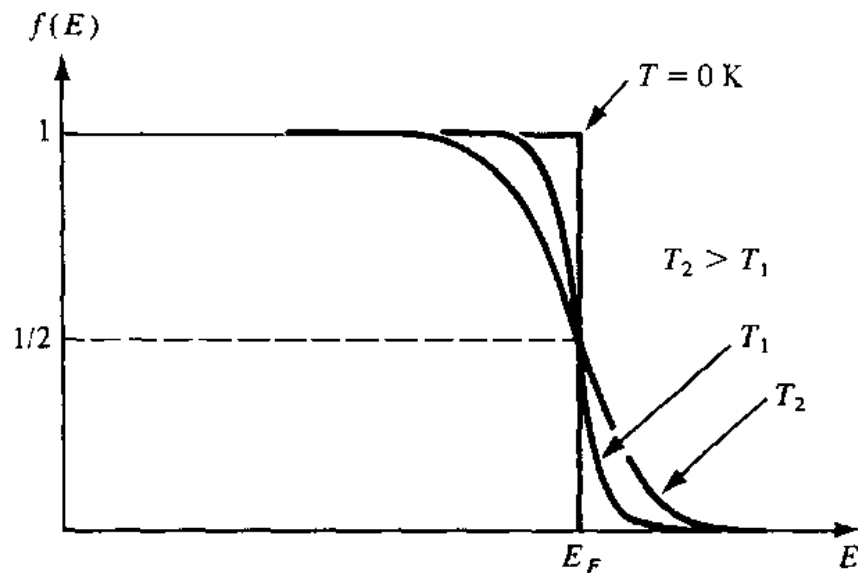
The function  $f(E)$  called **the Fermi-Dirac distribution function** gives the probability that an available energy state at  $E$  will be occupied by an electron at absolute temperature  $T$ .

The quantity  $E_F$  is called **the Fermi level**, and it represents an important quantity in the analysis of semiconductor behavior. For an energy  $E = E_F$  the occupation probability is

$$f(E_F) = [1 + \exp[(E_F - E_F)/kT]]^{-1} = \frac{1}{1+1} = \frac{1}{2} \quad (4.7)$$

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

# The Fermi - Dirac distribution function



The Fermi - Dirac distribution function for different temperatures

At  $T=0\text{K}$   $f(E)$  has rectangular shape  
 the denominator of the exponent is  
 $1/(1+0)=1$  when  $(E < E_f)$ , exp. negative  
 $1/(1+\infty)=0$  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. The probability exists for

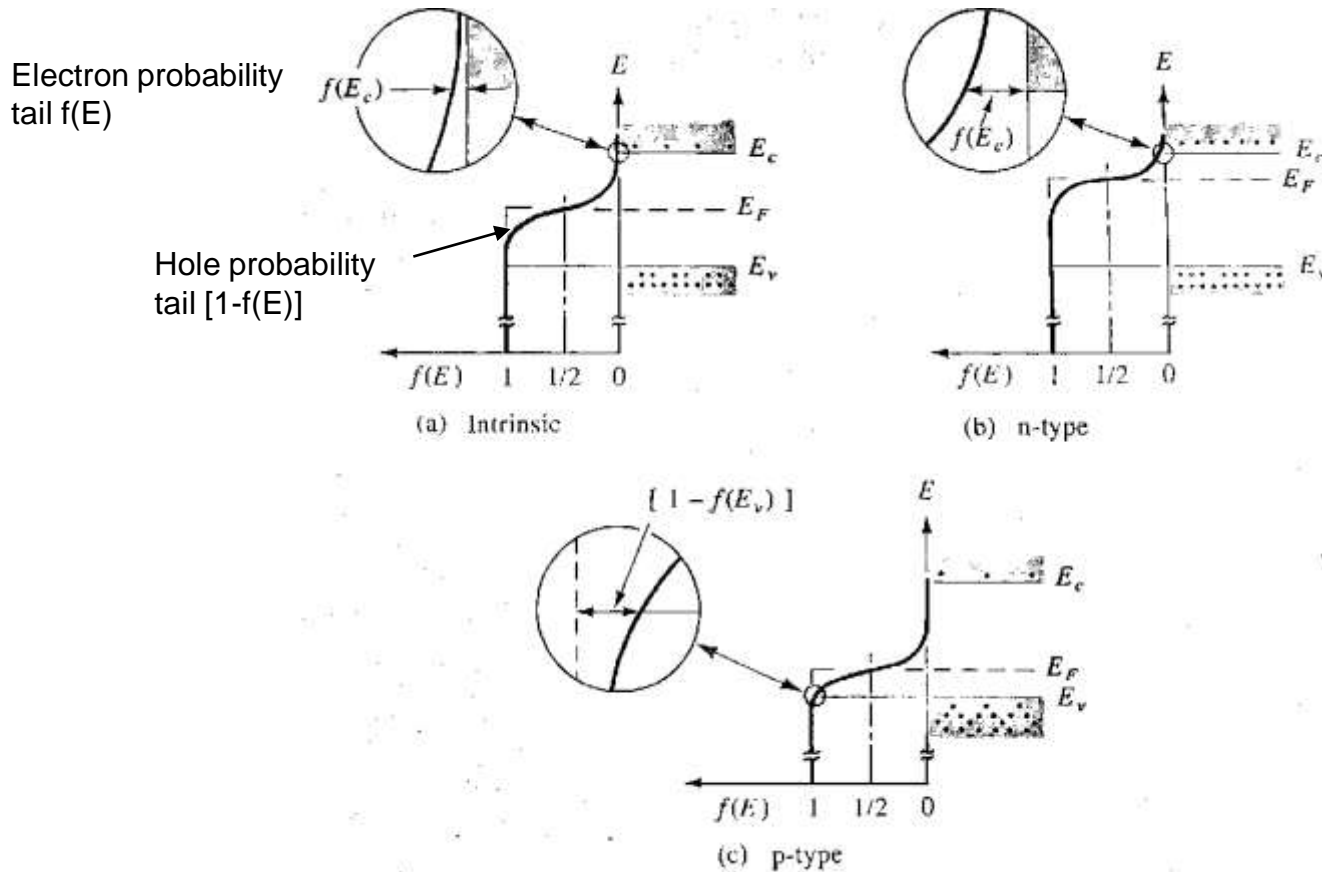
state  $\Delta E$  above  $E_F$  is filled –  $f(E_F + \Delta E)$

state  $\Delta E$  below  $E_F$  is filled –  $[1 - f(E_F - \Delta E)]$

The symmetry of the distribution of empty and filled states about  $E_F$  makes the Fermi level a natural reference point in calculations of electron and hole concentrations in semiconductors.

In applying the Fermi-Dirac distribution to semiconductors, we must recall that  $f(E)$  is the probability of occupancy of an available state at  $E$ . Thus if there is no available state at  $E$  (e.g., in the band gap of a semiconductor), there is no possibility of finding an electron there.

# Relation between $f(E)$ and the band structure



In intrinsic material the Fermi level  $E_F$  must lie at the middle of the band gap.

In n-type material the distribution function  $f(E)$  must lie above its intrinsic position on the energy scale. The energy difference  $(E_c - E_F)$  gives a measure of  $n$ .

For p-type material the Fermi level lies near the valence band such that the  $[1-f(E)]$  tail below  $E_v$  is larger than the  $f(E)$  tail above  $E_c$ . The value of  $(E_F - E_v)$  indicates how strongly p-type the material is.

The distribution function has values within the band gap between  $E_v$  and  $E_c$ , but there are no energy states available, and no electron occupancy results from  $f(E)$  in this range.

# 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

$$n_0 = \int_{E_c}^{\infty} f(E)N(E)dE \quad (4.8)$$

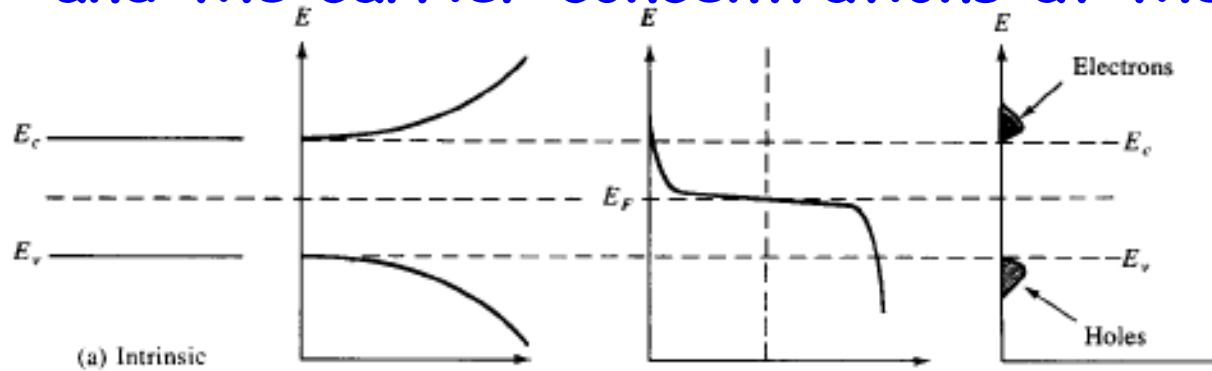
where  $\mathbf{N(E)dE}$  is the density of states ( $\text{cm}^{-3}$ ) in the energy range  $\mathbf{dE}$ . The subscript 0 used for the electron and hole concentration symbols ( $n_0, p_0$ ) indicates equilibrium conditions.

