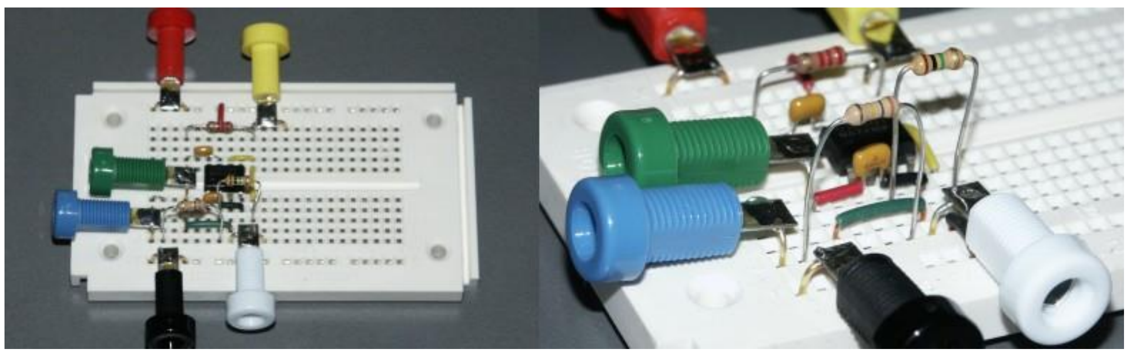
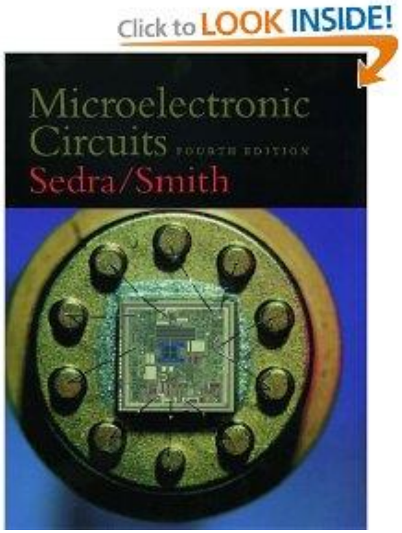
PHY 251 Electronics I
CSM251 Introductory Electronics



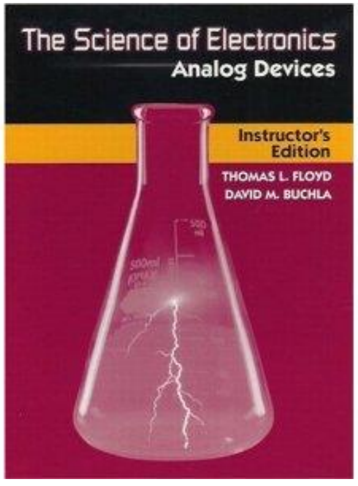
Prof. Francis Kofi Ampong
Department of Physics

Textbooks

- Microelectronic circuits ------ (Engineering library) By Sedra and Smith 3rd or higher editions



- The Science of Electronics Analog Devices By Thomas L. Floyd David M. Buchla



Course Structure: Lecture sessions , Assignments and Exams

Attendance 5 %

Assignments 5 %

Mid Sem Exam 20 %

End of Sem Exam 70%

AIM

learn about the basic devices from which electronic circuits are assembled, namely, diodes and transistors. These solid-state devices are made using semiconductor materials, predominantly silicon

Outline of syllabus for CSM/PHY 251

1.1 Basic Semiconductor physics

1.2 Analysis of diode circuits

1.3 Applications of diode circuits

1.4 The bipolar junction transistor (BJT) – analysis and applications

1.5 MOSFETs

1.7 Operational Amplifiers

LECTURE 1:

Basic Semiconductor physics

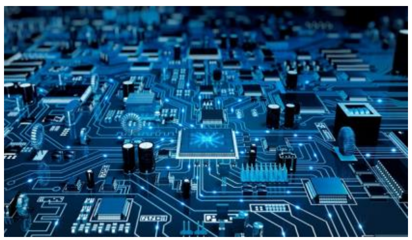
Objective:

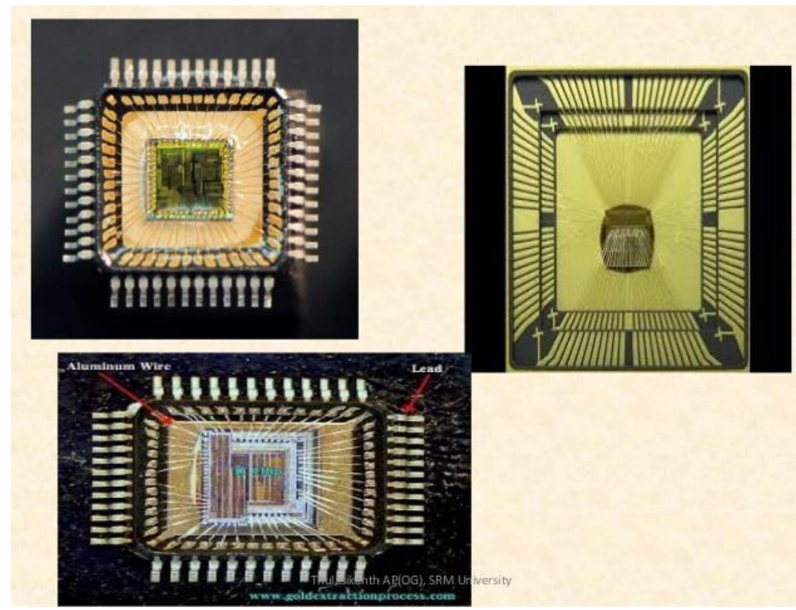
To develop a background knowledge of semiconductor theory sufficient to understand modern semiconductor devices.

Semiconductor devices, such as transistors and diodes, form the basis of nearly all modern electronic systems.

To understand how diodes, transistors and integrated circuits work, you first have to study semiconductors: materials that are neither conductors nor insulators.

Semiconductor devices serve as the heart of microelectronics.





A basic knowledge of semiconductor devices is essential to understanding of advanced courses in electronics.

Lecture 1: Basic Semiconductor physics

- Topics
- Semiconductor Energy Band Model
- Intrinsic and Extrinsic semiconductors
- P-N Junction formation and behavior

IN THIS CHAPTER YOU WILL LEARN

- The basic properties of semiconductors and in particular silicon, which is the material used to make most of today's electronic circuits.
- How doping a pure silicon crystal dramatically changes its electrical conductivity, which is the fundamental idea underlying the use of semiconductors in the implementation of electronic devices.
- The structure and operation of the p-n junction; a basic semiconductor structure that implements the diode and plays a dominant role in transistor

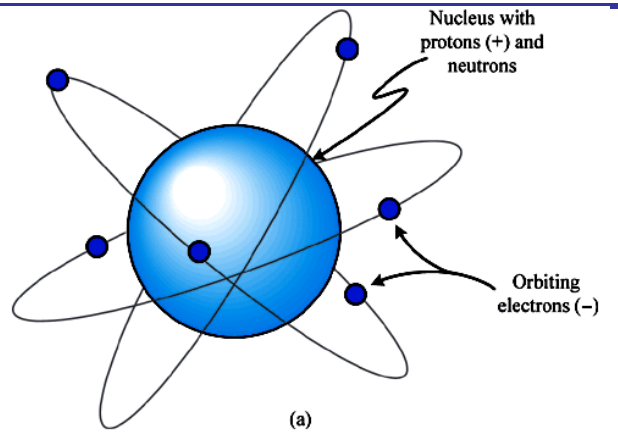
Although many of the concepts studied in this chapter apply to semiconductor materials in general, our treatment is heavily biased toward silicon, simply because it is the material used in the vast majority of microelectronic circuits.

Semiconductor Energy Band Model

FROM DISCRETE ENERGY LEVELS TO ENERGY BANDS

Review of Basic Atomic Model

- Atoms are comprised of electrons, neutrons, and protons.
- Electrons are found orbiting the nucleus of an at atom at specific intervals, based upon their energy levels.
- The outermost orbit is the *valence* orbit.



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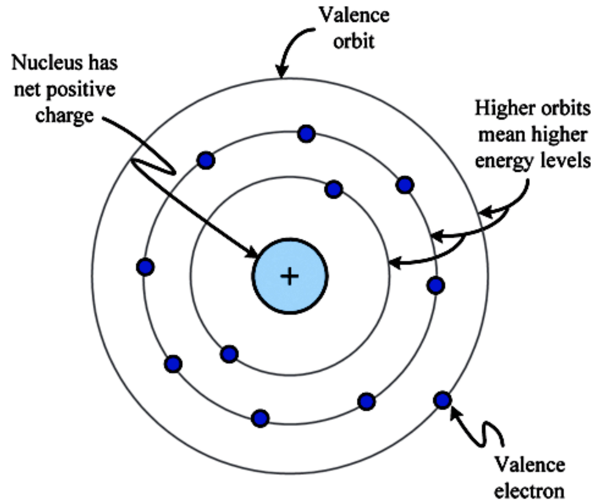
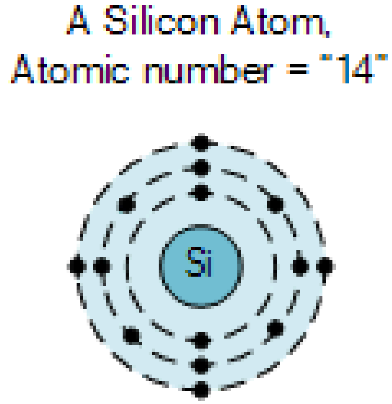
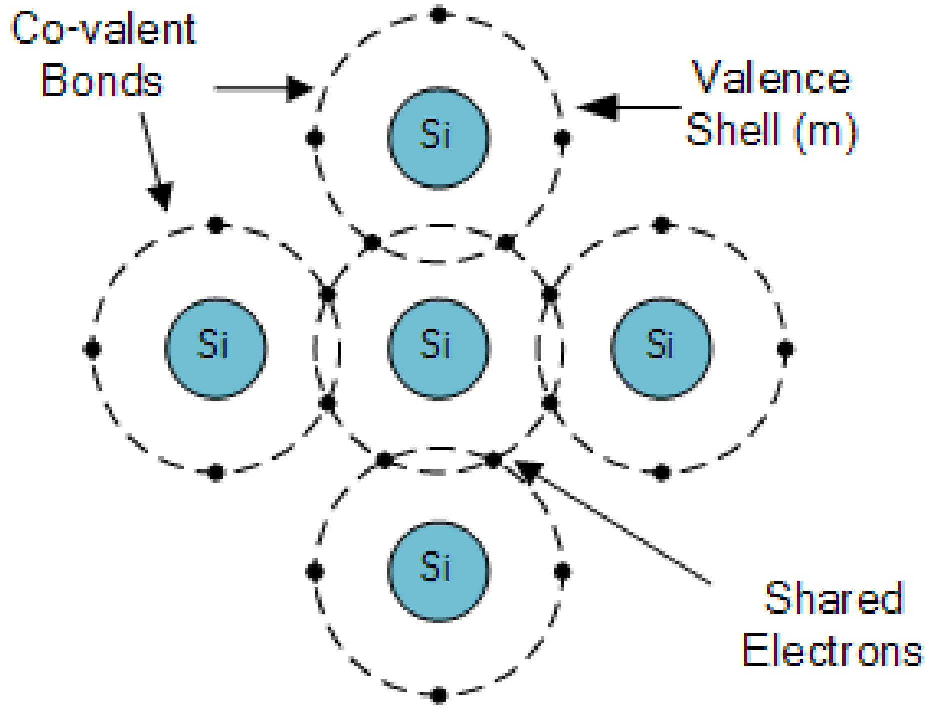


(b)

Silicon Covalent Bond Model

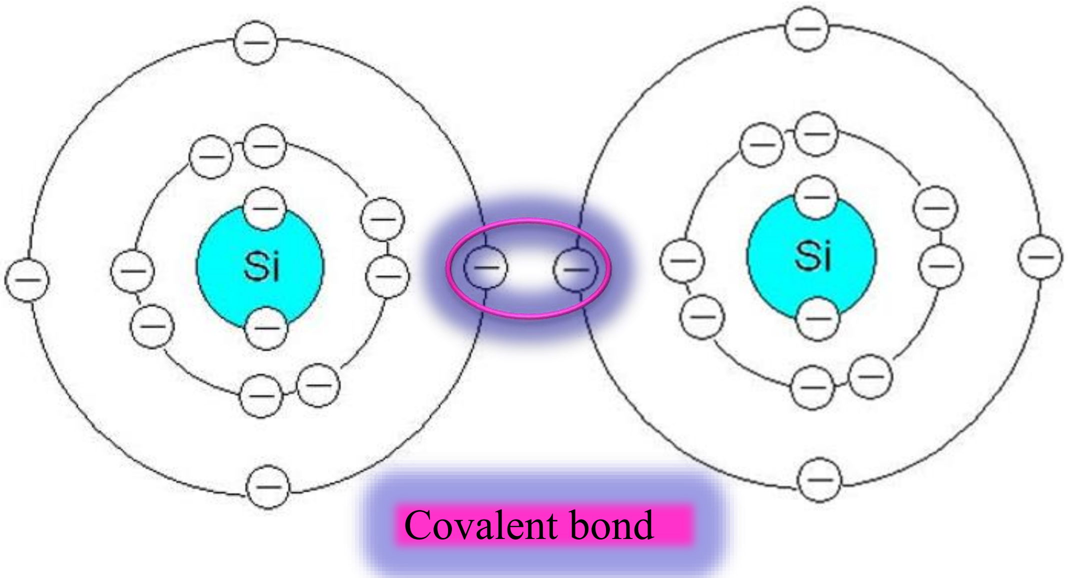


Silicon atom showing 4 electrons in its outer valence shell (m)



Silicon Crystal Lattice

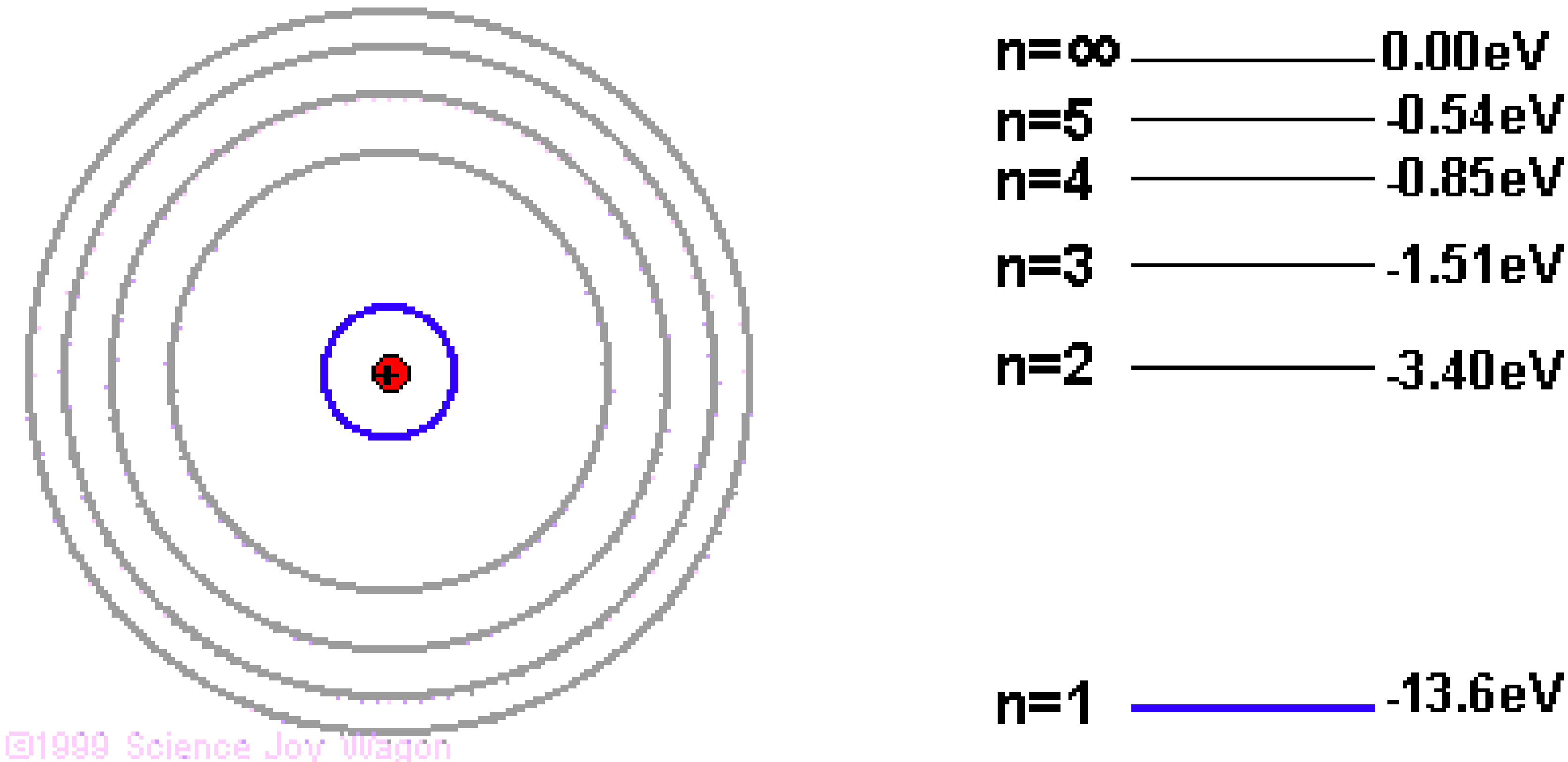
Silicon Covalent Bond Model (cont.)