The number of electrons per unit volume in the energy range  $\mathbf{dE}$  is the product of the density of states and the probability of occupancy  $\mathbf{f(E)}$ . Thus the total electron concentration is the integral over the entire conduction band. The function  $\mathbf{N(E)}$  can be calculated by using quantum mechanics and the Pauli exclusion principle.

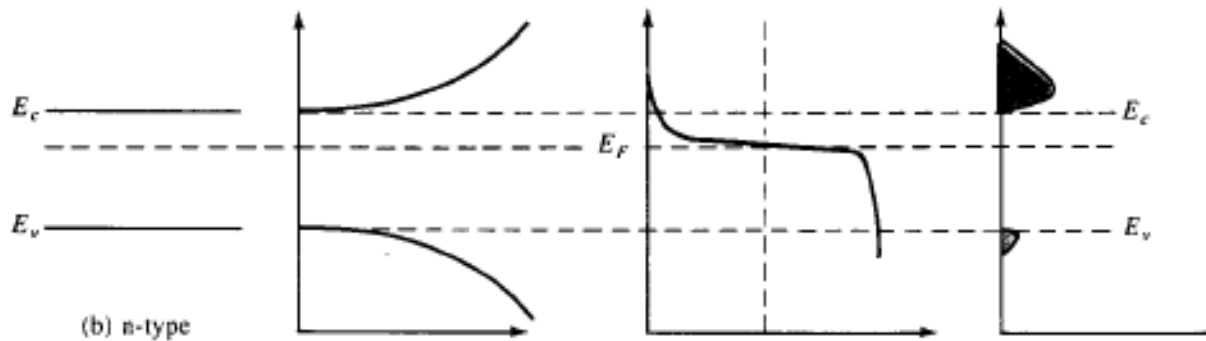
$\mathbf{N(E)}$  is proportional to  $\mathbf{E^{1/2}}$ , so the density of states in the conduction band increases with electron energy. On the other hand, the Fermi function becomes extremely small for large energies. The result is that the product  $\mathbf{f(E)N(E)}$  decreases rapidly above  $\mathbf{E_c}$ , and very few electrons occupy energy states far above the conduction band edge.

Similarly, the probability of finding an empty state (hole) in the valence band  $\mathbf{[1 - f(E)]}$  decreases rapidly below  $\mathbf{E_v}$ , and most holes occupy states near the top of the valence band.

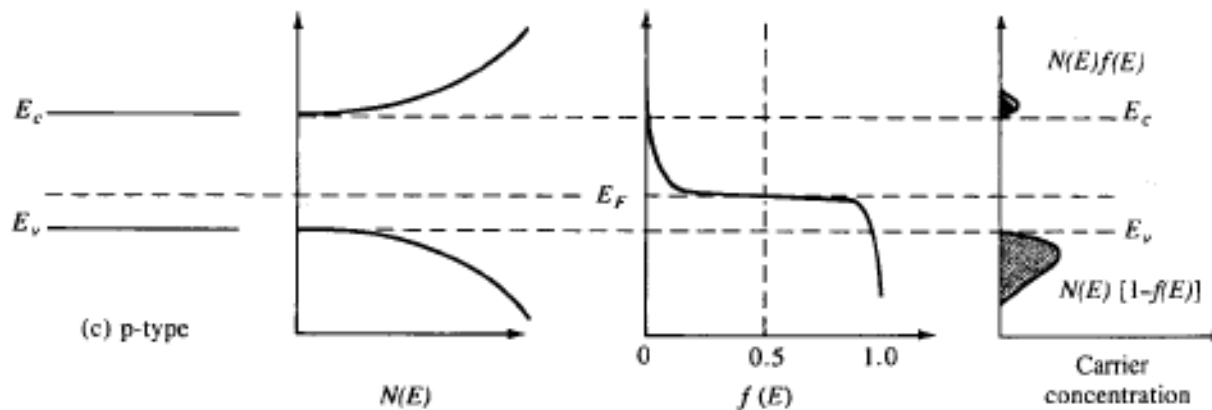
# Band diagram, density of states, Fermi-Dirac distribution, and the carrier concentrations at thermal equilibrium



Intrinsic semiconductor



n-type semiconductor



p-type semiconductor

The conduction band electron concentration is simply the effective density of states at  $E_c$  times the probability of occupancy at  $E_c$ :

$$n_0 = N_c f(E_c) \quad (4-9)$$

In this expression we assume the Fermi level  $E_F$  lies at least several  $kT$  below the conduction band. Then the exponential term is large compared with unity, and the Fermi function  $f(E_c)$  can be simplified as

$$f(E_c) = \frac{1}{1 + \exp[(E_c - E_F)/kT]} \cong \exp[-(E_c - E_F)/kT] \quad (4-10)$$

Since  $kT$  at room temperature is only **0.026 eV**, this is generally a good approximation. For this condition the concentration of electrons in the conduction band is

$$n_0 = N_c \exp[-(E_c - E_F)/kT] \quad (4-11)$$

It can be shown that the effective density of states  $N_c$  is

$$N_c = 2 \left( \frac{2\pi m_n^* kT}{h^2} \right)^{3/2} \quad (4-12)$$

Values of  $N_c$  can be tabulated as a function of temperature. As Eq. (4-11) indicates, the electron concentration increases as  $E_F$  moves closer to the conduction band.

By similar arguments, the concentration of holes in the valence band is

$$p_0 = N_v [1 - f(E_v)] \quad (4-13)$$

where  $N_v$  is the effective density of states in the valence band.



The probability of finding an empty state at  $E_v$ , is

$$1 - f(E_v) = 1 - \frac{1}{1 + \exp[(E_v - E_F)/kT]} \cong \exp[-(E_F - E_v)/kT] \quad (4-14)$$

for  $E_F$  larger than  $E_v$  by several  $kT$ . From these equations, the concentration of holes in the valence band is

$$p_0 = N_v \exp[-(E_F - E_v)/kT] \quad (4-15)$$

The effective density of states in the valence band reduced to the band edge is

$$N_v = 2 \left( \frac{2\pi m_p^* kT}{h^2} \right)^{3/2} \quad (4-16)$$

Eq. (4-15) predicts that the hole concentration increases as  $E_F$  moves closer to the valence band.

The electron and hole concentrations predicted by Eqs. (4-11) and (4-15) are valid whether the material is intrinsic or doped, provided thermal equilibrium is maintained. Thus for intrinsic material,  $E_F$  lies at some intrinsic level  $E_i$  near the middle of the band gap, and the intrinsic electron and hole concentrations are

$$n_i = N_c \exp[-(E_c - E_i)/kT] , \quad p_i = N_v \exp[-(E_i - E_v)/kT] \quad (4-17)$$

The product of  $n_0$  and  $p_0$  at equilibrium is a constant for a particular material and temperature, even if the doping is varied:

$$\begin{aligned} n_0 p_0 &= (N_c \exp[-(E_c - E_F)/kT])(N_v \exp[-(E_F - E_v)/kT]) = \quad (4-18a) \\ &= N_c N_v \exp[-(E_c - E_v)/kT] = N_c N_v \exp[-E_g/kT] \end{aligned}$$

$$\begin{aligned} n_i p_i &= (N_c \exp[-(E_c - E_i)/kT])(N_v \exp[-(E_i - E_v)/kT]) = \quad (4-18b) \\ &= N_c N_v \exp[-E_g/kT] \end{aligned}$$

In Eqns. (4-18a) and (4-18b)  $E_g = E_c - E_v$ . The intrinsic electron and hole concentrations are equal (since the carriers are created in pairs),  $n_i = p_i$ ; thus the intrinsic concentration is

$$n_i = \sqrt{N_c N_v} \exp(-E_g/2kT) \quad (4-19)$$

The constant product of electron and hole concentrations in Eq. (4-18) can be written conveniently as

$$n_0 p_0 = n_i^2 \quad (4-20)$$

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

Comparing Eqs. (4-17) and (4-19), we note that the intrinsic level  $E_i$  is the middle of the band gap ( $E_c - E_i = E_g/2$ ), if the effective densities of states  $N_c$  and  $N_v$  are equal.

There is usually some difference in effective mass for electrons and holes (e.g. for Si –  $m_n^* = 0.26m_0$ ,  $m_p^* = 0.39m_0$ ), however, and, therefore,  $N_c$  and  $N_v$  are slightly different as Eqs. (4-12) and (4-16) indicate.

Another convenient way of writing Eqs. (4-11) and (4-15) is

$$n_0 = n_i \exp[(E_F - E_i)/kT] \quad (4-21)$$

$$p_0 = n_i \exp[(E_i - E_F)/kT] \quad (4-22)$$

obtained by the application of Eq. (4-17). This form of the equations indicates directly that the electron concentration is  $n_i$ , when  $E_F$  is at the intrinsic level  $E_i$ , and that  $n_0$  increases exponentially as the Fermi level moves away from  $E_i$  toward the conduction band. Similarly, the hole concentration  $p_0$  varies from  $n_i$ , to larger values as  $E_F$  moves from  $E_i$  toward the valence band. Since these equations reveal the qualitative features of carrier concentration so directly, they are particularly convenient to remember.

# Conductivity of Intrinsic and Extrinsic Semiconductors

The **conductivity** of material is determined as a product

$$\sigma = nq\mu \quad (\Omega \cdot \text{cm})^{-1}; \quad \sigma = 1/\rho$$

where  $n$  - the number of charge carriers (in  $\text{cm}^3$ ),  $q$  - the charge per carrier, and  $\mu$  - the mobility of each carrier

For **semiconductors** we can write  $\sigma = n_n q \mu_n + n_p q \mu_p$ . Since for **intrinsic semiconductors**  $n_i = n_n = n_p = n_0 = p_0 = A \exp(-E_g/2kT)$ , where  $A$  is a constant ( $A = \sqrt{N_c N_v}$ ), we can rewrite

$\sigma = n_n q \mu_n + n_p q \mu_p = n_i q (\mu_n + \mu_p)$  (where  $\mu$  is measured in  $\text{m}^2/\text{Vs}$ ) or  $\sigma = Aq(\mu_n + \mu_p) \exp(-E_g/2kT)$  or  $\sigma = \sigma_0 \exp(-E_g/2kT)$ , where  $\sigma_0$  is a constant  $\rightarrow$  carrier density, mobility.

For **extrinsic semiconductors** one type (n- or p-) of carriers are much higher than the other type, but the product  $n_0 p_0 = n_i^2$  is still a constant.

The carriers with higher density is majority carriers  $\rightarrow$  determine the conductivity of **extrinsic semiconductor**.

For Si  $\mu_n = 0.135 \text{ m}^2/\text{Vs}$ ,  $\mu_p = 0.048 \text{ m}^2/\text{Vs}$ ;  
for Ge  $\mu_n = 0.39 \text{ m}^2/\text{Vs}$ ,  $\mu_p = 0.19 \text{ m}^2/\text{Vs}$ .

# Conductivity of Extrinsic Semiconductors

Typical carrier densities in intrinsic & extrinsic semiconductors

Si at 300K, intrinsic carrier density  $n_i = 1.5 \times 10^{16}/\text{m}^3$

Extrinsic Si doped with As  $\rightarrow$  typical concentration  $10^{21}$  atoms/ $\text{m}^3$ :

Majority carriers  $n_0 = 10^{21} \text{ e}/\text{m}^3$  ; Mass action law:  $n_i^2 = n_0 p_0$

Minority carriers:  $p_0 = (1.5 \times 10^{16})^2 / 10^{21} = 2.25 \times 10^{11} \text{ holes}/\text{m}^3$

Conductivity:

Majority carriers:  $\sigma_n = 10^{21} \times 0.135 \times 1.6 \times 10^{-19} \text{ (e}/\text{m}^3 \text{) (m}^2 \text{ /Vs) (A}\cdot\text{s C) = } 0.216 \text{ (}\Omega \text{ cm)}^{-1}$

Minority carriers:  $\sigma_p = 2.25 \times 10^{11} \times 0.048 \times 1.6 \times 10^{-19} = 0.173 \times 10^{-10} \text{ (}\Omega \text{ cm)}^{-1}$

Conductivity total  $\sigma_{\text{total}} = \sigma_n + \sigma_p \approx 0.216 \text{ (}\Omega \text{ cm)}^{-1}$

## Summary – Extrinsic Semiconductors

<u>Extrinsic Semicon.</u>	<u>Majority Carrier</u>	<u>Minority Carrier</u>	<u>Conductivity <math>\sigma</math></u>
n-type:	$n_0$ density of electrons in n-semi.	$p_0$ density of holes in n-semi.	$\sigma = n_0 q \mu_n$
p-type	$p_0$ density of holes in p-semi.	$n_0$ density of electrons in p-semi.	$\sigma = p_0 q \mu_p$

# Conductivity of Intrinsic and Extrinsic Semiconductors: Effect of Temperature

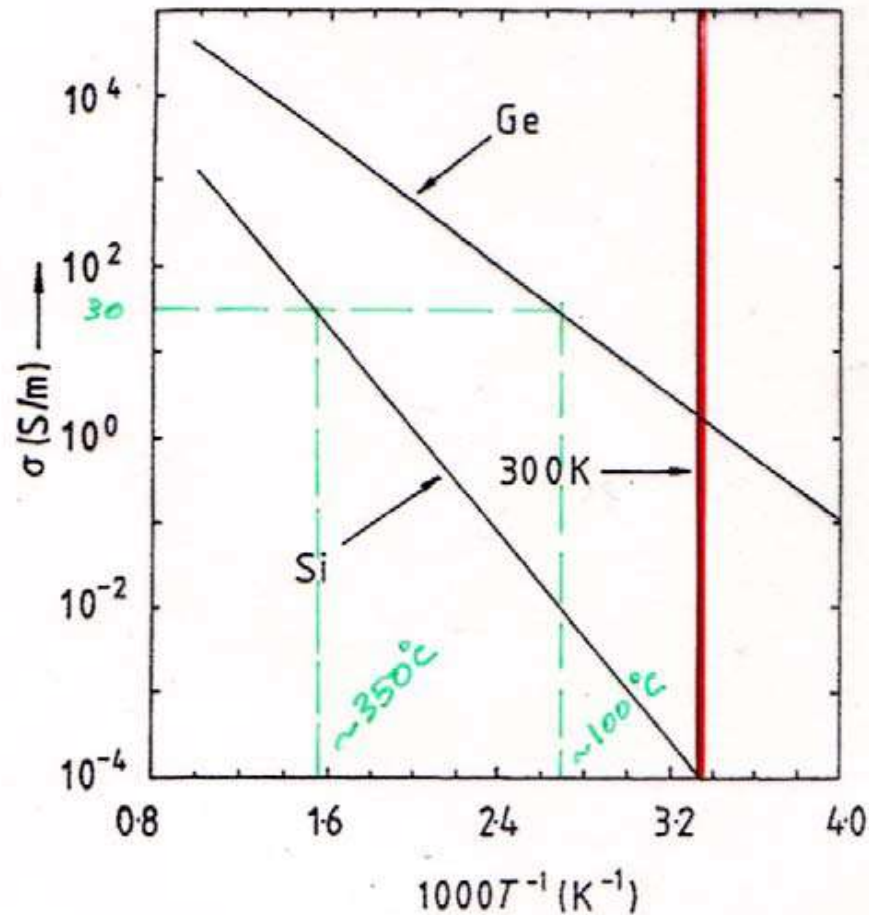
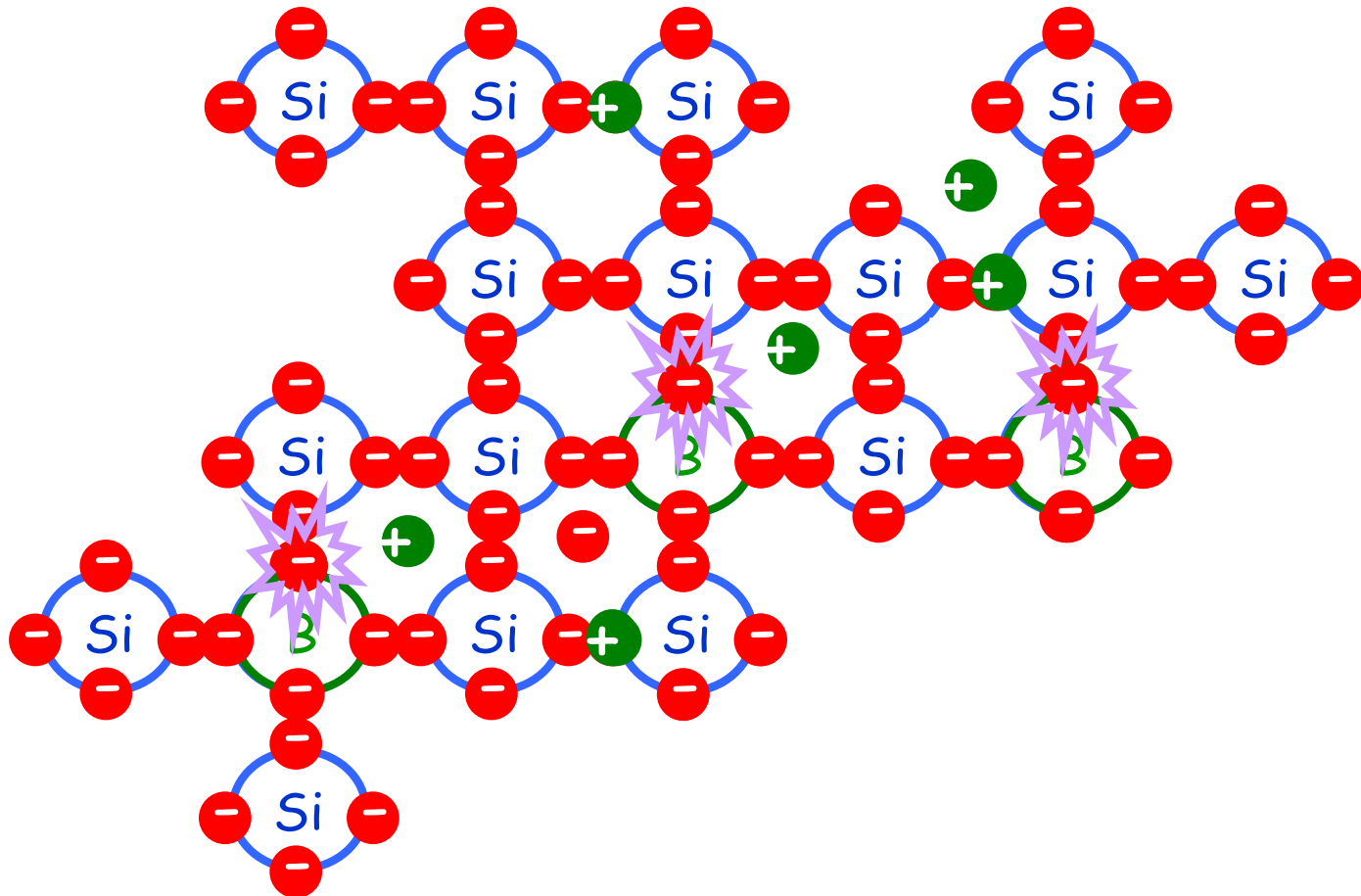