Silicon atom　　　Silicon atom

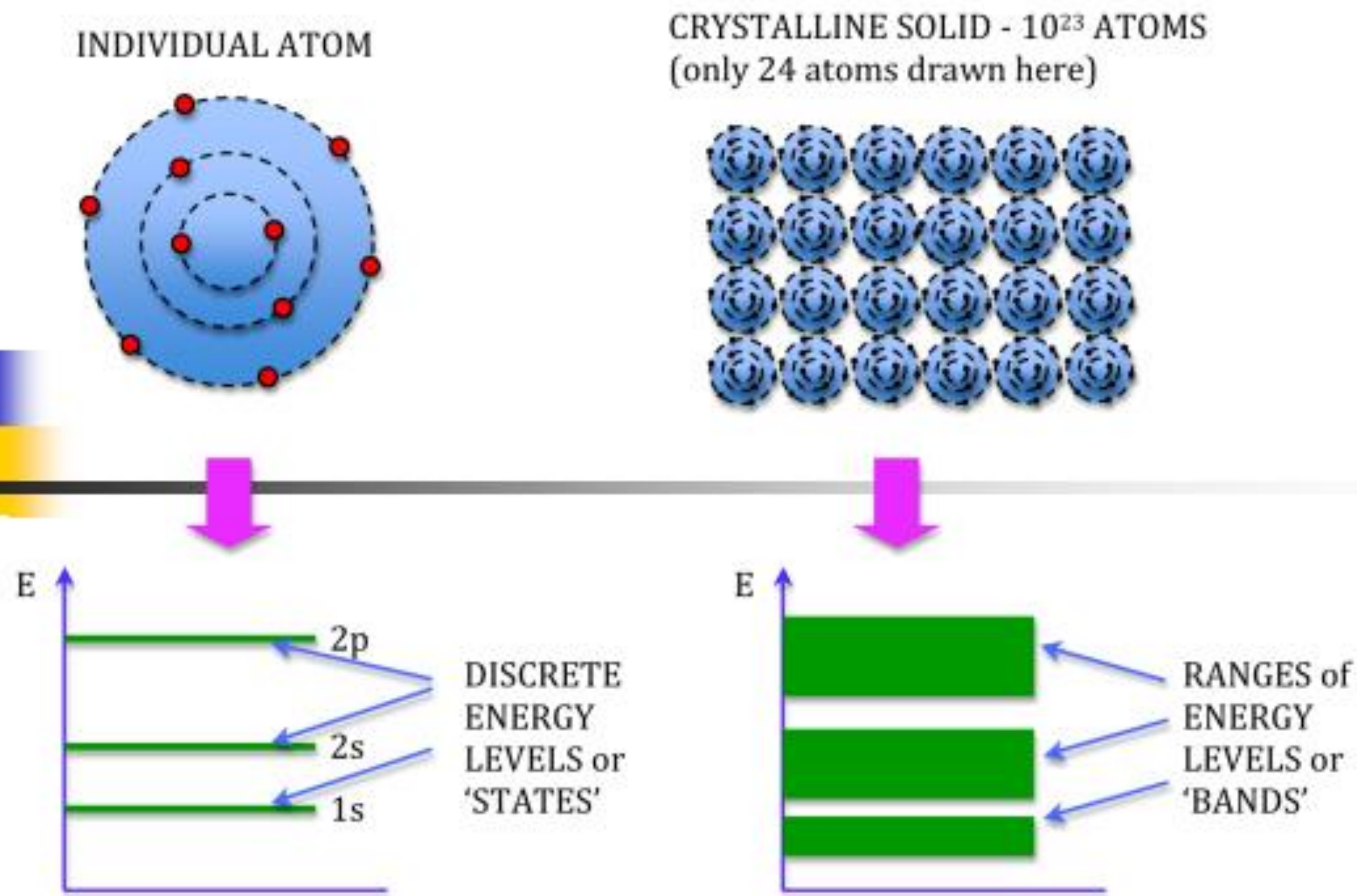
• Silicon has four electrons in the outer shell.
• Single crystal material is formed by the covalent bonding of each silicon atom with its four nearest neighbors.

From discrete energy levels to energy bands: - atoms have discrete energy levels which are widely spaced.

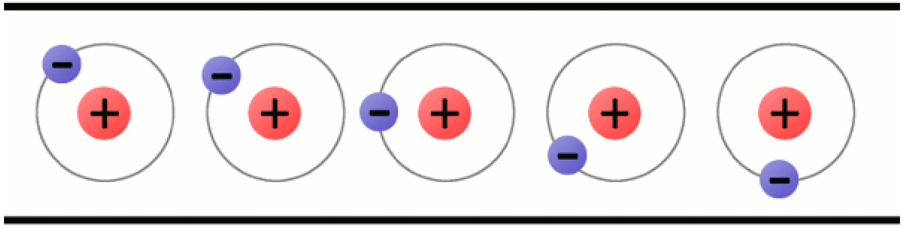


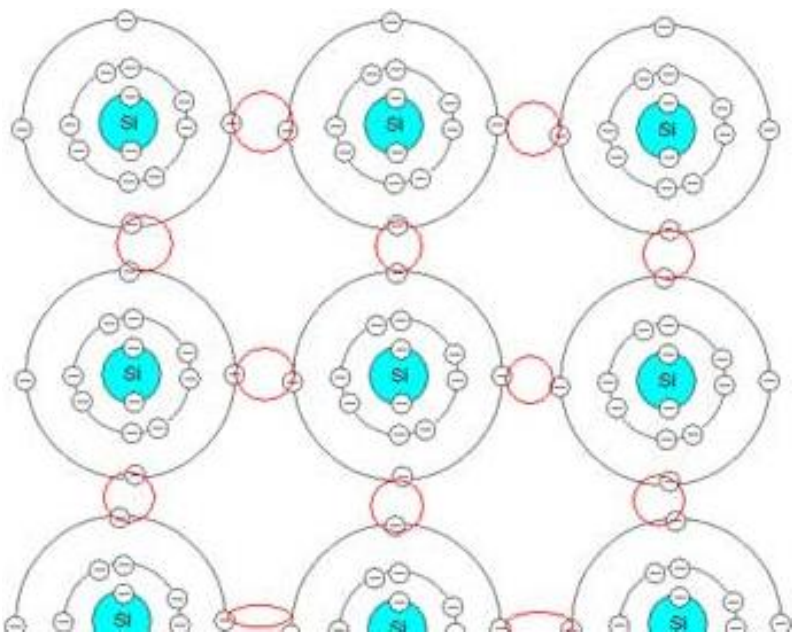
– The electrons can only be found in these energy states

Silicon Covalent Bond Model (cont.)

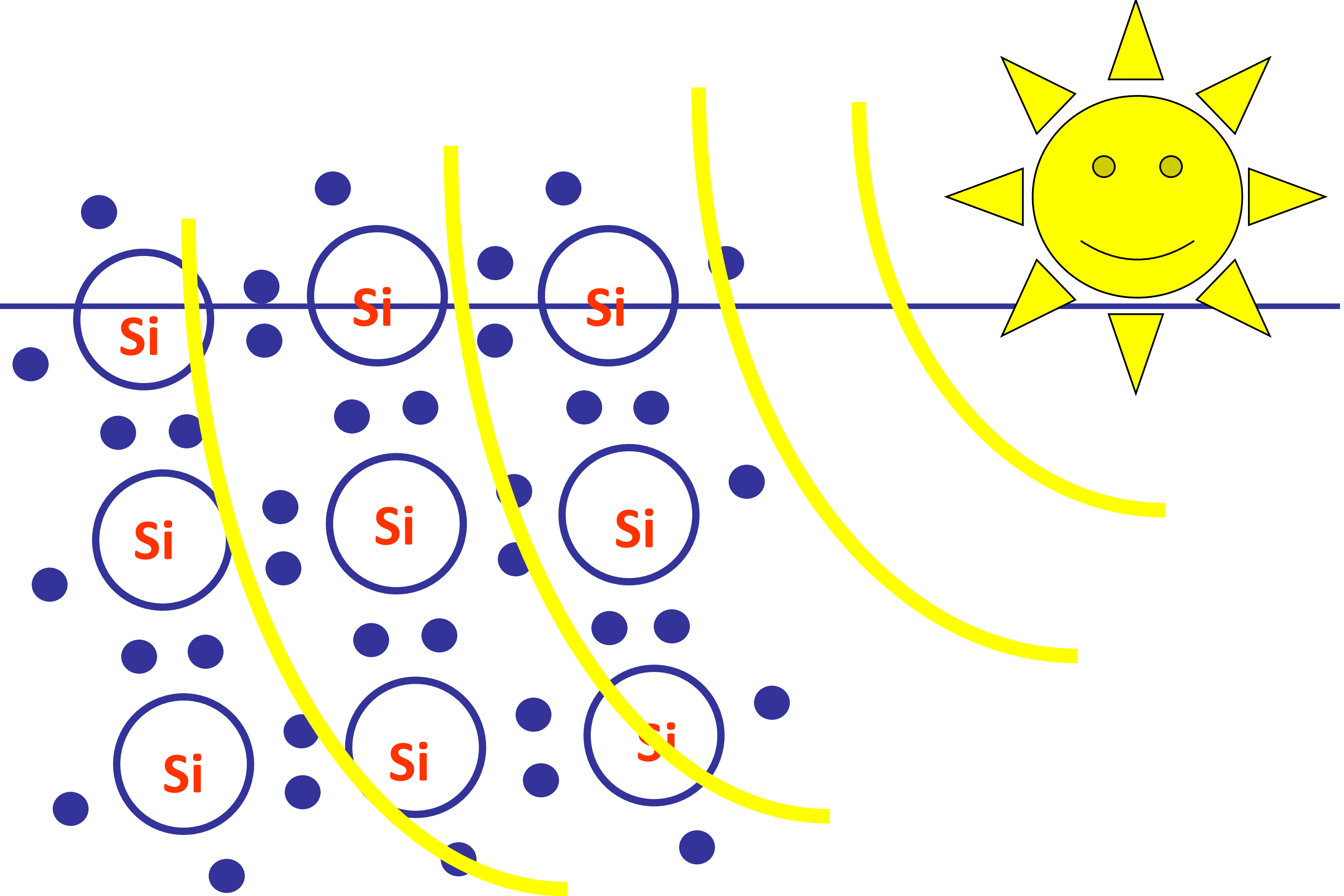


Conduction in materials

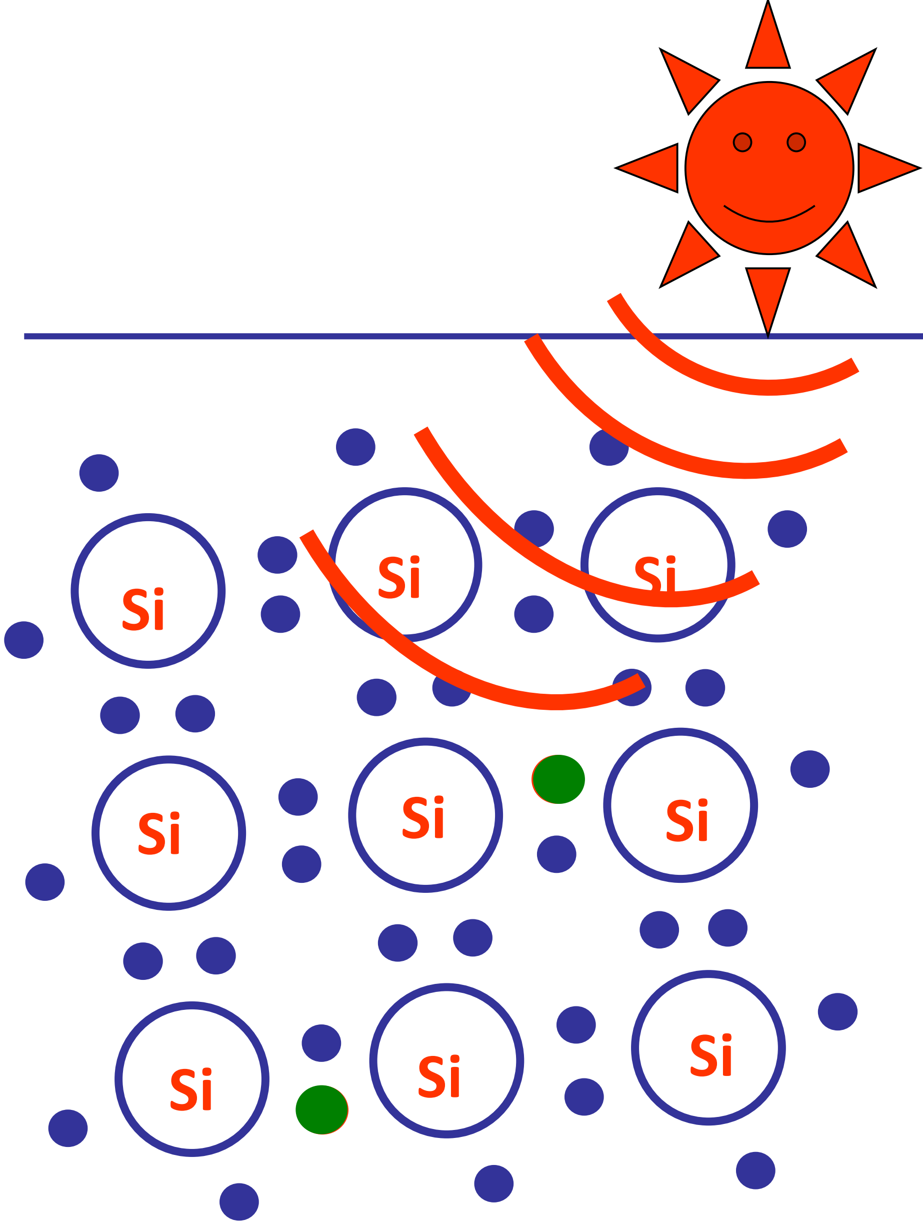


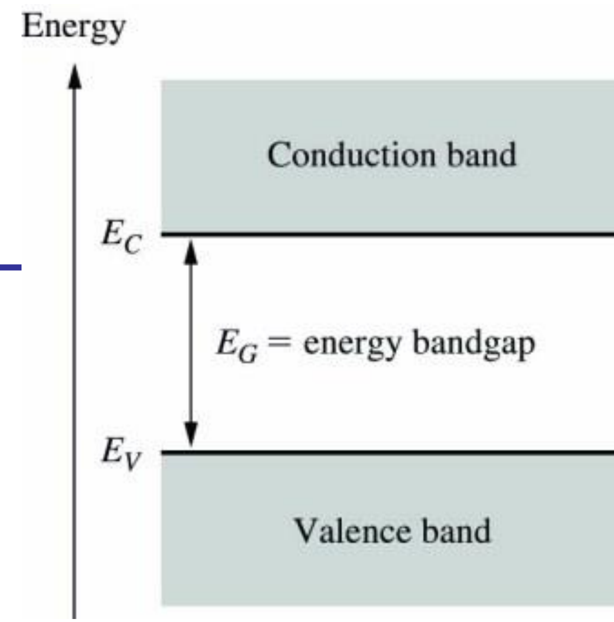


- What is crucial to the conduction process is the availability of free electrons.
- That is before a material can conduct electric current it must have some electrons which can move freely inside the material.
- In silicon the bonding process uses up all the available electrons, so at absolute zero temperature, there are no electrons available for conduction.