Fig.5-2(a) Conductivity  $\sigma$  versus  $1/T$  for Si and Ge

**Illustrative Problem:** calculate  $\sigma$  of Si at room temperature (20 °C  $\rightarrow$  293 K) and at 150 °C  $\rightarrow$  423 K).

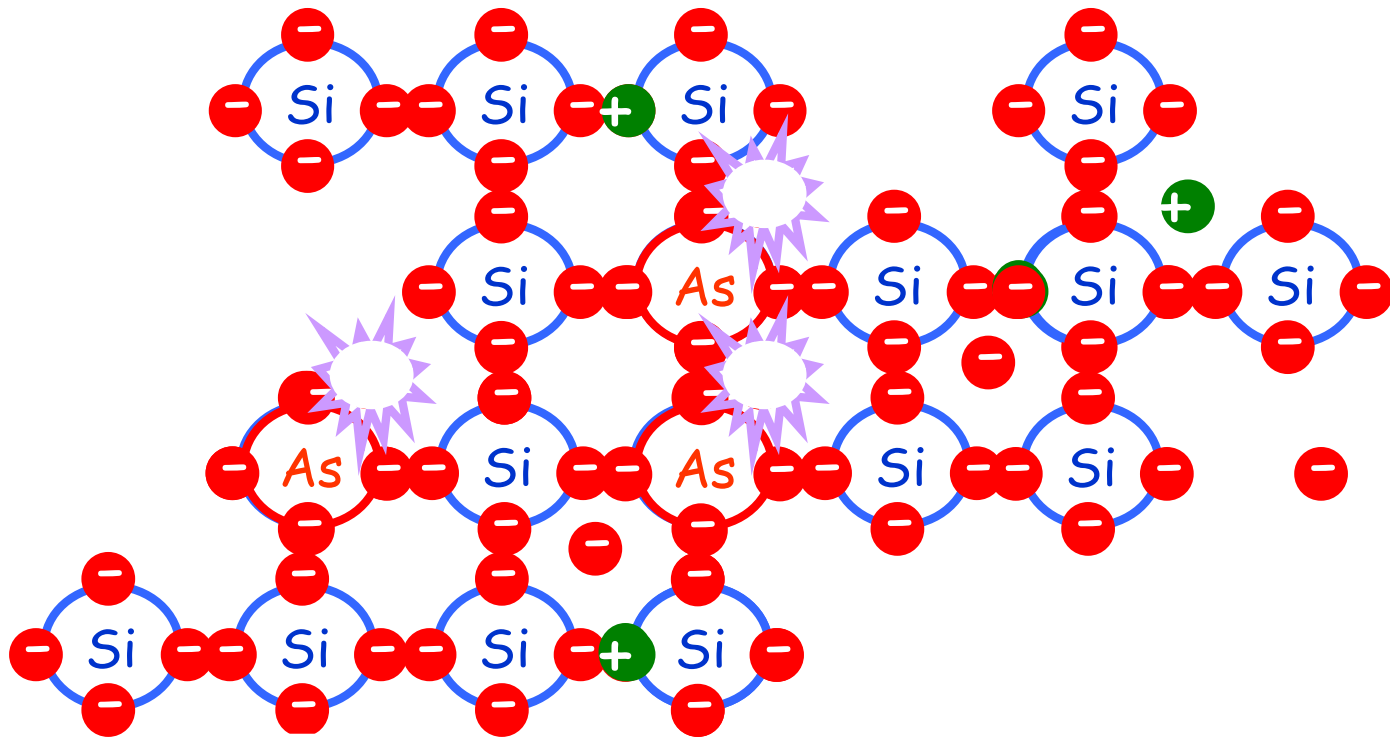
# Increasing conductivity by doping



- Inject Boron into the crystal with an implant step.
- Boron is Group 3 element and 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)



# Increasing conductivity by doping



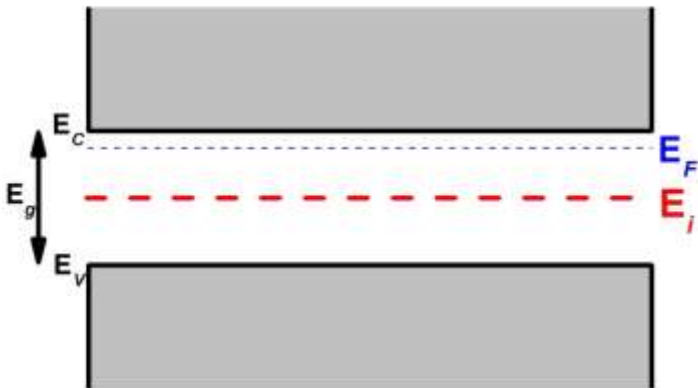
- Inject Arsenic into the crystal with an implant step.
- Arsenic is Group 5 element with 5 electrons in its outer shell, (one more than silicon).
- This introduces extra electrons into the lattice which can be released through the application of heat and so produces an electron current
- The result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