At finite temperatures however, the atoms vibrate randomly, having occasionally much more than the average thermal energy





At certain instants at certain atoms there is there is enough energy to break the covalent bond and liberate an electron. Once liberated, they wander aimlessly through the crystal, and are said to be in the conduction band, where they can contribute to electric current. Those electrons which still remain bound are said to be in the valence band

So what can we say about this?

- We may say that all the electrons are in the valence band at 0ºK (that is all electrons remain bound to their parent atom).
- There is an energy gap above the valence band before the conduction band starts.
- This means that for an electron to be in the conduction band; that is, to get an electron in a state in which it can take up kinetic energy from an electric field and can contribute to an electric current, we first have to give it a package of energy.
- This can come from thermal excitation, or by photon excitation quite independently of temperature

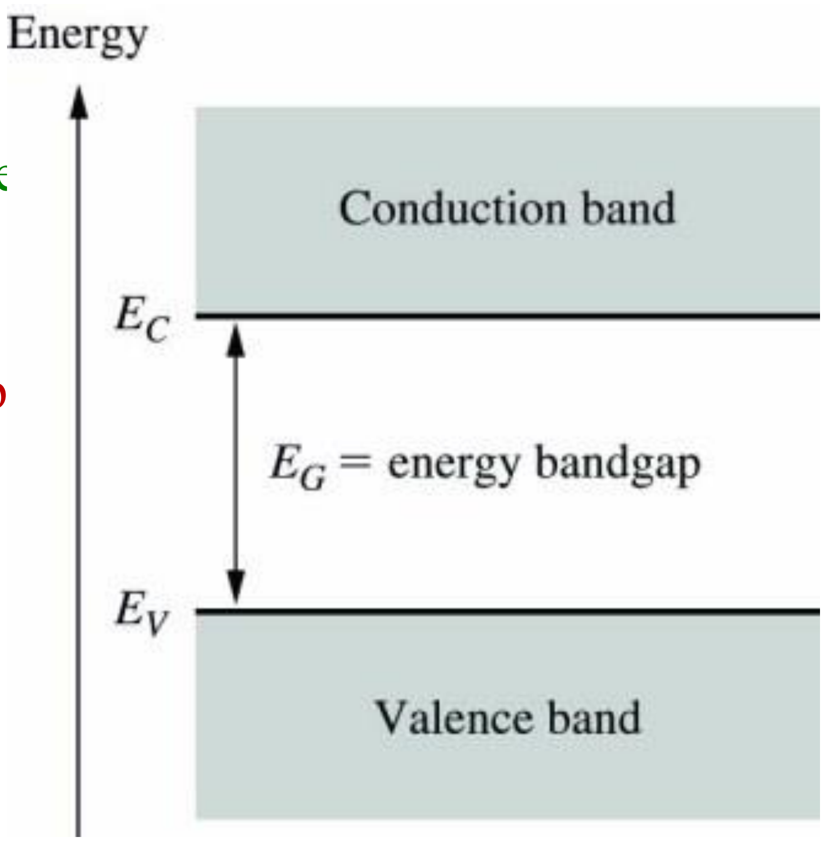
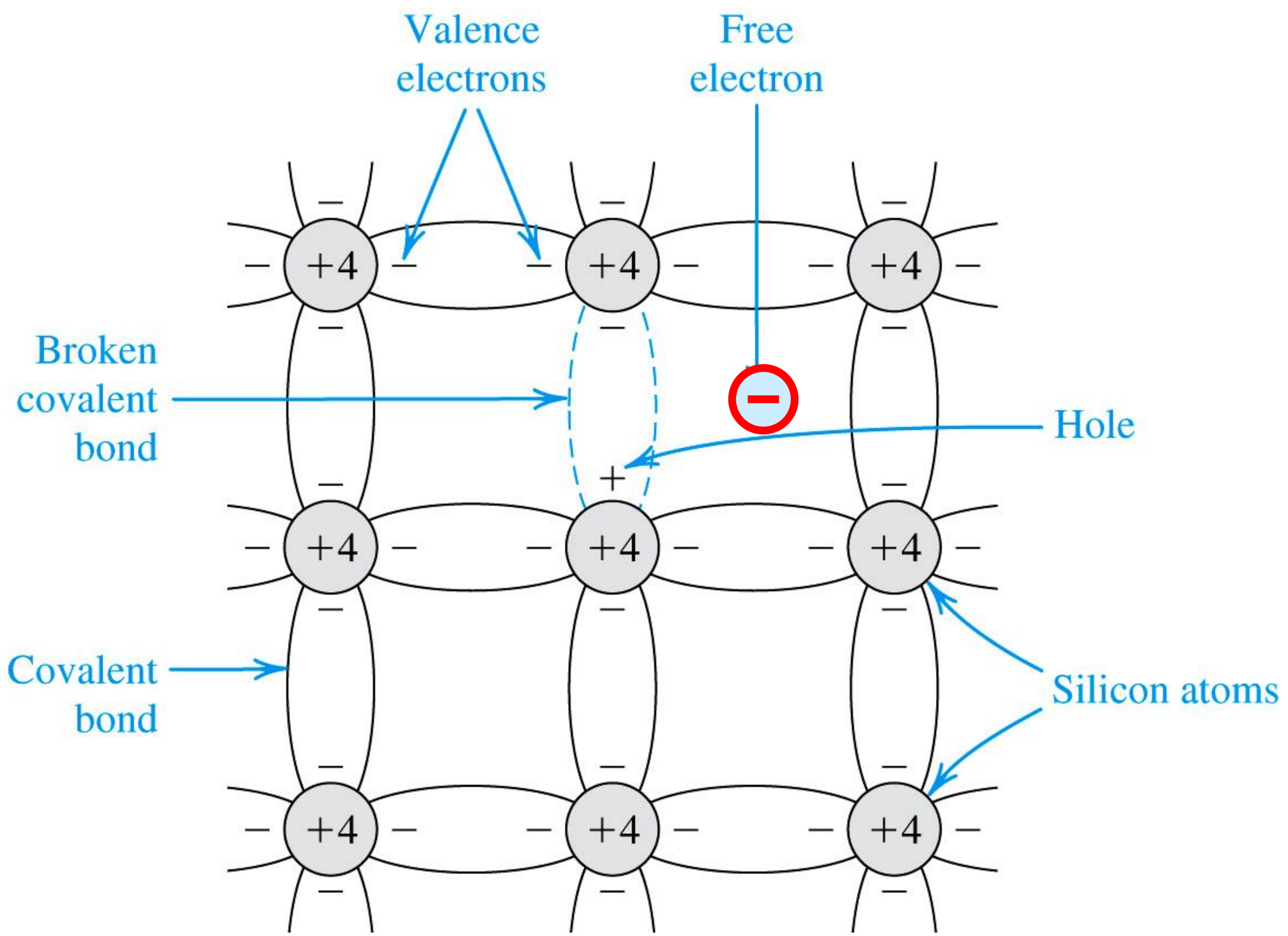


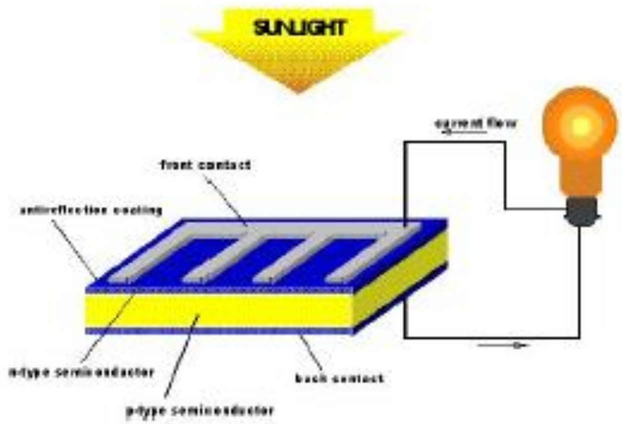
Figure 3.2: At room temperature, some of the covalent bonds are broken by thermal generation. Each broken bond gives rise to a free electron and a hole, both of which become available for current conduction.



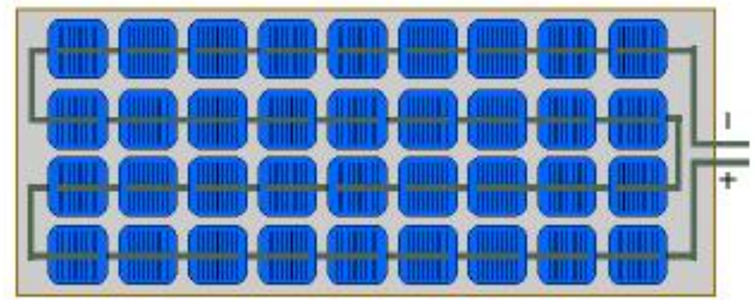
Questions ?

Can you think of a device that generates free electrons when external energy such as light is applied to it?

Solar cell

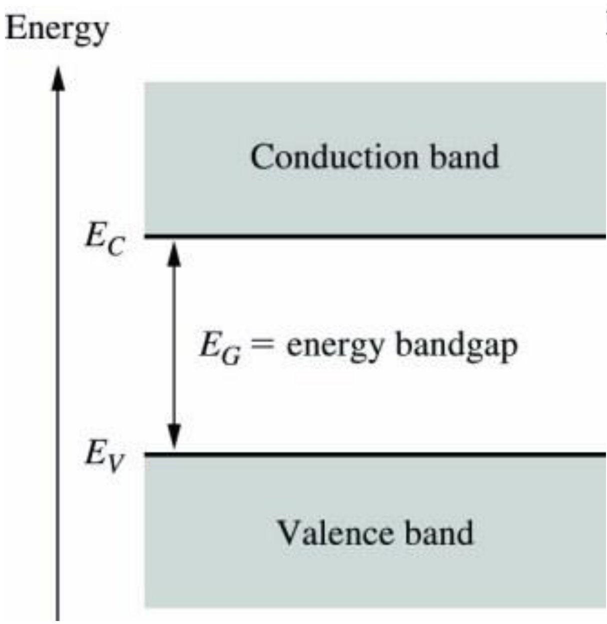


Module

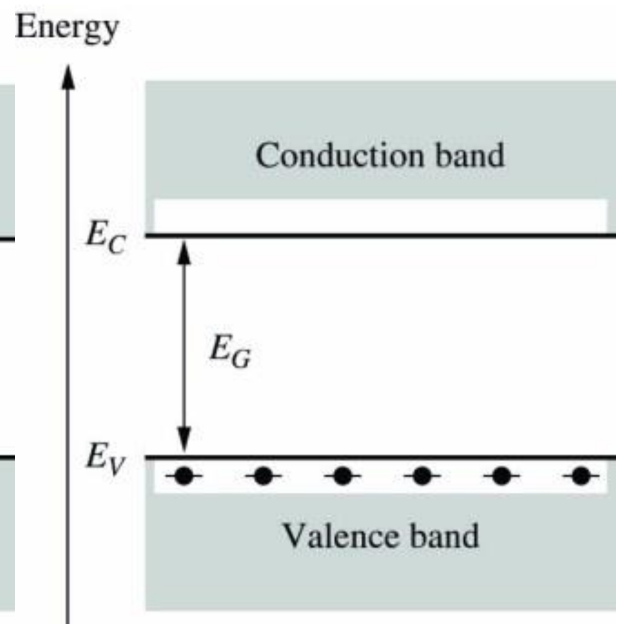


System

Semiconductor Energy Band Model



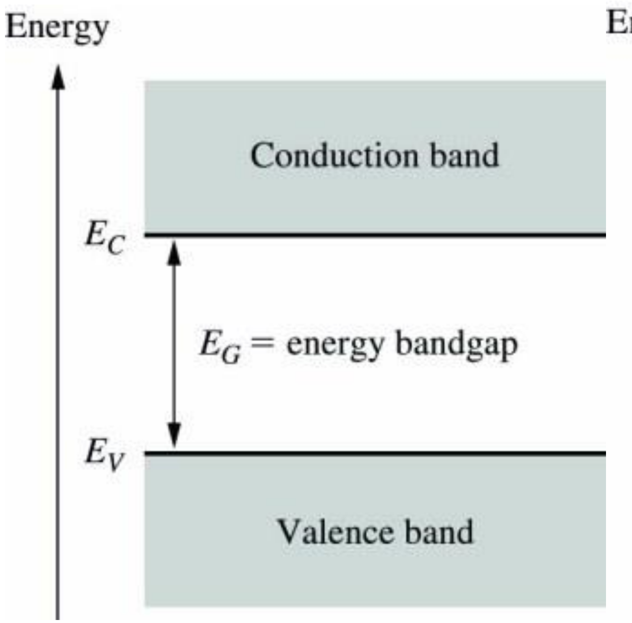
Semiconductor energy band model. E_C and E_V are energy levels at the edge of the conduction and valence bands.

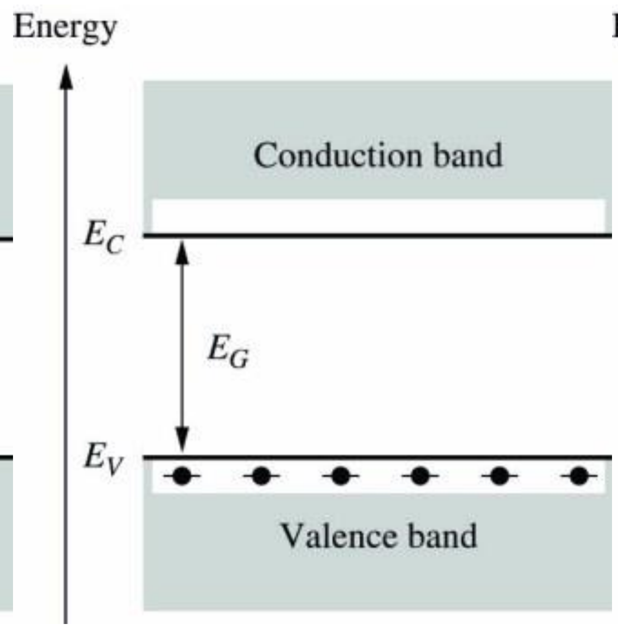


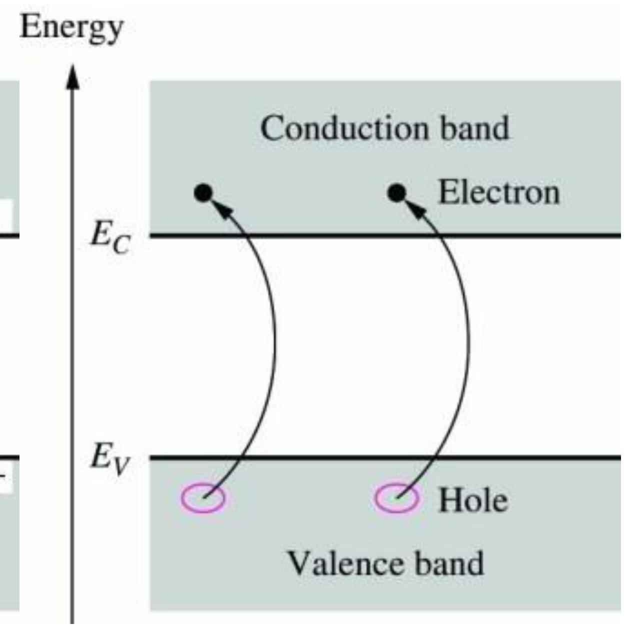
Electron participating in a covalent bond is in a lower energy state in the valence band. This diagram represents 0 K.