# Summary



Doped semiconductors

*n*-type



$$n_0 = n_i \exp[(E_F - E_i) / kT]$$

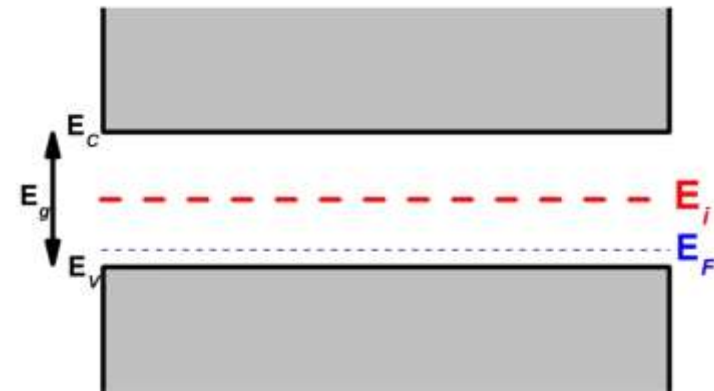
Intrinsic semiconductors

$$n_i = N_c \exp[-(E_c - E_i) / kT]$$

$$p_i = N_v \exp[-(E_i - E_v) / kT]$$

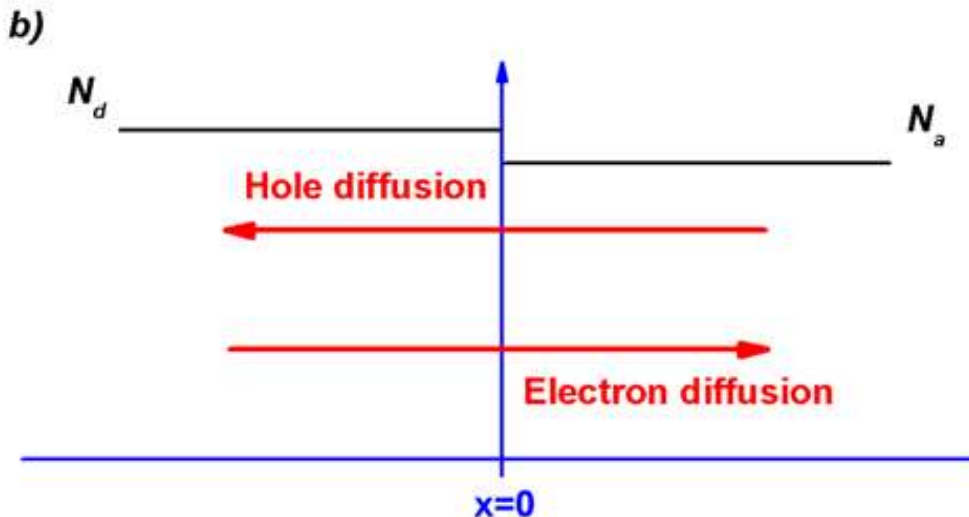
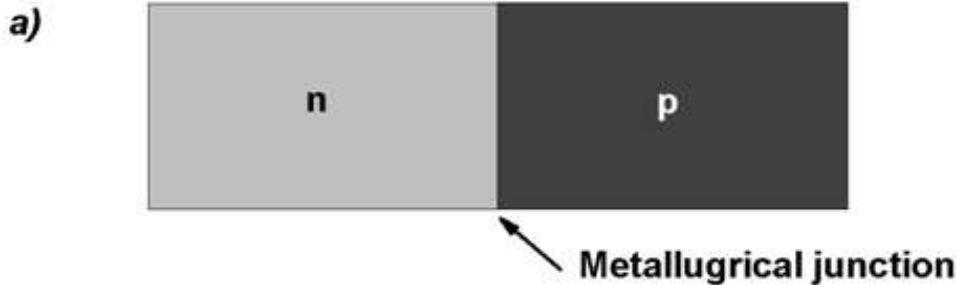
$$n_0 p_0 = n_i^2$$

*p*-type



$$p_0 = n_i \exp[(E_i - E_F) / kT]$$

# *pn Junction*



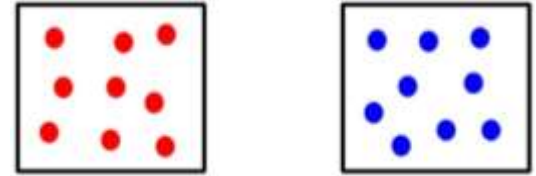
The interface separating the *n* and *p* regions is referred to as the *metallurgical junction*.

For simplicity we will consider a **step junction** in which the doping concentration is uniform in each region and there is an abrupt change in doping at the junction.

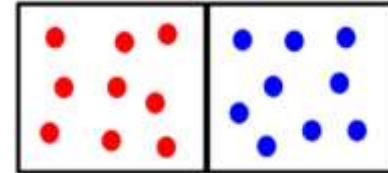
Initially there is a very large density gradient in both the electron and hole concentrations. Majority carrier electrons in the *n* region will begin diffusing into the *p* region and majority carrier holes in the *p* region will begin diffusing into the *n* region. If we assume there are no external connections to the semiconductor, then this diffusion process cannot continue indefinitely.

# Diffusion

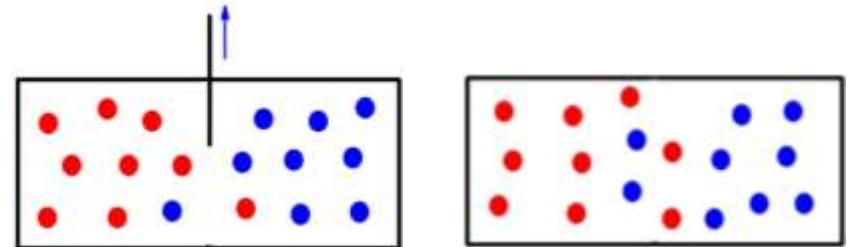
Let us assume that we have two boxes- one contains red air molecules while another one contains blue molecules. This could be due to appropriate types of pollution.



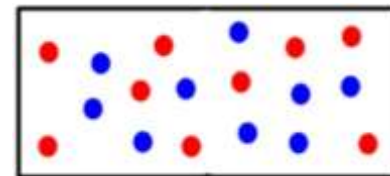
Let us join these 2 boxes together and remove the wall between them.



Each type of molecules starts to move to the region of their low concentration due to the concentration gradient in the middle.

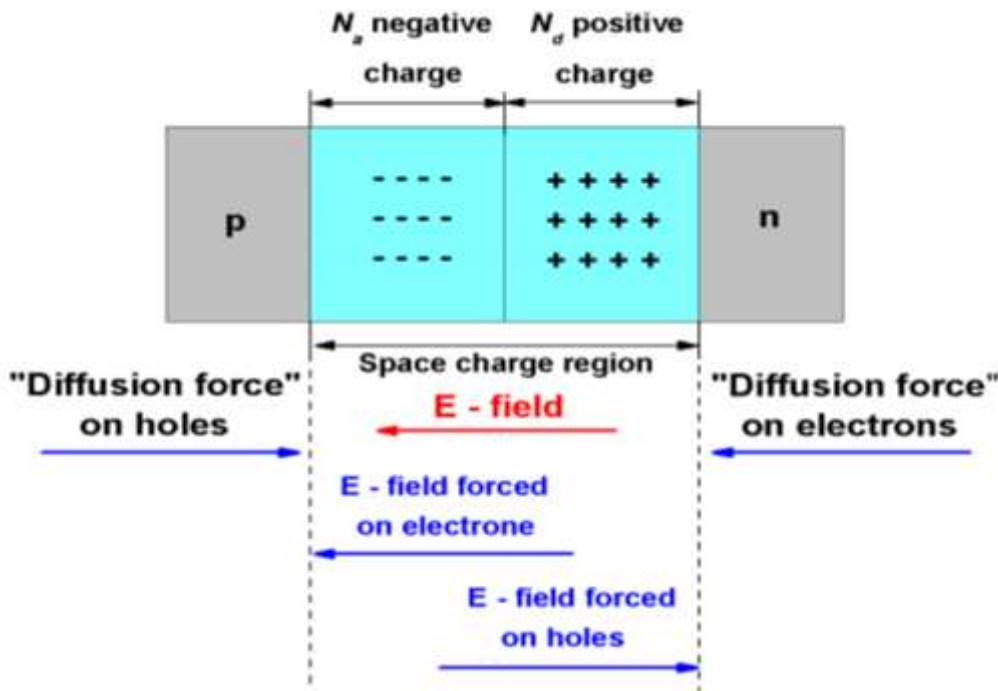


Eventually there would be a homogeneous mixture of two types of molecules.



# pn Junction

This cannot occur in the case of the charged particles in a  $p$ - $n$  junction because of the development of space charge and the electric field  $\epsilon$ .