What happens as temperature increases?

Semiconductor Energy Band Model





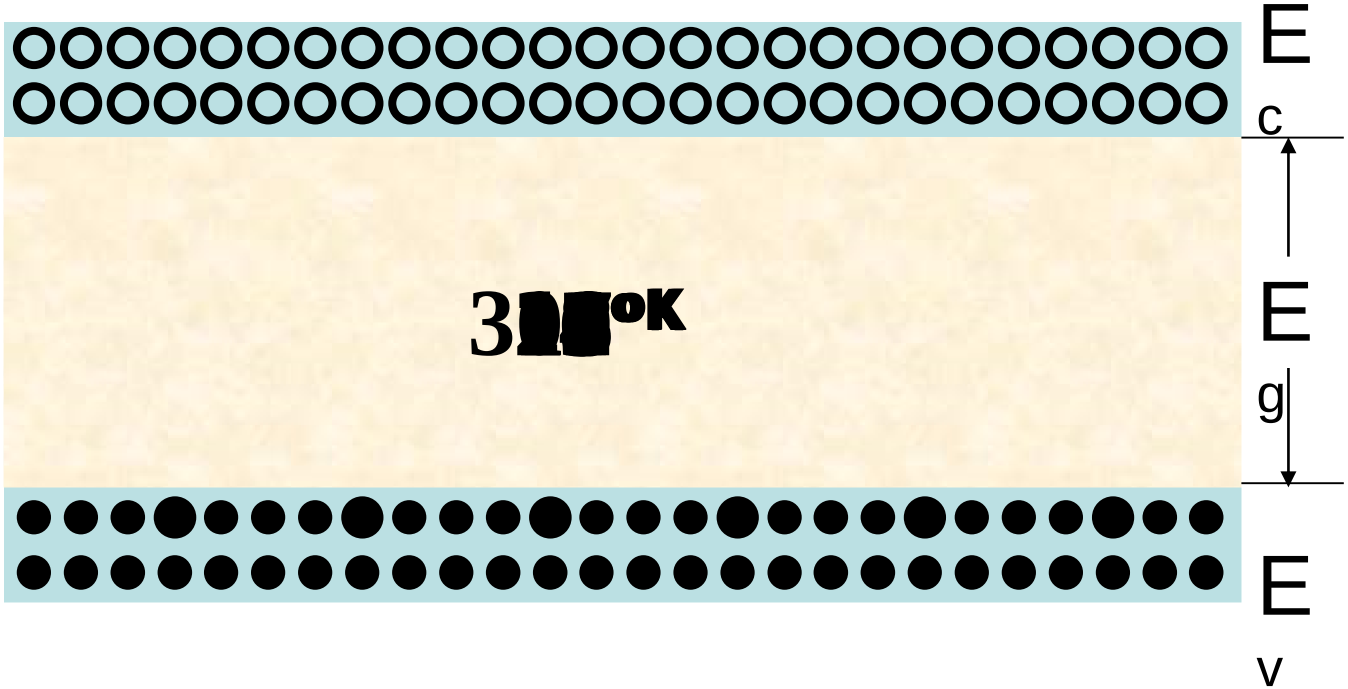


Semiconductor energy band model. E_C and E_V are energy levels at the edge of the conduction and valence bands.

Electron participating in a covalent bond is in a lower energy state in the valence band. This diagram represents 0 K.

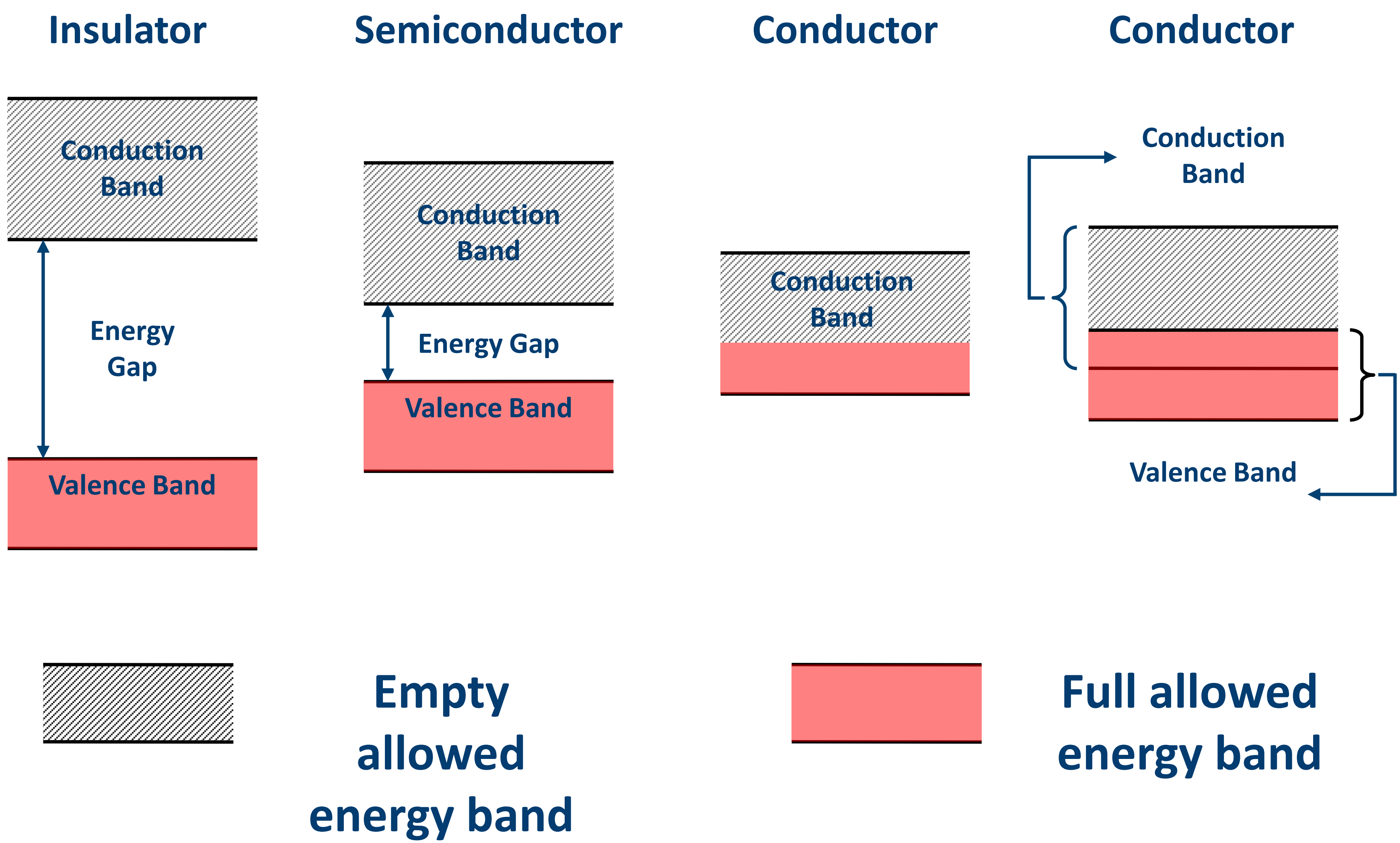
Thermal energy breaks covalent bonds and moves the electrons up into the conduction band.

3-2. Carriers in Semiconductors



Electron Hole Pair

Energy-band diagram – classification of materials



Energy-band Diagram

- A very important concept in the study of semiconductors is the energy-band diagram
- It is used to represent the range of energy a valence electron can have
- For semiconductors the electrons can have any one value of a continuous range of energy levels while they occupy the valence shell of the atom
  - That band of energy levels is called the ***valence band***
- Within the same valence shell, but at a slightly higher energy level, is yet another band of continuously variable, allowed energy levels
  - This is the ***conduction band***

Band Gap

- Between the valence and the conduction band is a range of energy levels where there are no allowed states for an electron E_G
- This is the band gap $E_G = 1.1\ eV$
- In silicon at room temperature [in electron volts]:
- ***Electron volt*** is an atomic measurement unit, 1 eV energy is necessary to decrease of the potential of the electron with 1 V.

$$1\text{eV} = 1.602 \times 10^{-19}\ \text{joule}$$

Insulators, Semiconductors, and Metals

- This separation of the valence and conduction bands determines the electrical properties of the material
- Insulators have a large energy gap
  - electrons can't jump from valence to conduction bands
  - no current flows
- Conductors (metals) have a very small (or nonexistent) energy gap
  - electrons easily jump to conduction bands due to thermal excitation
  - current flows easily
- Semiconductors have a moderate energy gap
  - only a few electrons can jump to the conduction band
    - leaving "holes"
  - only a little current can flow

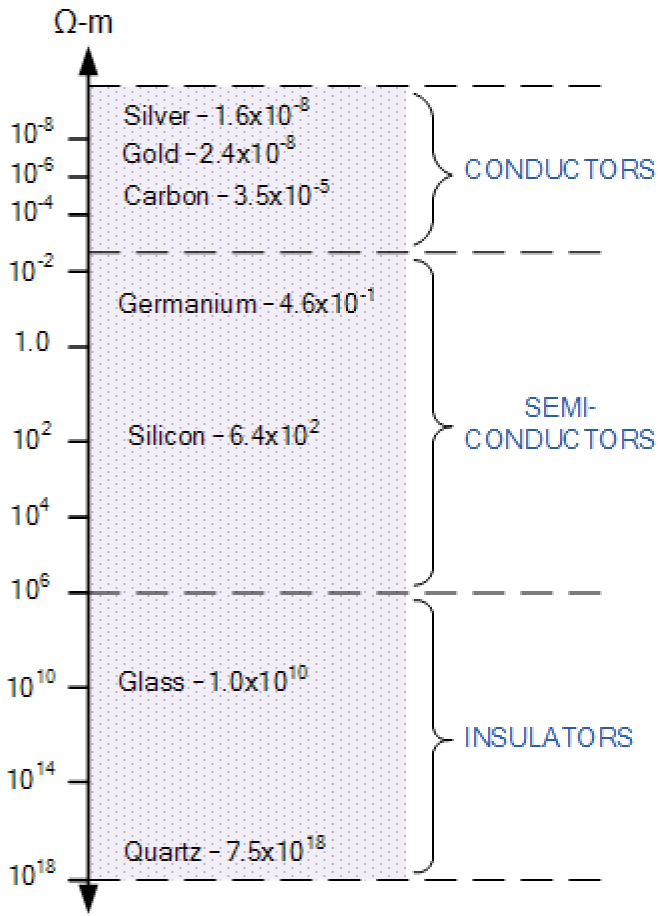
THE SEMICONDUCTOR

With the aid of the band theory we have succeeded in classifying solids into metals, insulators and semiconductors.

We are now going to consider semiconductors (technologically the newest class) in more detail

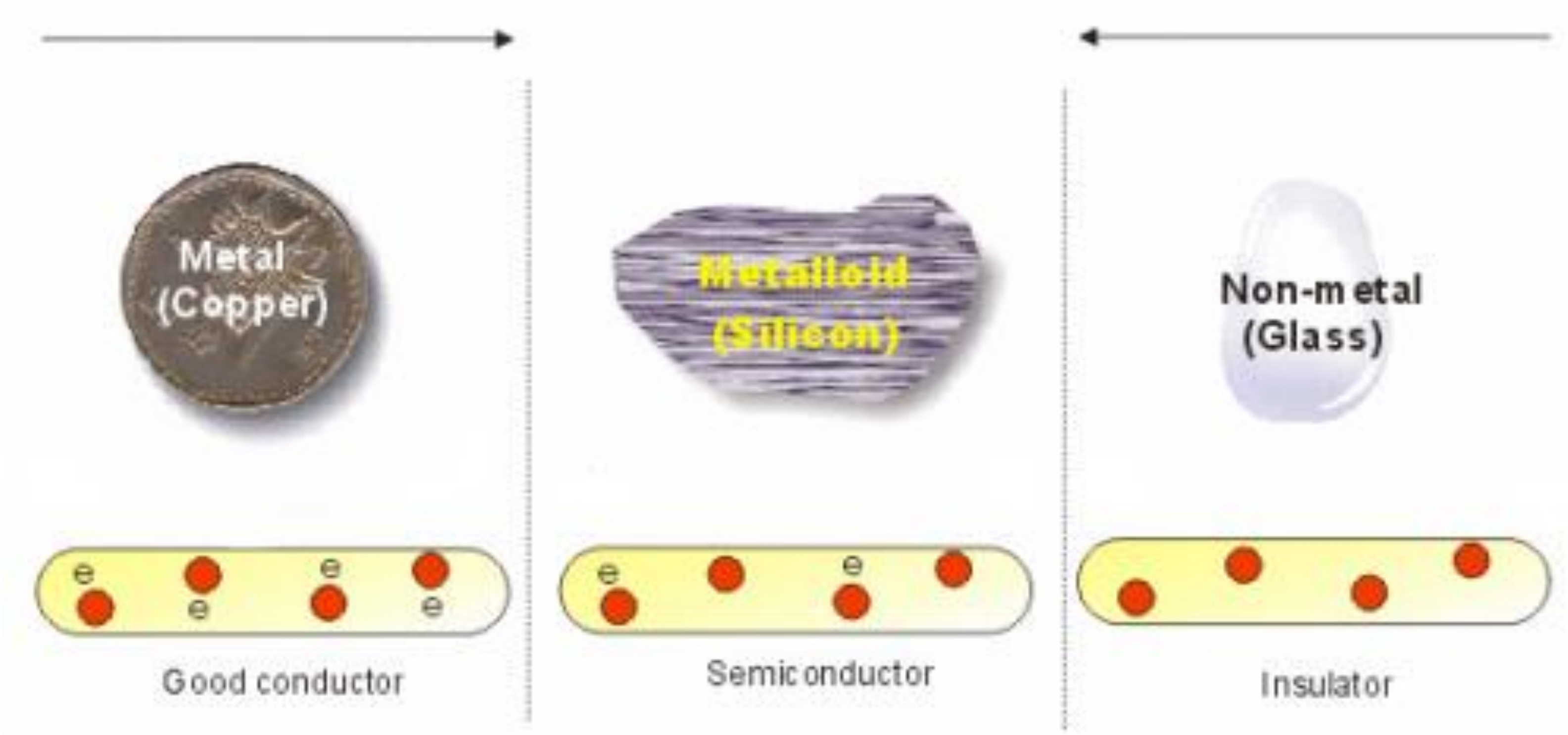
Semi-conductor concepts

- Semiconductors are a group of solids whose electrical properties are intermediate between conductors and insulators. For example, the resistivity of a conductor is of the order of 10^{-8} Ωm, that of an insulator is 10^{4} Ωm and above whiles that of a semiconductor is $10^{-1}\Omega$m.
- Most semiconductor devices require materials with an energy gap of about 1eV at normal room temperature. Hence, the most extensively used semiconducting elements in the electronic industry are ***silicon*** (1.2eV) and ***germanium*** (0.76 eV). Silicon and germanium are group IV elements