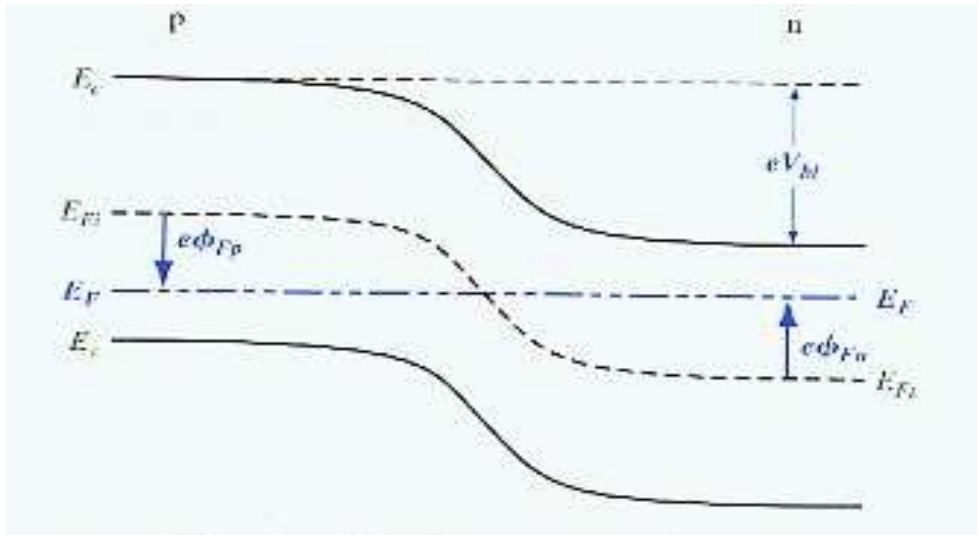
As electrons diffuse from the  $n$  region, positively charged donor atoms are left behind. Similarly, as holes diffuse from the  $p$  region, they uncover negatively charged acceptor atoms. These are *minority carriers*.

The net positive and negative charges in the  $n$  and  $p$  regions induce an electric field in the region near the metallurgical junction, in the direction from the positive to the negative charge, or from the  $n$  to the  $p$  region.

The net positively and negatively charged regions are shown in Figure. These two regions are referred to as the **space charge region (SCR)**. Essentially all electrons and holes are swept out of the space charge region by the electric field. Since the space charge region is depleted of any mobile charge, this region is also referred to as the **depletion region**.

Density gradients still exist in the majority carrier concentrations at each edge of the space charge region. This produces a "diffusion force" that acts on the electrons and holes at the edges of the space charge region. The electric field in the SCR produces another force on the electrons and holes which is in the opposite direction to the diffusion force for each type of particle. In thermal equilibrium, the diffusion force and the  $E$ -field ( $\epsilon$ ) force exactly balance each other.

# ***pn* Junction – built-in potential barrier**



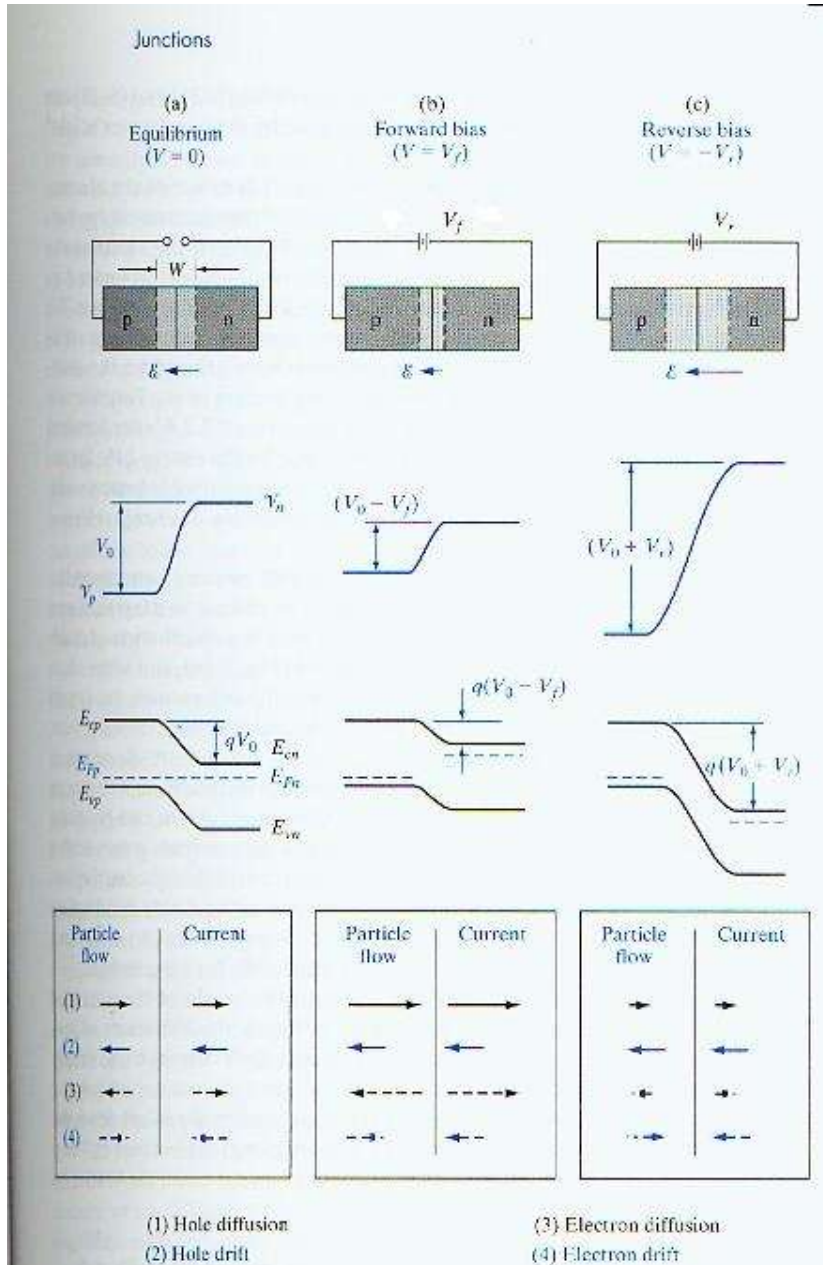
No applied voltage across *pn*-junction

The junction is in thermal equilibrium — the Fermi energy level is constant throughout the entire system. The conduction and valence band energies must bend as we go through the space charge region, since the relative position of the conduction and valence bands with respect to the Fermi energy changes between *p* and *n* regions.

Electrons in the conduction band of the *n* region see a potential barrier in trying to move into the conduction band of the *p* region. This potential barrier is referred to as the *built-in potential barrier* and is denoted by  $V_{bi}$  (or  $V_0$ ). The built-in potential barrier maintains equilibrium between majority carrier electrons in the *n* region and minority carrier electrons in the *p* region, and also between majority carrier holes in the *p* region and minority carrier holes in the *n* region. The potential  $V_{bi}$  maintains equilibrium, so no current is produced by this voltage.

The intrinsic Fermi level is equidistant from the conduction band edge through the junction, thus the built-in potential barrier can be determined as the difference between the intrinsic Fermi levels in the *p* and *n* regions.