The name "semiconductor" implies that it conducts somewhere between the two cases (conductors or insulators)

classification of materials



Semiconductors

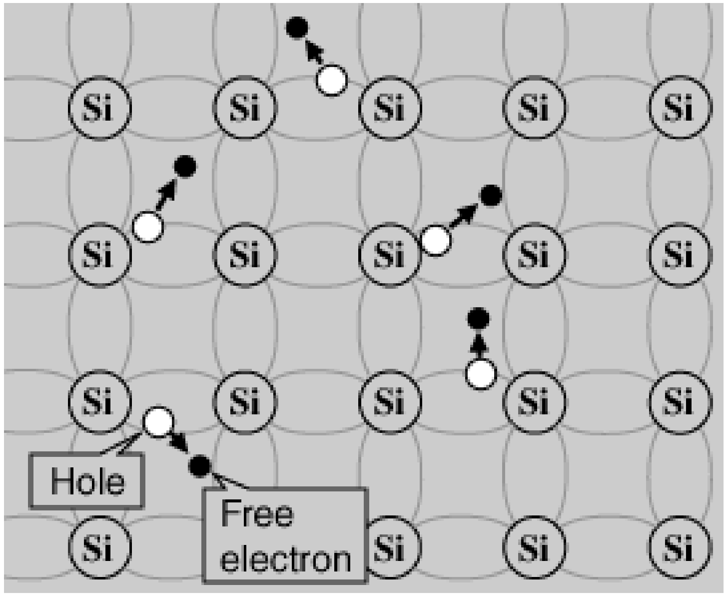
- A semiconductor is a substance that has specific electrical properties that enable it to serve as a foundation for computers and other electronic devices. It is typically a solid chemical element or compound that conducts electricity under certain conditions but not others.
- Some common semiconductors
  - elemental
    - Si - Silicon (most common)
    - Ge - Germanium
  - compound
    - GaAs - Gallium arsenide
    - GaP - Gallium phosphide
    - AlAs - Aluminum arsenide
    - AlP - Aluminum phosphide
    - InP - Indium Phosphide

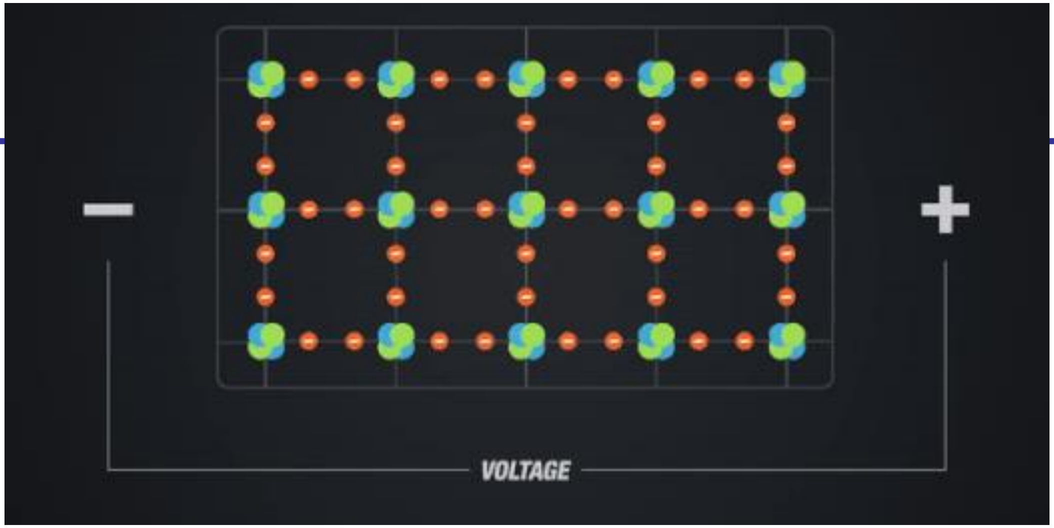
Basic Semiconductor Concepts

- Intrinsic Semiconductor
- Extrinsic Semiconductor

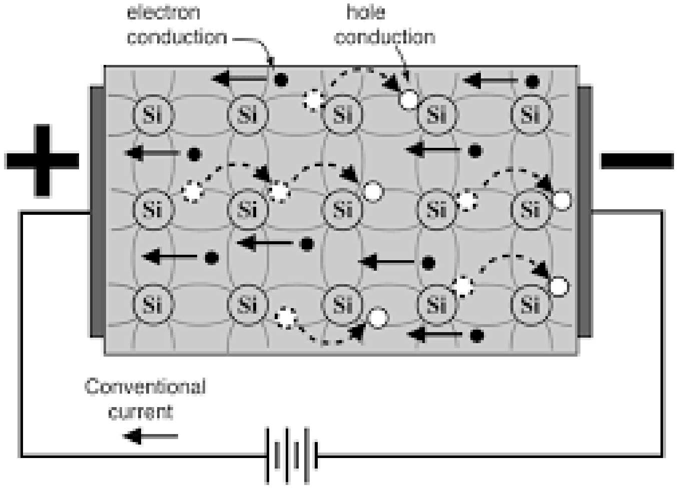
Intrinsic semiconductor

- A semiconductor whose electrical conductivity is dominated by thermally generated electron-hole pairs is called an intrinsic semiconductor.



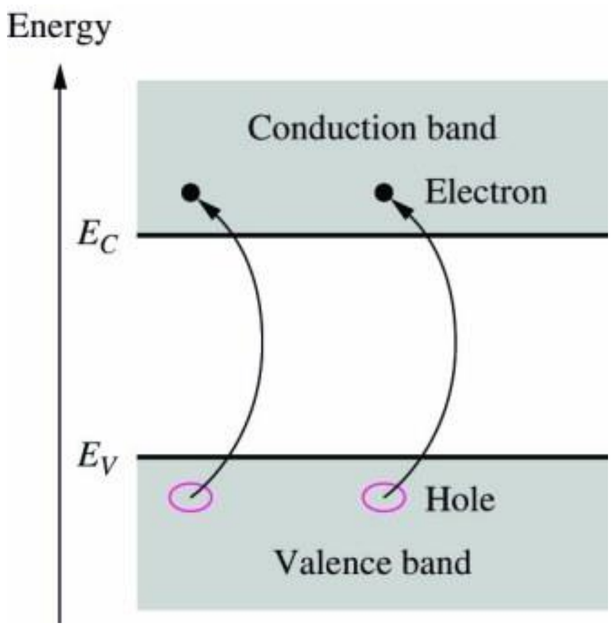


VOLTAGE



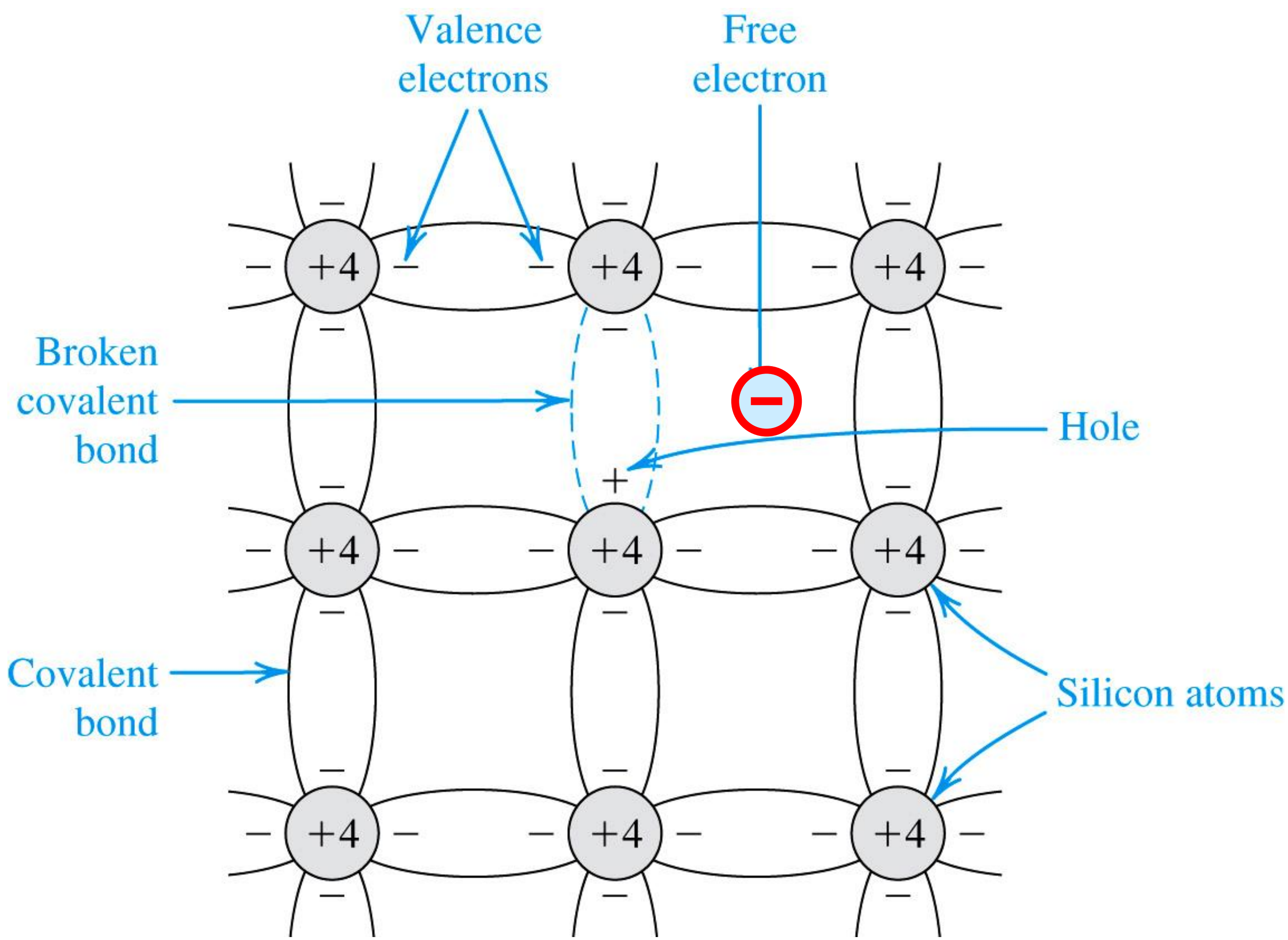
electron conduction
hole conduction
Si
Conventional current

Charge Generation & Recommendation

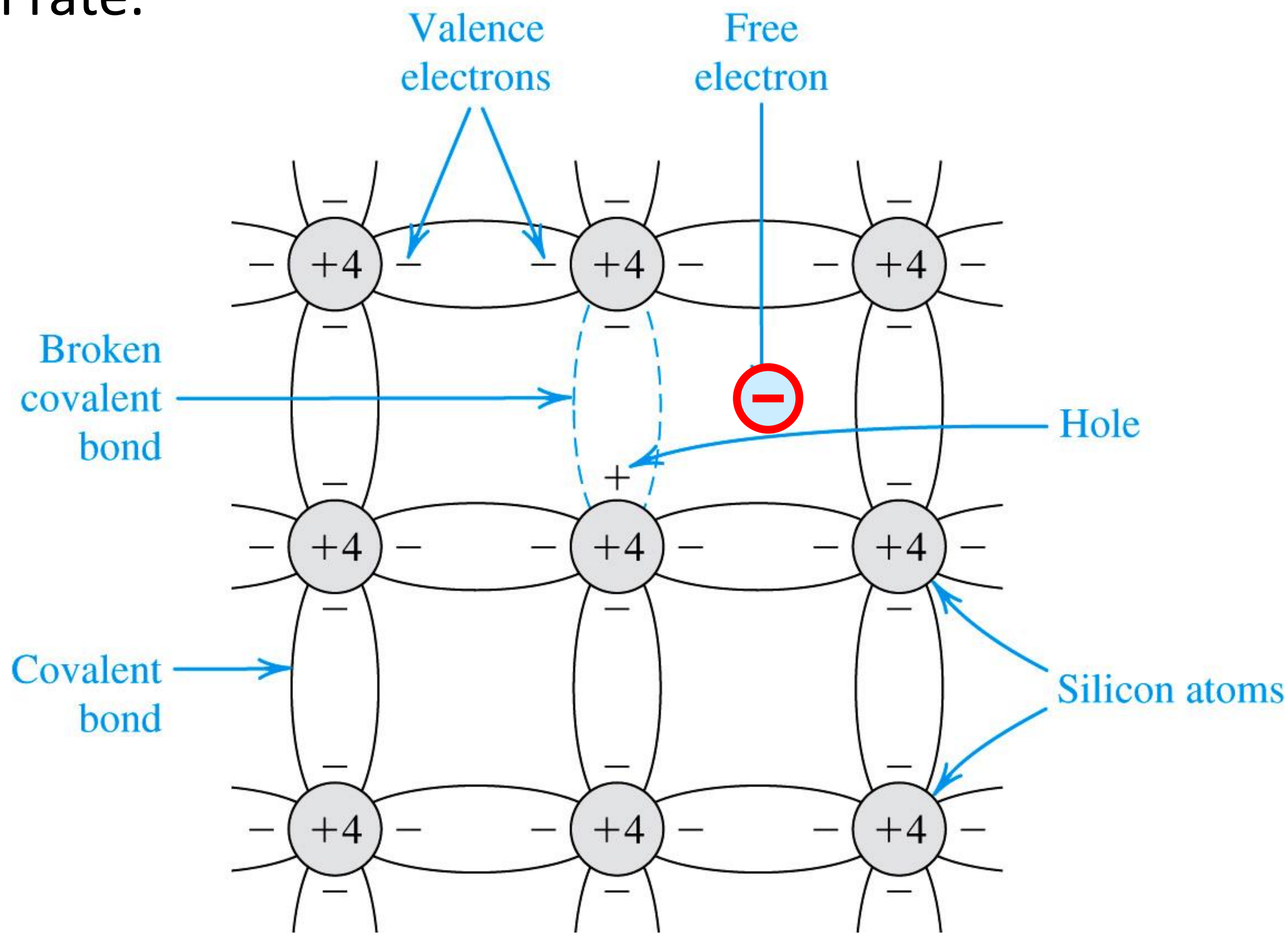


- Thermal generation results in free electrons and holes in equal numbers and hence equal concentrations, where concentration refers to the number of charge carriers per unit volume (cm^3).