# pn Junction



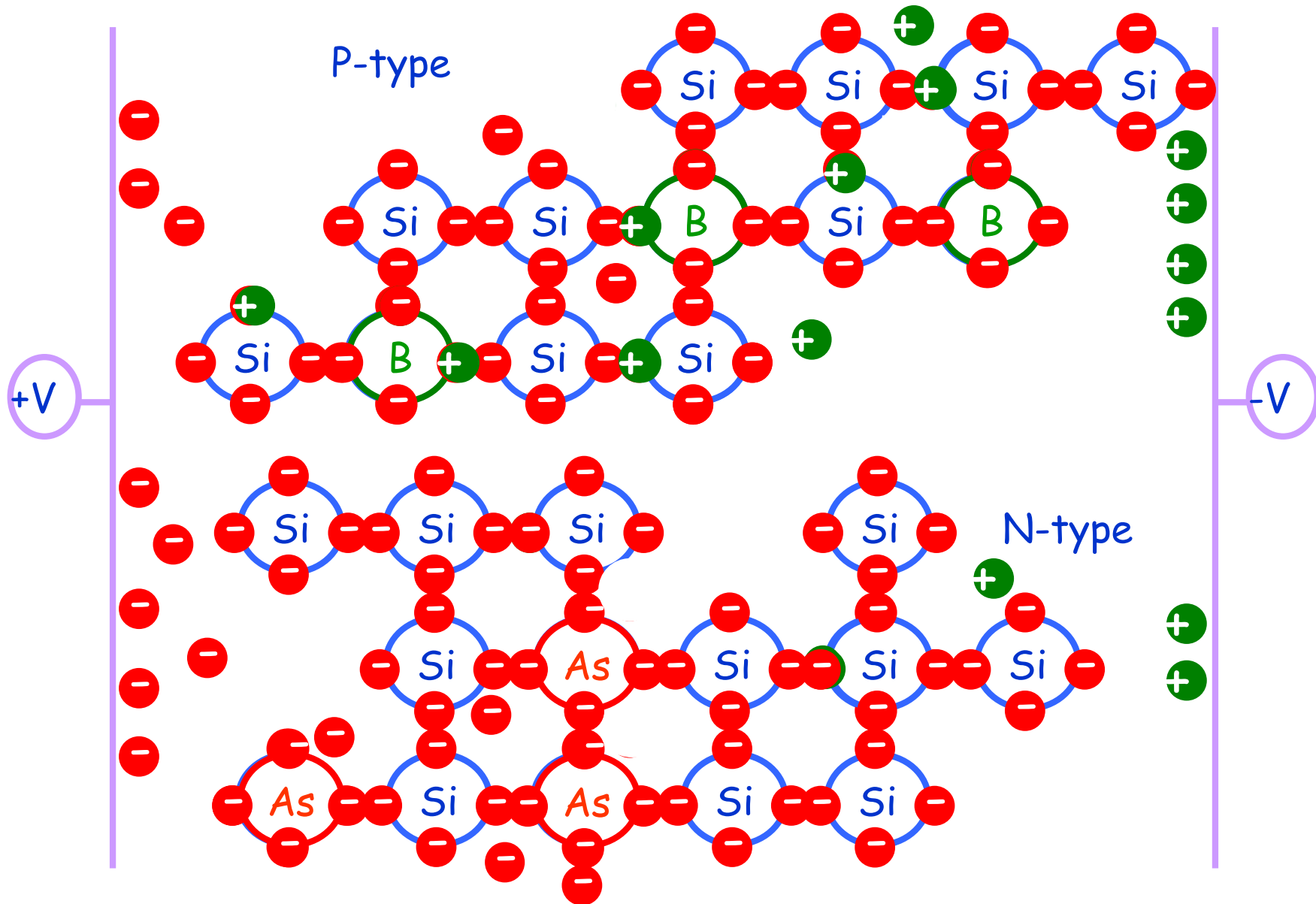
An applied voltage bias  $V$  appears across the transition region of the junction rather than in the neutral  $n$  and  $p$  region. Of course, there will be some voltage drop in the neutral material, if a current flows through it. But in most  $p$ - $n$  junction devices, the length of each region is small compared with its area, and the doping is usually moderate to heavy; thus the resistance is small in each neutral region, and only a small voltage drop can be maintained outside the space charge (transition) region.  $V$  consider to be positive when the external bias is positive on the  $p$  side relative to the  $n$  side.

The electrostatic potential barrier at the junction is lowered by a forward bias  $V_f$  from the equilibrium contact potential  $V_0$  to the smaller value  $V_0 - V_f$ . This lowering of the potential barrier occurs because a forward bias ( $p$  positive with respect to  $n$ ) raises the electrostatic potential on the  $p$  side relative to the  $n$  side. For a reverse bias ( $V = -V_r$ ) the opposite occurs; the electrostatic potential of the  $p$  side is depressed relative to the  $n$  side, and the potential barrier at the junction becomes larger ( $V_0 + V_r$ ).

The electric field within the transition region can be deduced from the potential barrier. We notice that the field decreases with forward bias, since the applied electric field opposes the built-in field. With reverse bias the field at the junction is increased by the applied field, which is in the same direction as the equilibrium field.



# Apply voltage/electric field



# Modulators of conductivity

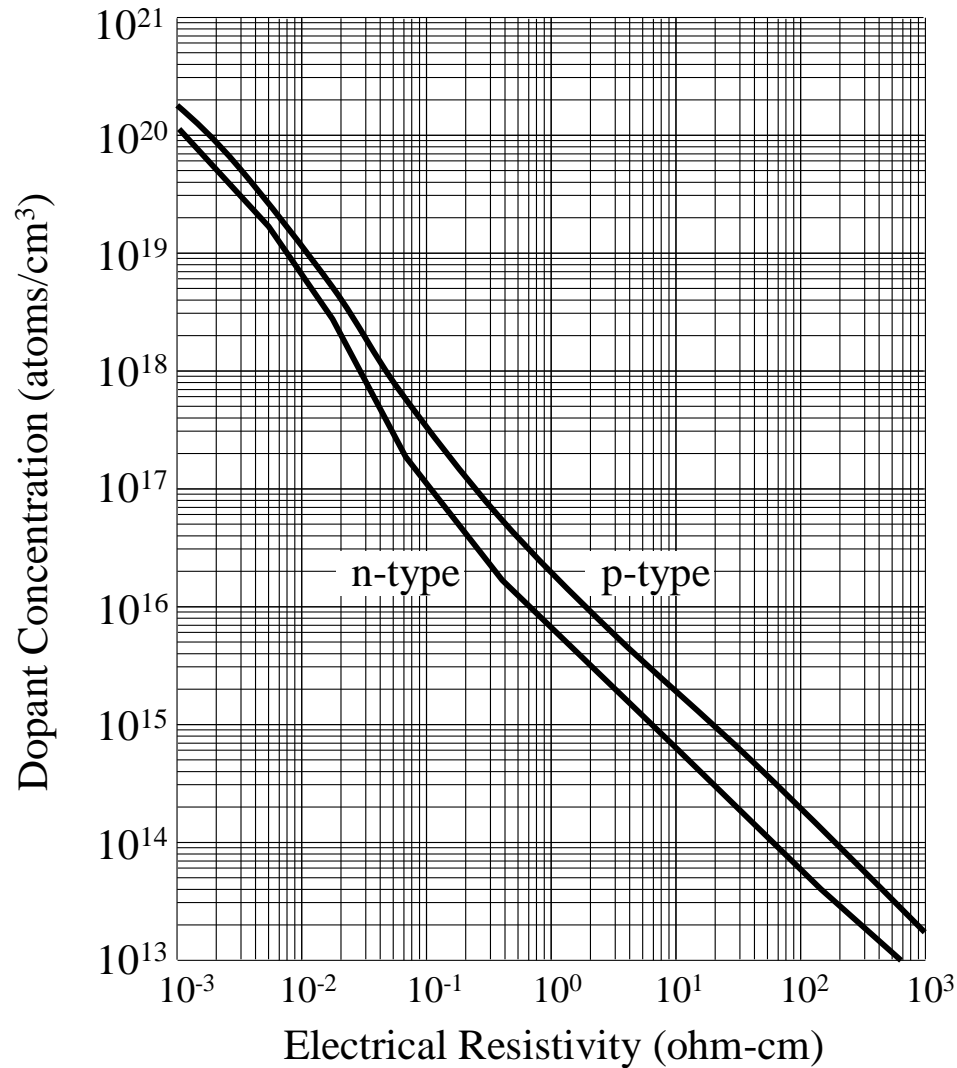
Just reviewed how conductivity of a semiconductor is affected by:

**Temperature** - Increasing temperature causes conductivity to increase

- **Dopants** - Increasing the number of dopant atoms (implant dose) cause conductivity to increase.
- Holes are slower than electrons therefore n-type material is more conductive than p-type material.
- These parameters are in addition to those normally affecting conducting material,