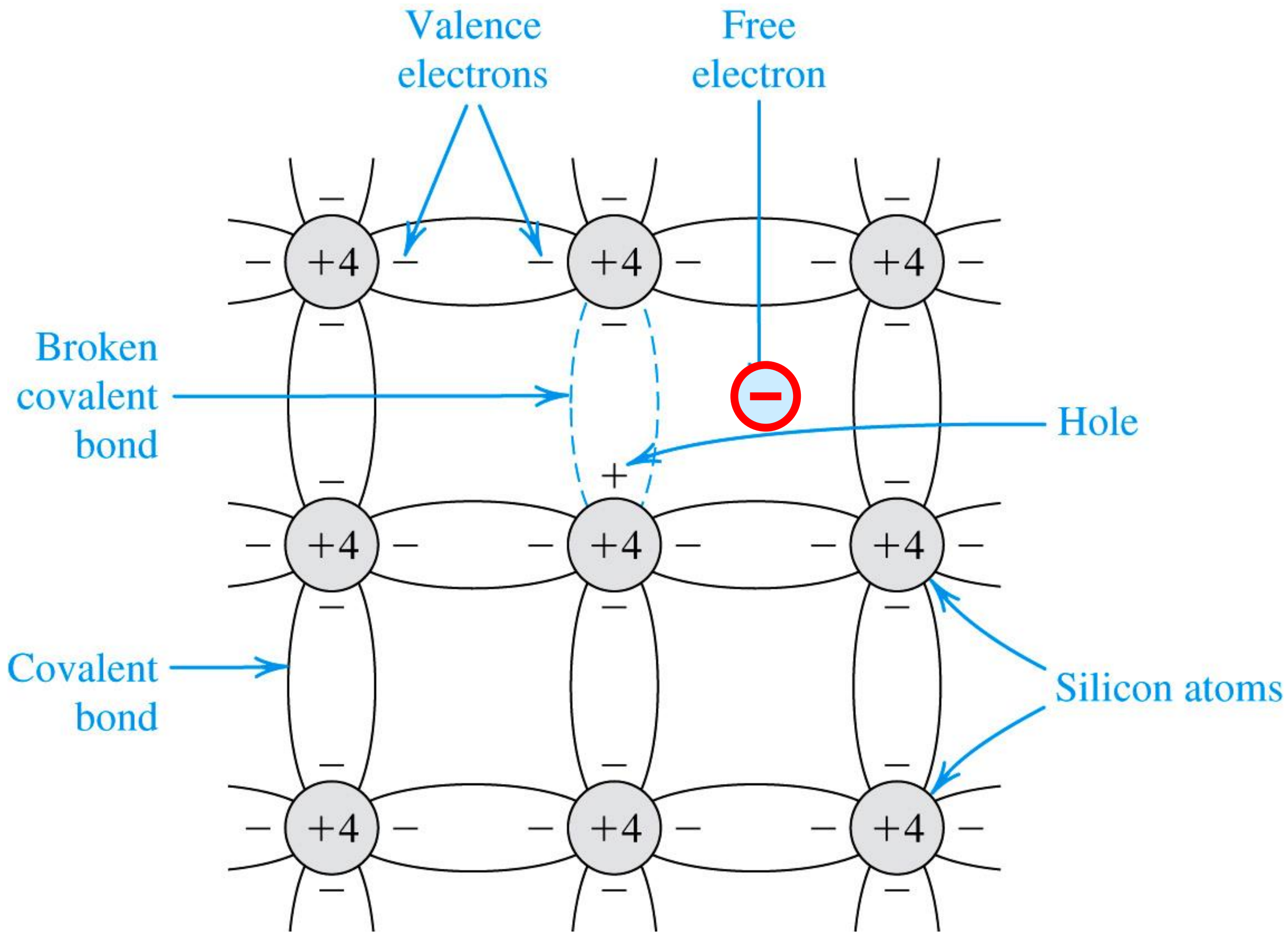
▪The free electrons and holes move randomly through the silicon crystal structure, and in the process some electrons may fill some of the holes.



- This process, called recombination, results in the disappearance of free electrons and holes.
- The recombination rate is proportional to the number of free electrons and holes, which in turn is determined by the thermal generation rate.

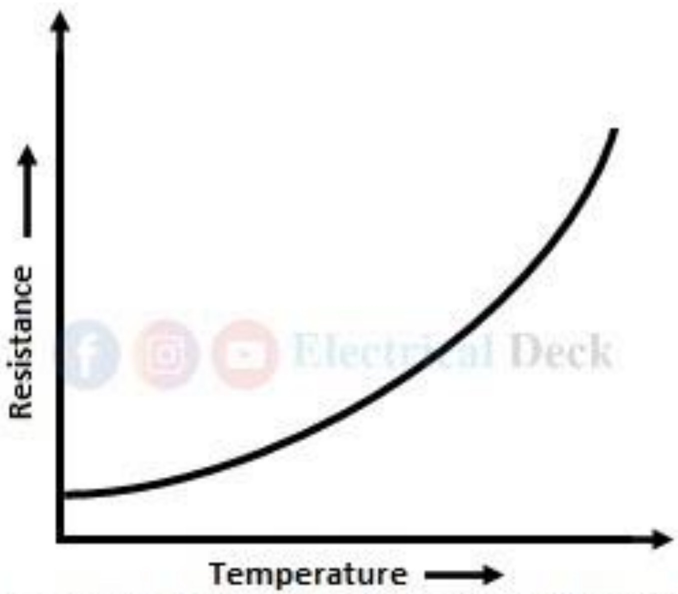


▪In thermal equilibrium, the recombination rate is equal to the generation rate, and one can conclude that the concentration of free electrons n is equal to the concentration of holes p,

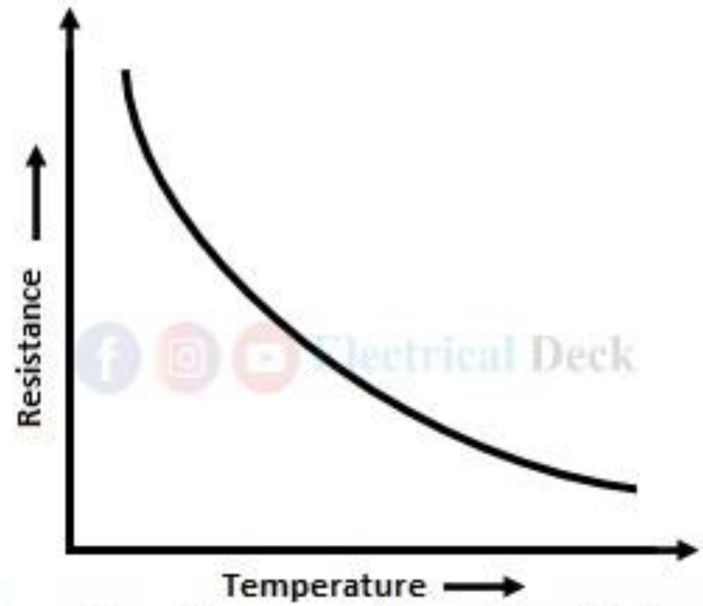


Electron Distribution

- As more energy is applied to a semiconductor, more electrons will move into the conduction band and current will flow more easily through the material.
- Therefore, the resistance of intrinsic semiconductor materials decreases with increasing temperature.
- This is a *negative temperature coefficient.*



Positive Temperature Coefficient of Resistance



Negative Temperature Coefficient of Resistance

Intrinsic Carrier Concentration

- The density of carriers in a semiconductor as a function of temperature and material properties is:

$$n_i^2 = BT^3 \exp\left(-\frac{E_G}{kT}\right) \quad \text{cm}^{-6}$$

- E_G = semiconductor bandgap energy in eV (electron volts)
- k = Boltzmann's constant, 8.62 x 10^{-5} eV/K
- T = absolute temperature, K
- B = material-dependent parameter, 1.08 x 10^{31} K^{-3} cm^{-6} for Si
- Bandgap energy is the minimum energy needed to free an electron by breaking a covalent bond in the semiconductor crystal.
- $n_i^2 \approx 1.5 \times 10^{10}$ cm^{-3} for Si at 300 K (room temperature)

Free Electron Density at a Given Temperature

$$n_i = 5.2 \times 10^{15} T^{3/2} \exp \frac{-E_g}{2kT} \, electrons/cm^3$$

$$n_i(T = 300^0 K) = 1.08 \times 10^{10} \, electrons/cm^3$$

$$n_i(T = 600^0 K) = 1.54 \times 10^{15} \, electrons/cm^3$$

- E_g, or bandgap energy determines how much effort is needed to break off an electron from its covalent bond.
- There exists an exponential relationship between the free-electron density and bandgap energy.

where B is a material-dependent parameter that is $7.3 \times 10^{15} \text{cm}^{-3}\text{K}^{-3/2}$ for silicon; E_g, a parameter known as the **bandgap energy**, is 1.12 electron volt (eV) for silicon[2]; and k is Boltzmann's constant (8.62×10^{-5} eV/K). It is interesting to know that the bandgap energy E_g is the minimum energy required to break a covalent bond and thus generate an electron-hole pair.

Example 3.1

Calculate the value of n_i for silicon at room temperature ($T \simeq 300$ K).

Solution

Substituting the values given above in Eq. (3.1) provides

$$\begin{aligned} n_i &= 7.3 \times 10^{15}(300)^{3/2} e^{-1.12/(2 \times 8.62 \times 10^{-5} \times 300)} \\ &= 1.5 \times 10^{10} \text{carriers/cm}^3 \end{aligned}$$

Although this number seems large, to place it into context note that silicon has 5×10^{22} atoms/cm^3. Thus at room temperature only one in about 5×10^{12} atoms is ionized and contributing a free electron and a hole!

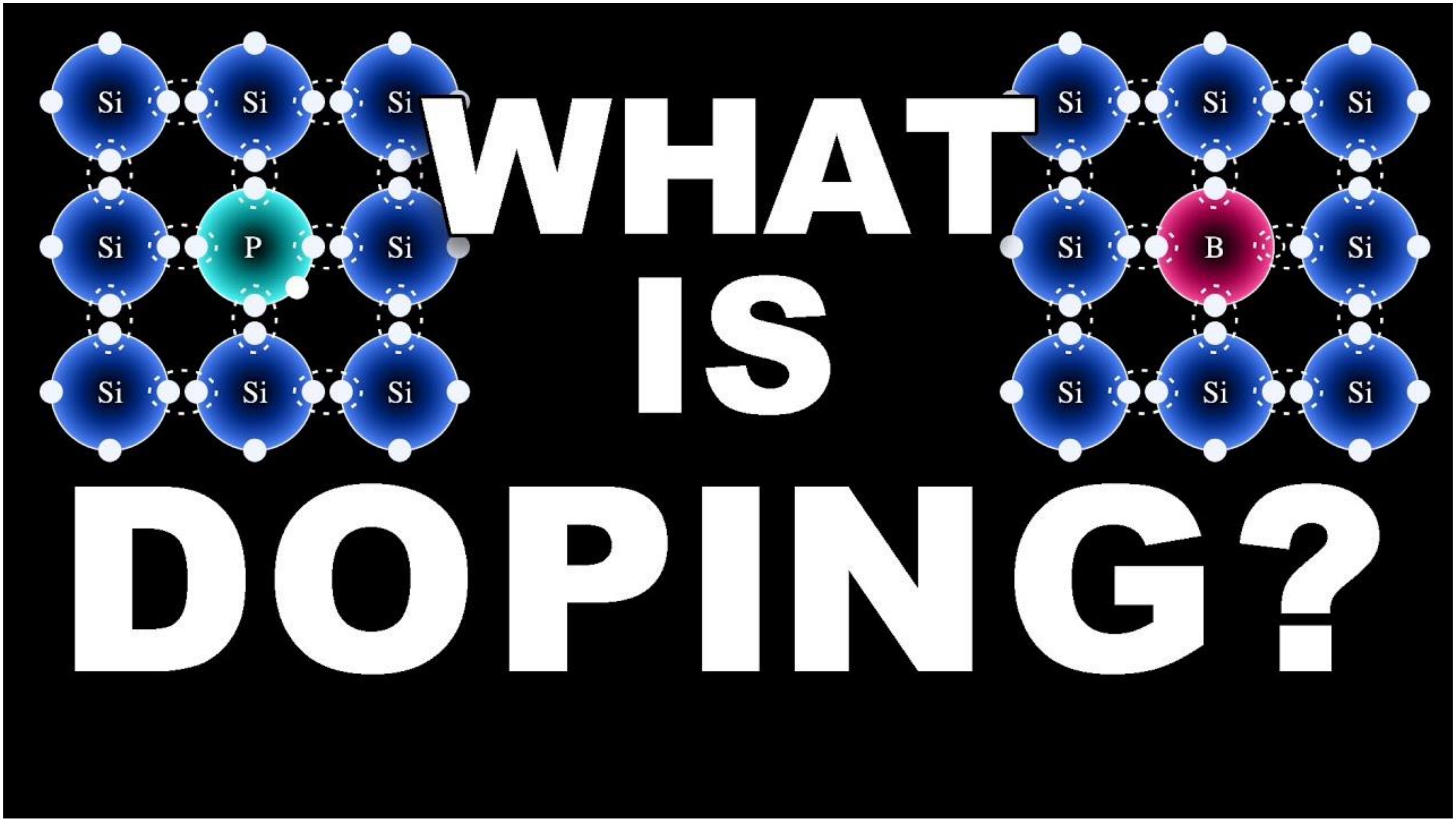
Summary of Electron-hole concentrations

- A vacancy is left when a covalent bond is broken.
- The vacancy is called a hole.
- A hole moves when the vacancy is filled by an electron from a nearby broken bond (hole current).
- The electron density is n (n_i for intrinsic material)
- Hole density is represented by p.
- For intrinsic silicon, $n = n_\mathrm{i} = p$.
- The product of electron and hole concentrations is $\boldsymbol{pn = n_i^2}$.
- The pn product above holds when a semiconductor is in thermal equilibrium (not with an external voltage applied).

- Finally, it is useful for future purposes to express the product of the hole and free-electron concentration as

$$pn = n_i^2 \tag{3.3}$$

where for silicon at room temperature, $n_i \simeq 1.5 \times 10^{10}/\mathrm{cm}^3$. As will be seen shortly, this relationship extends to extrinsic or doped silicon as well.


WHAT
IS
DOPING?
Si
P
B

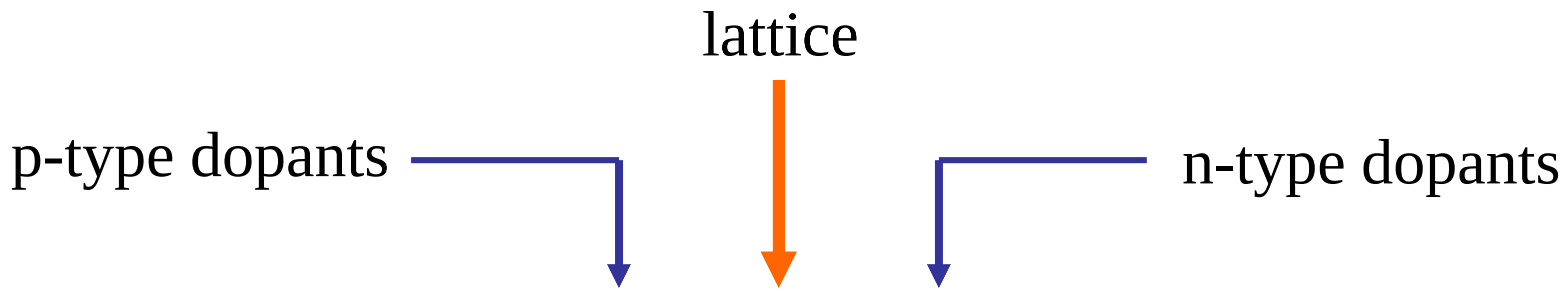
Semiconductor Doping

- The interesting properties of semiconductors emerges when impurities are introduced.
- Doping is the process of adding very small well controlled amounts of impurities into a semiconductor.
- Doping enables the control of the resistivity and other properties over a wide range of values.
- For silicon, impurities are from columns III and V of the periodic table.

Extrinsic Semiconductors

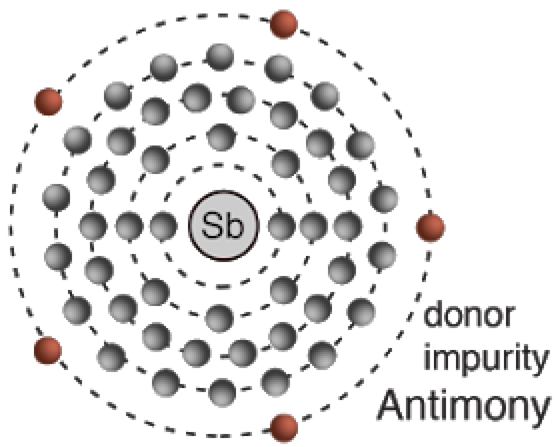
- The problem with intrinsic semiconductors are;
- **Charge carriers are thermally generated and very few in number resulting in very little current.**
- **Thus for device applications, where an appreciable current is required we need to carry out the "doping process" resulting in extrinsic semiconductors**

Doped Semiconductors

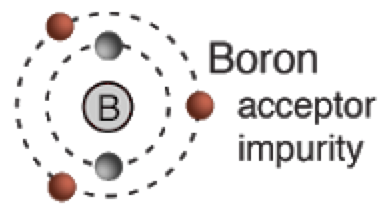


3A	4A	5A	
BORON 10.81 2.34 B 5 $1s^2 2s^2 2p^1$ 8.73 TET 0.576 2600 1250	CARBON 12.01 2.26 C 6 $1s^2 2s^2 2p^2$ 3.57 DIA (4300) 1860	NITROGEN 14.007 1.03 N 7 $1s^2 2s^2 2p^3$ 4.039 HEX 1.651 63.3 (β) 79^{LT}	OXY 1.43 6.83 54.7
ALUMINUM 26.982 2.70 Al 13 [Ne] $3s^2 3p^1$ 4.05 FCC 933 394	SILICON 28.086 2.33 Si 14 [Ne] $3s^2 3p^2$ 5.43 DIA 1683 625	PHOSPHORUS 30.974 1.82 (white) P 15 [Ne] $3s^2 3p^3$ 7.17 CUB 317.3	SUL 2.07 10.4 386
GALLIUM 69.72 5.91 Ga 31 [Ar] $3d^{10} 4s^2 3p^1$ 4.51 ORC 1.695 1.001 303 240	GERMANIUM 72.59 5.32 Ge 32 [Ar] $3d^{10} 4s^2 4p^2$ 5.66 DIA 1211 360	ARSENIC 74.922 5.72 As 33 [Ar] $3d^{10} 4s^2 4p^3$ 4.13 RHL 54°10′ 1090 285	SELI 4.79 [A 4.36 490
INDIUM 114.82 7.31 In 49 [Kr] $4d^{10} 5s^2 5p^1$ 4.59 TET 1.076 429.8 129	TIN 118.69 7.30 Sn 50 [Kr] $4d^{10} 5s^2 5p^2$ 5.82 TET 0.546 505 170	ANTIMONY 121.75 6.62 Sb 51 [Kr] $4d^{10} 5s^2 5p^3$ 4.51 RHL 57°6′ 904 200	TEL 6.24 [K 4.45 723
THALLIUM 204.37 11.85 Tl 81 [Xe] $4f^{14} 5d^{10} 6s^2 6p^1$ 3.46 HEX 1.599 577 96	LEAD 207.19 11.4 Pb 82 [Xe] $4f^{14} 5d^{10} 6s^2 6p^2$ 4.95 FCC 601 88	BISMUTH 208.98 9.8 Bi 83 [Xe] $4f^{14} 5d^{10} 6s^2 6p^3$ 4.75 RHL 57°14′ 544.5 120	POL 9.4 [Xe] 3.35 527

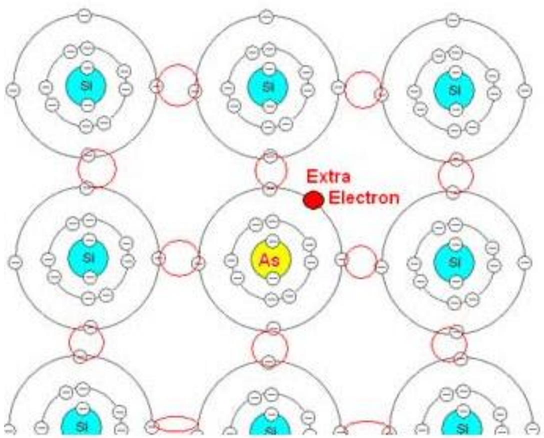
Antimony
Arsenic
Phosphorous



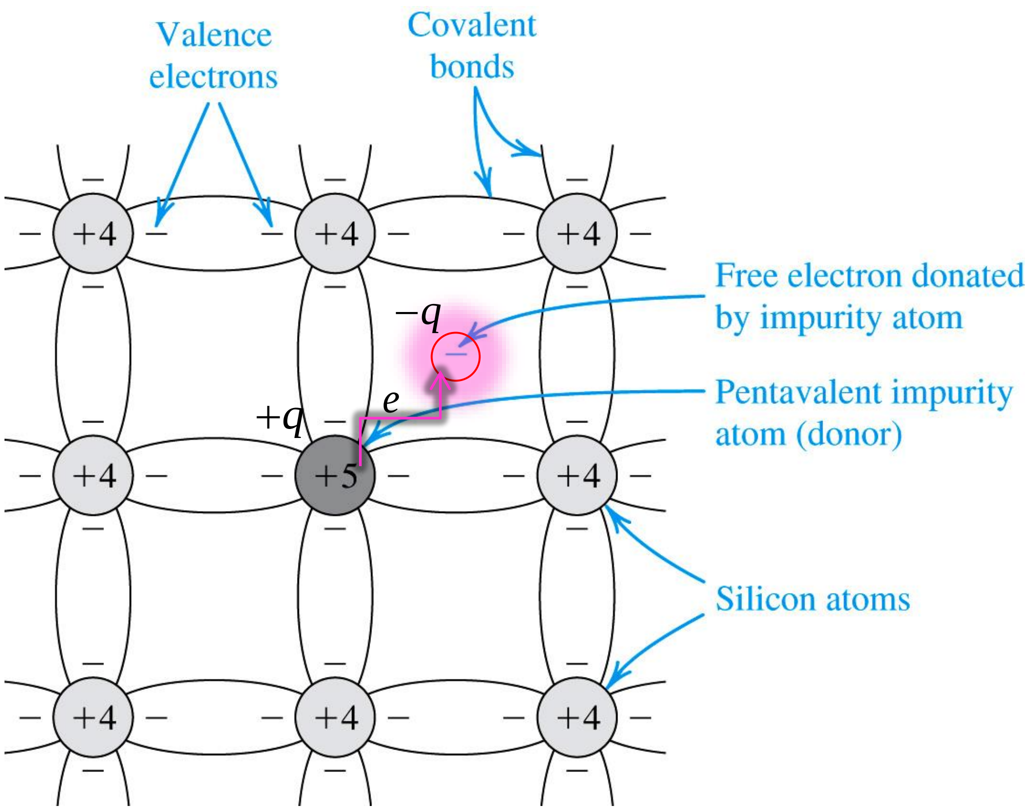
Boron
Aluminum
Gallium



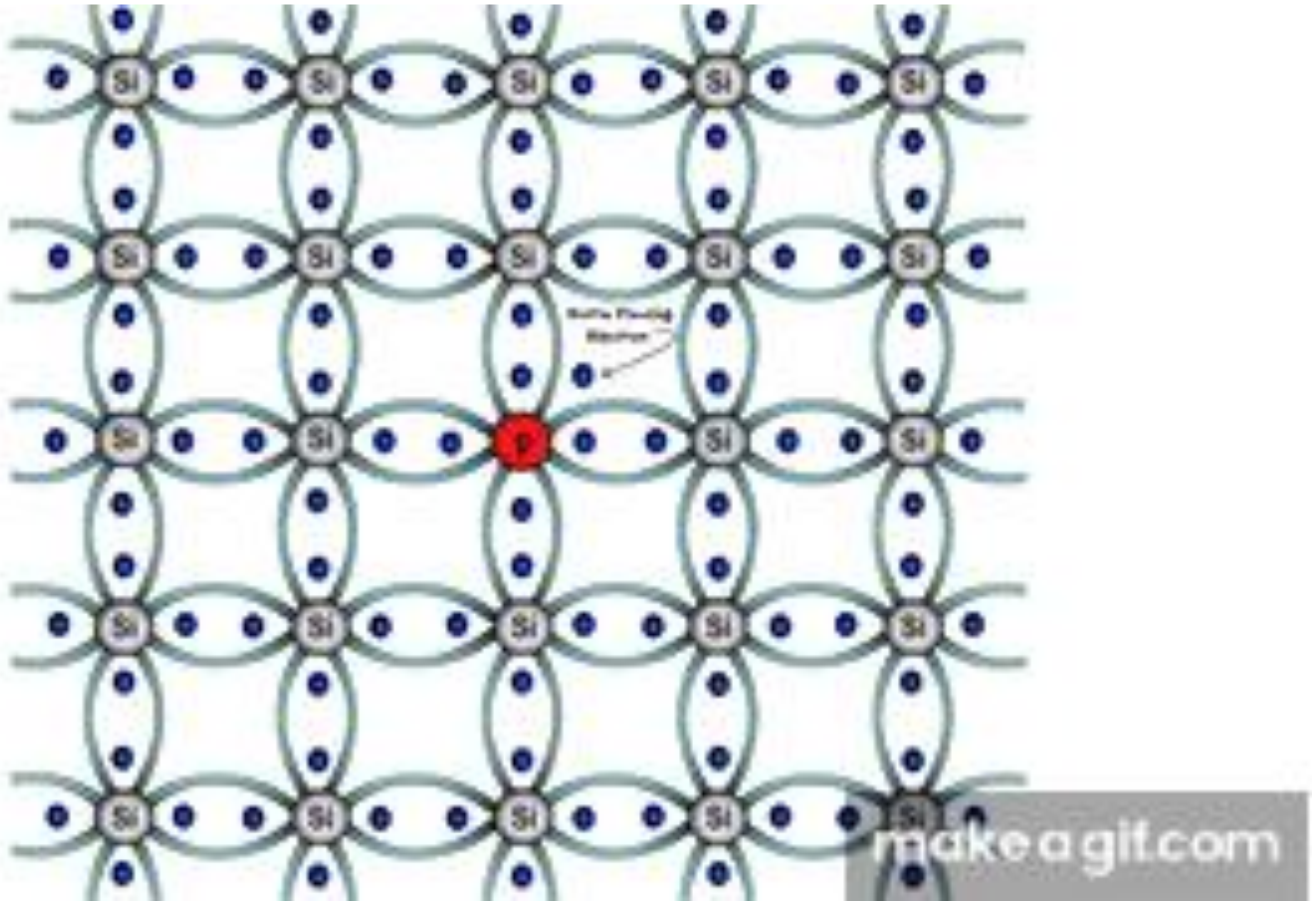
Donor Impurities in Silicon



- Phosphorous (or other column V element) atom replaces silicon atom in crystal lattice.
- Since phosphorous has five outer shell electrons, there is now an 'extra' electron in the structure.
- Material is still charge neutral, but very little energy is required to free the electron for conduction since it is not participating in a bond.

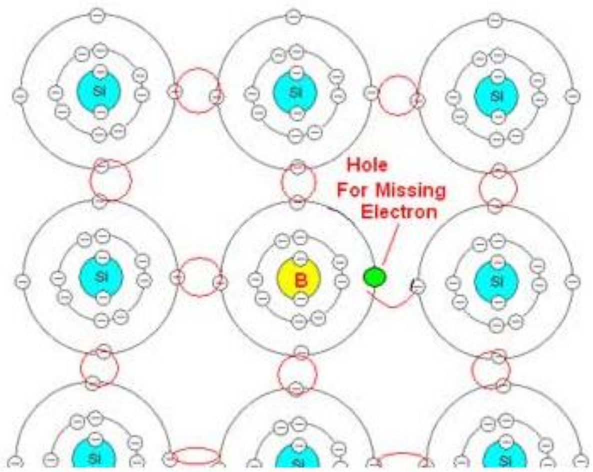


A silicon crystal doped by a pentavalent element (f. i. phosphorus). Each dopant atom donates a free electron and is thus called a donor. The doped **semiconductor becomes *n* type**.

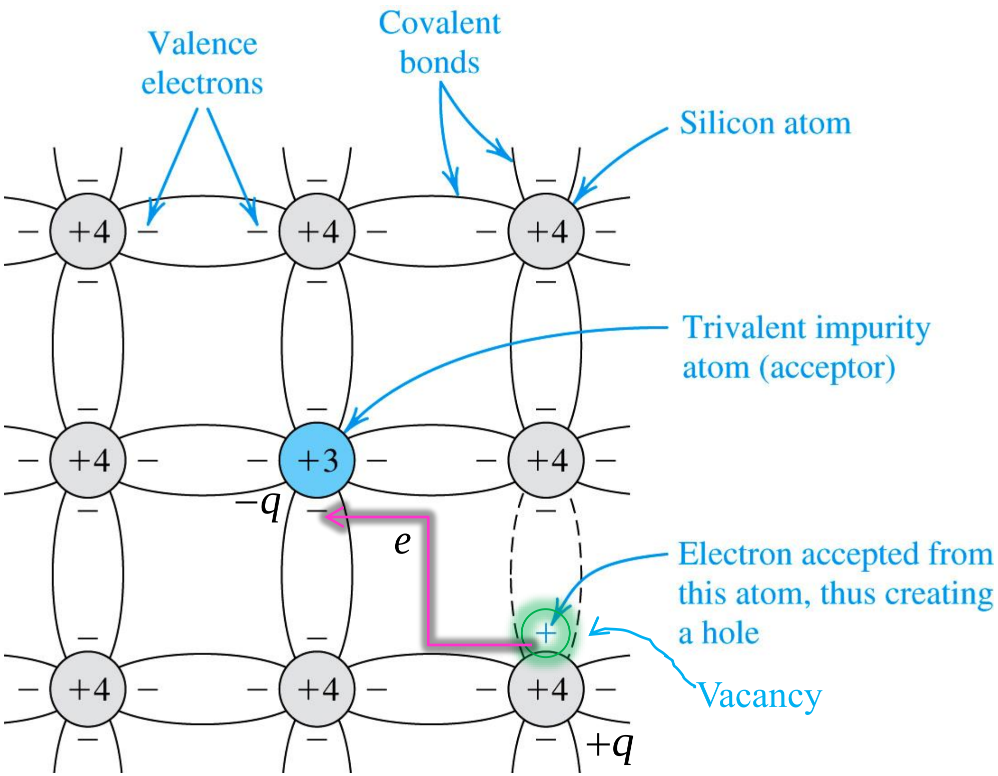

Si
P
makeagif.com


EXTRINSIC SEMICONDUCTOR
1. n-type Semiconductors
Si
Si
Si
As
Si
Si
This allows four of the five electrons to bond with its neighboring silicon atoms leaving one free
electron to move about when electrical voltage is applied.