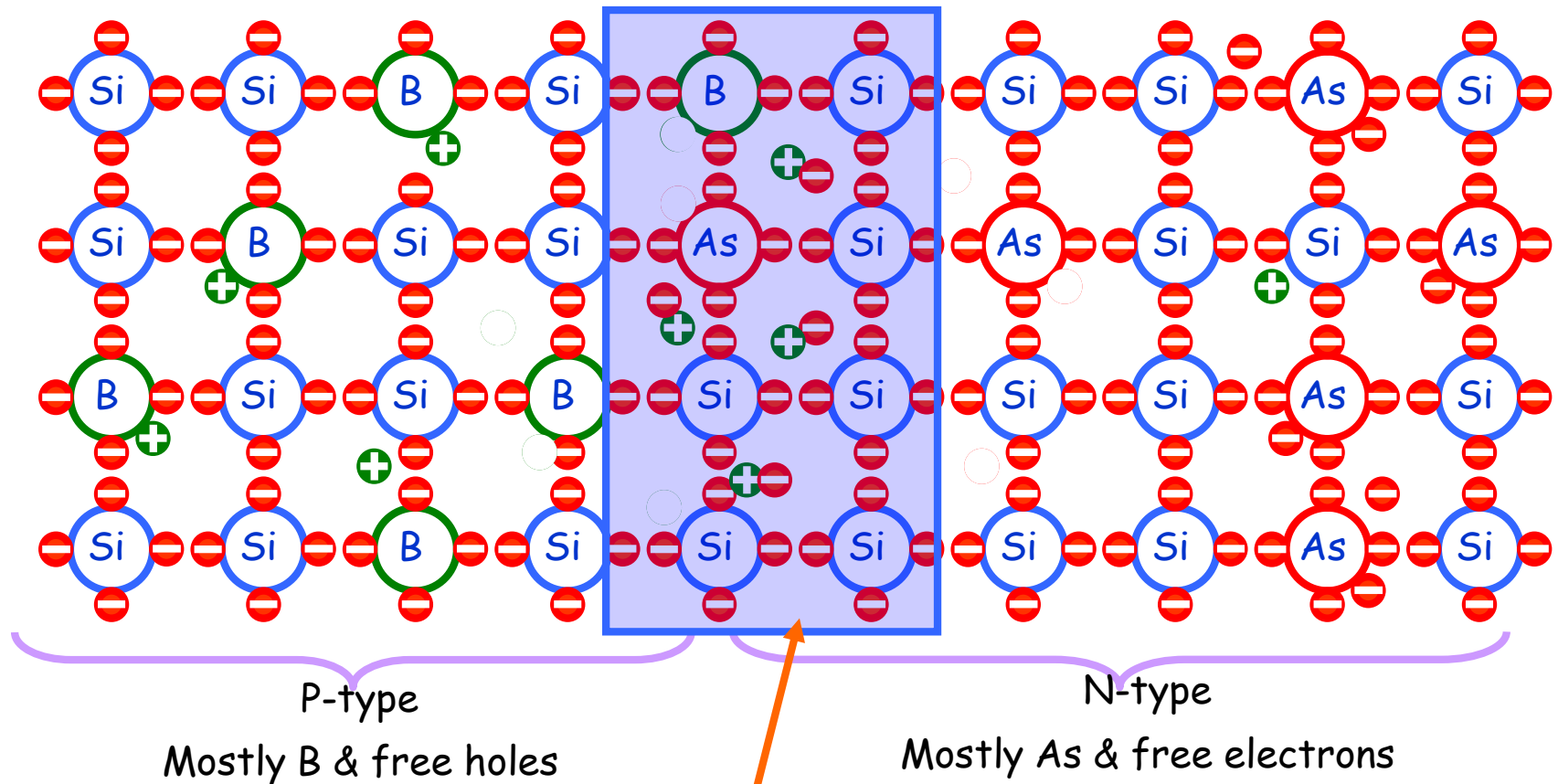
Cross sectional area ↑	Resistance ↓
Length ↑	Resistance ↑

# Silicon Resistivity Versus Dopant Concentration



Redrawn from *VLSI Fabrication Principles, Silicon and Gallium Arsenide*, John Wiley & Sons, Inc.

# PN Junction: No electrical bias applied



- Diffusion effects - The holes and electrons move from area of high concentration to areas of low concentration.
- Holes & electrons annihilate each other to form an area depleted of free charge. This is known as the depletion region and blocks any further flow of charge carriers across the junction

# Physics of the Depletion Region

- When n and p type material are placed in contact with each other, the electrons diffuse into the p-type region in order to equalise the Fermi levels.
- This loss of electrons from the n-type material leaves the surface layer positively charged.
- Similarly the p-type material will have a negatively charged surface layer.
- Thus an electric field is established which opposes the diffusion of electrons when the Fermi levels are equal (dynamic equilibrium is established)

# Size of the depletion region

- This can be calculated solving Poisson's Eqn. for the voltage distribution across the layer.
- The resultant equation shows that

$$N_d l_n = N_a l_p$$

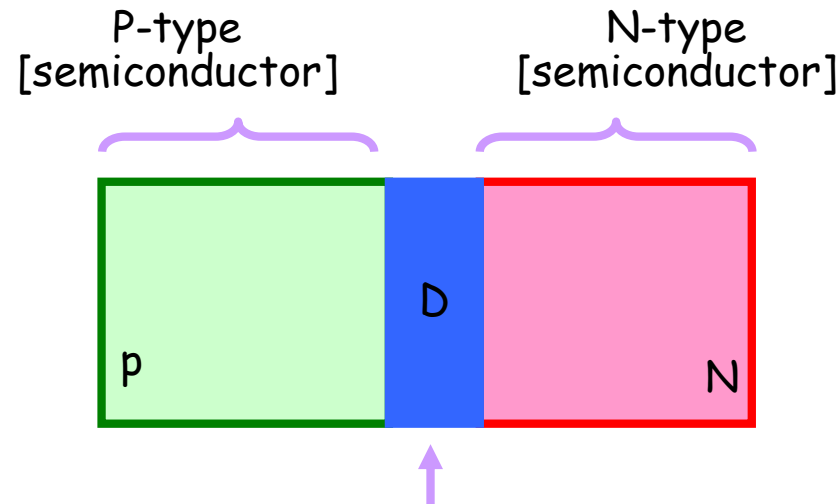
Where N is the dopant concentration and l the length on the p and n type sides.

- The length is given as

$$l_n = \sqrt{\frac{2 \epsilon \epsilon_0 |V|}{|e|} \frac{N_a}{N_d} \frac{1}{(N_a + N_d)}}$$

$$l_p = \sqrt{\frac{2 \epsilon \epsilon_0 |V|}{|e|} \frac{N_d}{N_a} \frac{1}{(N_a + N_d)}}$$

# PN Junction = Capacitor



Depletion region, barrier to free flow of current from P to N → insulator

Basically it forms parallel plate capacitor  $C = \frac{Q}{V}$

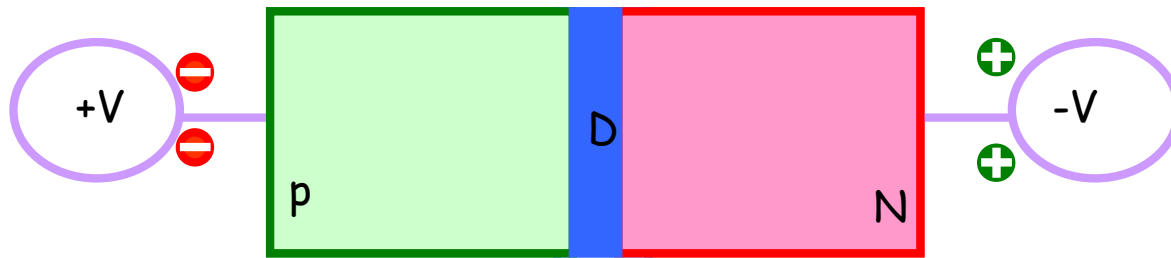
The capacitance per unit area of the junction can be defined as:

$$C = \frac{1}{2} V^{-\frac{1}{2}} \left[ 2 \varepsilon \varepsilon_0 e \left( \frac{N_a N_d}{N_a + N_d} \right) \right]^{\frac{1}{2}}$$

# PN Junction = Diode

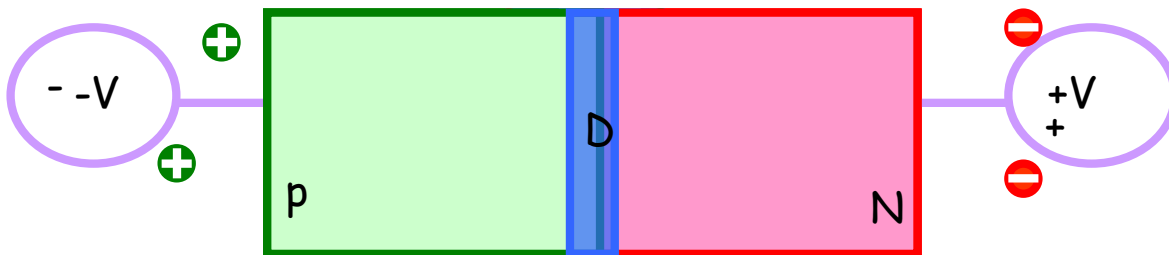
BUT - PN is no ordinary capacitor, actually a diode

Forward Bias: Shrink depletion region, current dragged through the barrier



Once the difficulty of getting through the depletion region has been overcome, current can rise with applied voltage (Ohm's law)

Reverse Bias: Grow depletion region, current finds it more and more difficult to get through the barrier



- Little current flows because barrier too high
- However increasing voltage further  $\rightarrow$  high electric field
- Depletion region eventually breaks down  $\rightarrow$  reverse current



# The Diode

- The diode is a two terminal semiconductor device that allows current to flow in only one direction.
- It is constructed of a P and an N junction connected together.

## Diode Operation

- No current flows because the holes and electrons are moving in the wrong direction.
- If you flip the battery around, the electrons are repelled by the negative terminal and the holes are repelled by the positive terminal allowing current to flow.