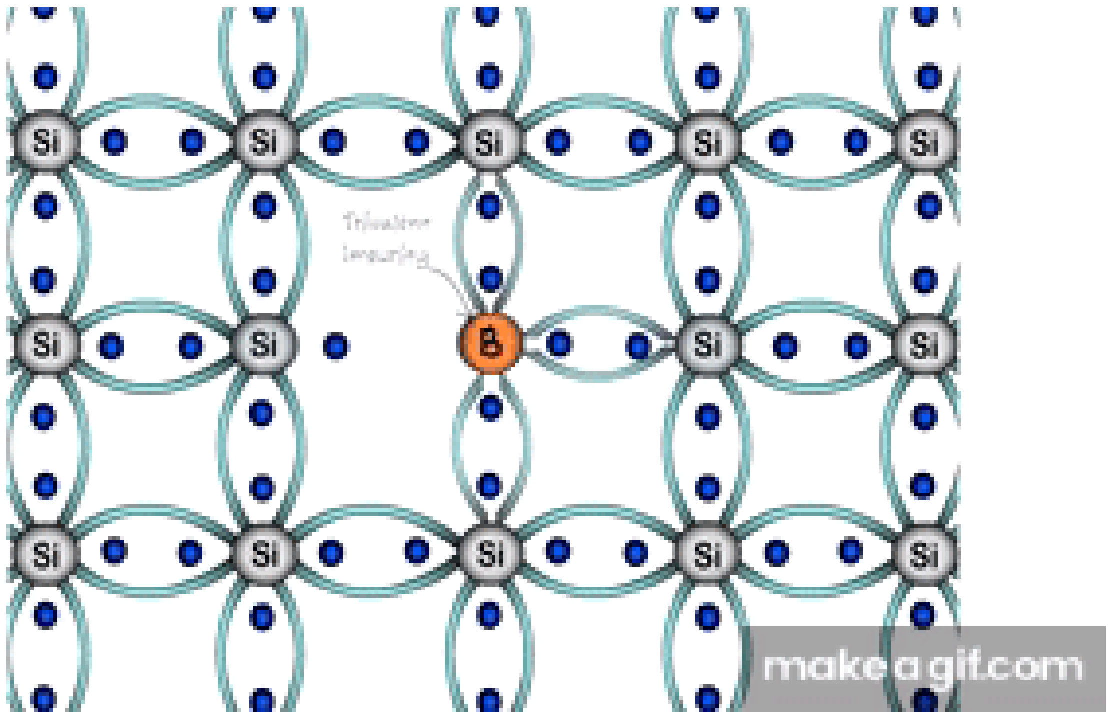
Acceptor Impurities in Silicon

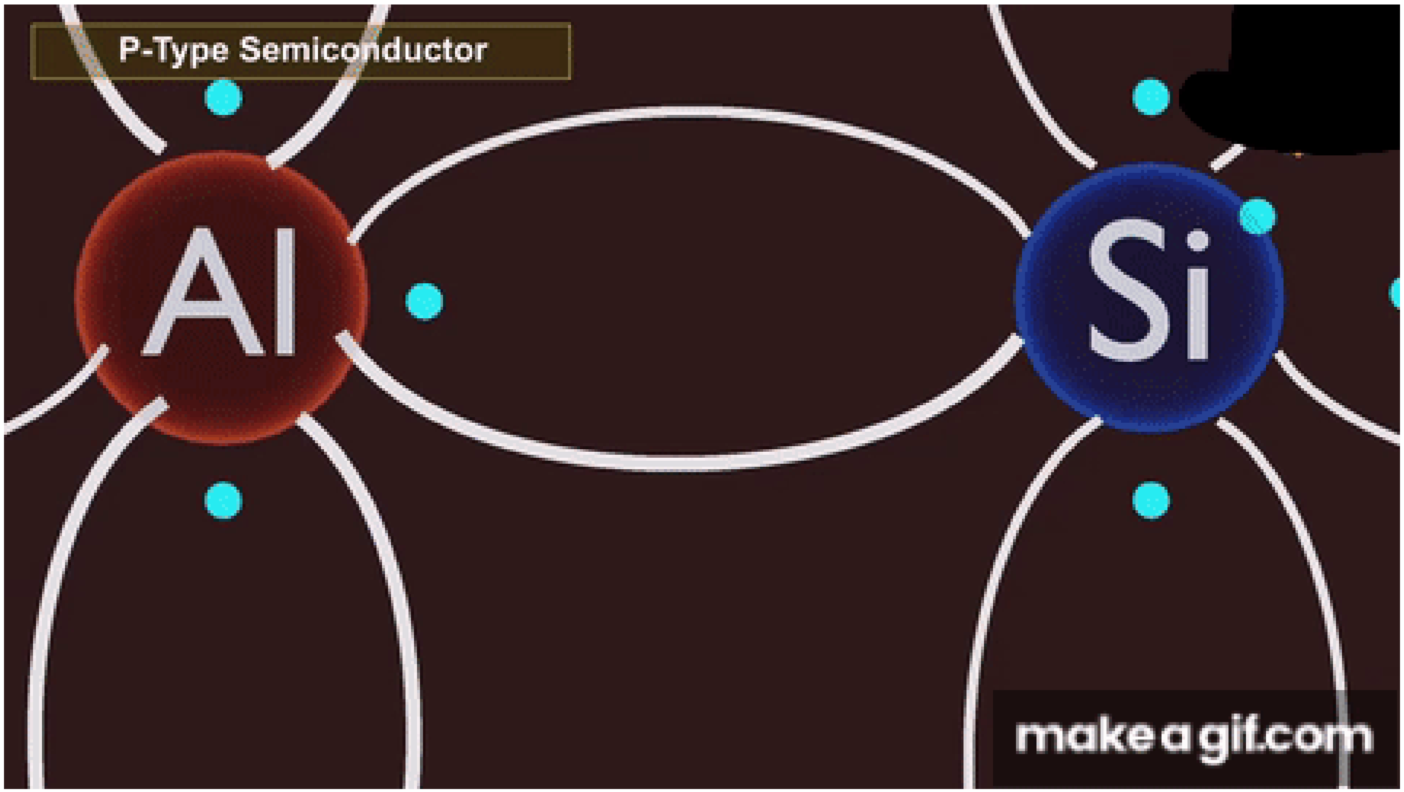


- Boron (column III element) has been added to silicon.
- There is now an incomplete bond pair, creating a vacancy for an electron.
- Little energy is required to move a nearby electron into the vacancy.
- As the 'hole' propagates, charge is moved across the silicon.

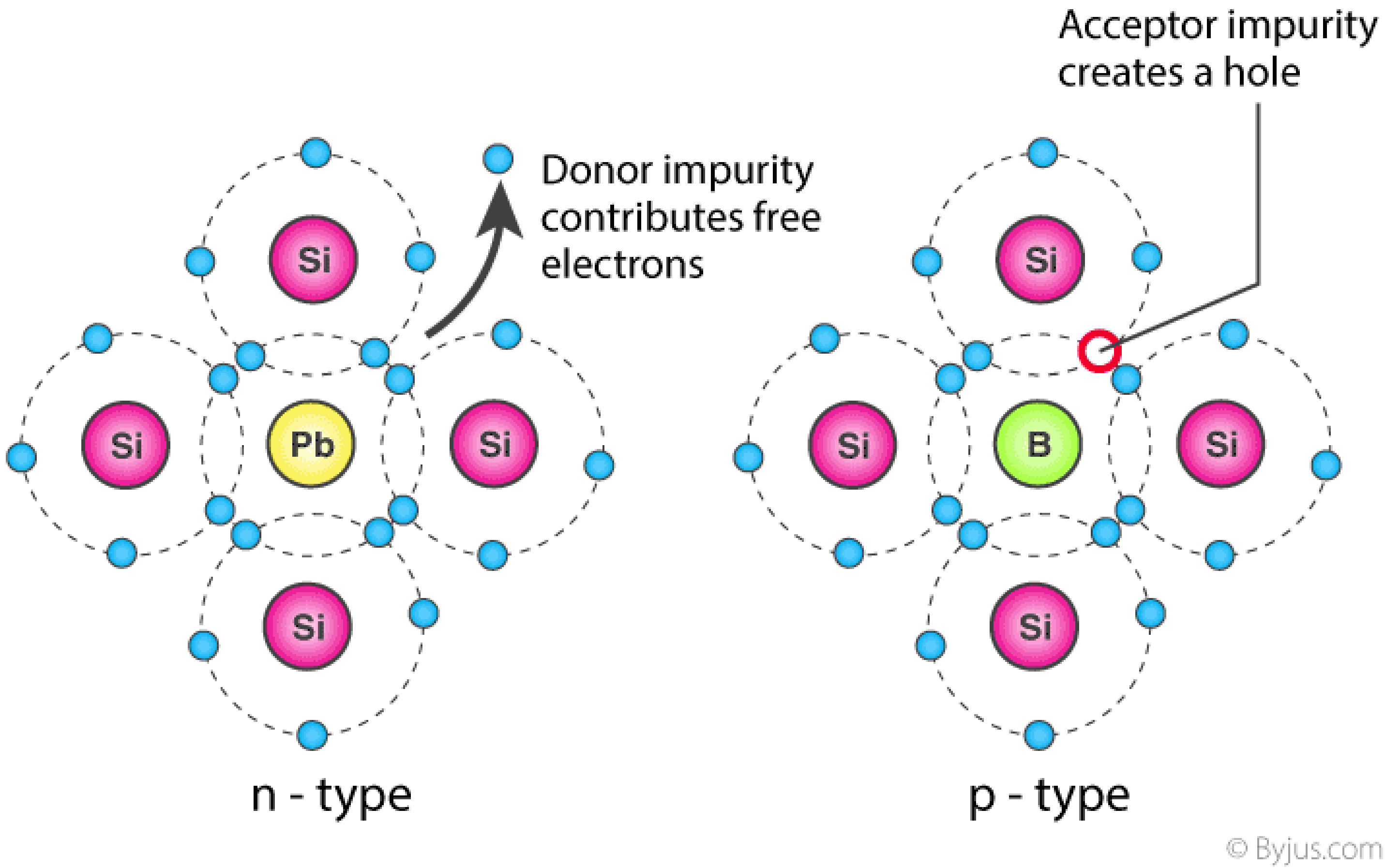


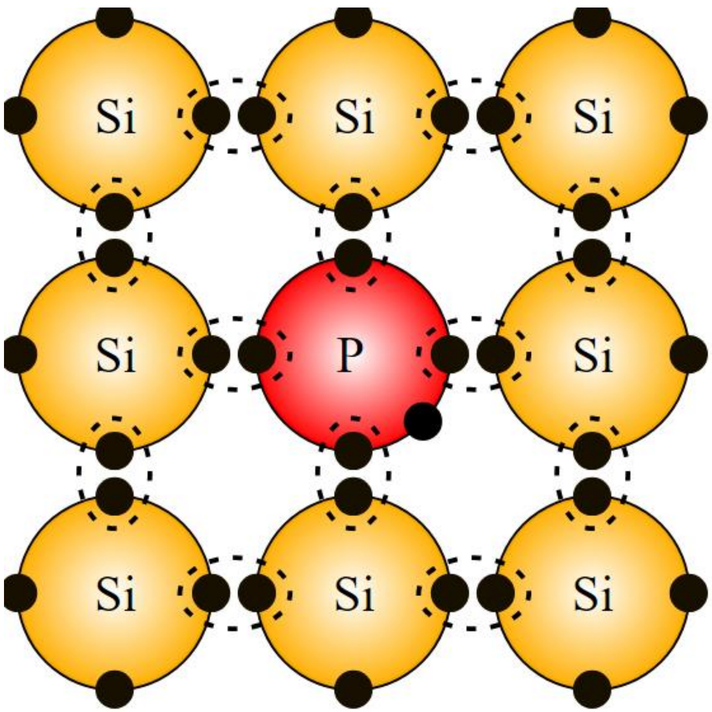
A silicon crystal doped with a trivalent impurity (f.i. boron). Each dopant atom gives rise to a hole, and the **semiconductor becomes *p* type.**


Si
B
makeagif.com

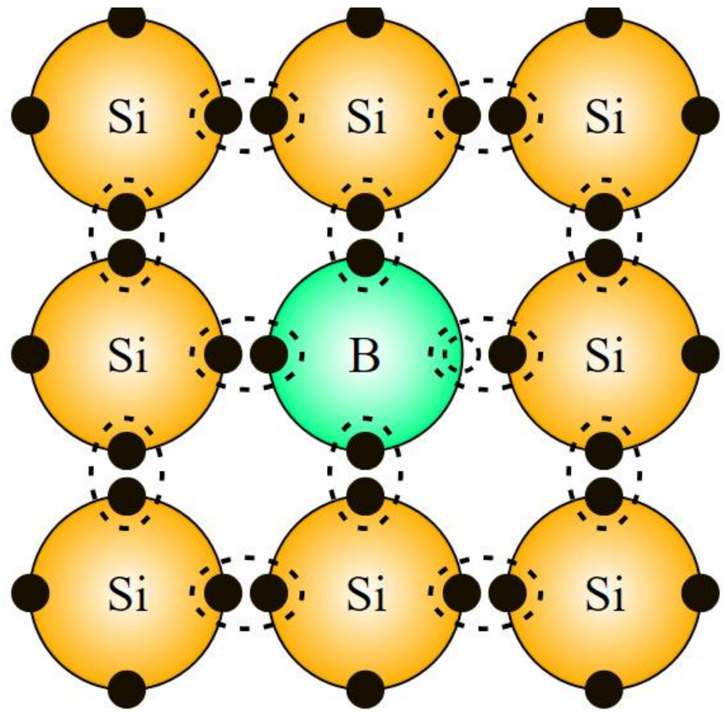

P-Type Semiconductor
Al
Si
makeagif.com

EXTRINSIC SEMICONDUCTORS





n-type



p-type

Summary of Doped Semiconductors

- The most significant property of semiconductors is that their conductivity can be varied over a very wide range through the introduction of controlled amounts of impurity atoms into the semiconductor crystal in a process called doping
- Doped semiconductors are materials in which carriers of one kind predominate.
- Only two types of doped semiconductors are available.

Doped Semiconductor

- Doping involves introducing impurity atoms into the silicon crystal in sufficient numbers to substantially increase the concentration of either free electrons or holes but with little or no change in the crystal properties of silicon.
- To increase the concentration of free electrons, n, silicon is doped with an element with a valence of 5, such as phosphorus.
- The resulting doped silicon is then said to be of n type.

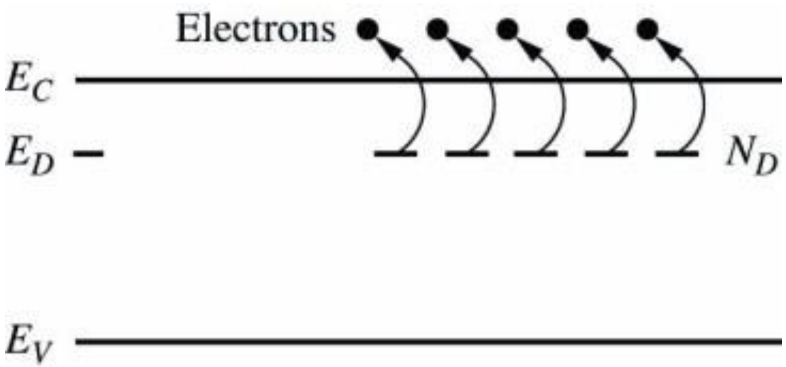
Doped Semiconductor

- To increase the concentration of holes, p, silicon is doped with an element having a valence of 3, such as boron, and the resulting doped silicon is said to be of p type
- Conductivity of doped semiconductor is much greater than the one of intrinsic semiconductor.
- The *pn* junction is formed by doped semiconductor.

Doped Semiconductor(cont'd)

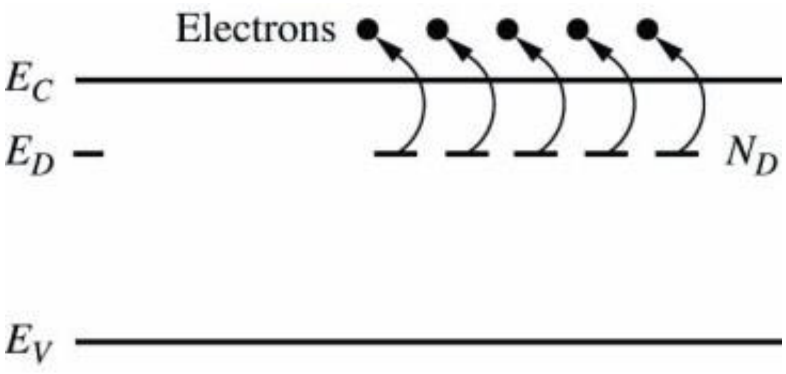
- Majority carrier is only determined by the impurity, but independent of temperature.
- Minority carrier is strongly affected by temperature.
- If the temperature is high enough, characteristics of doped semiconductor will decline to the one of intrinsic semiconductor.

Energy Band Model for a Doped Semiconductor

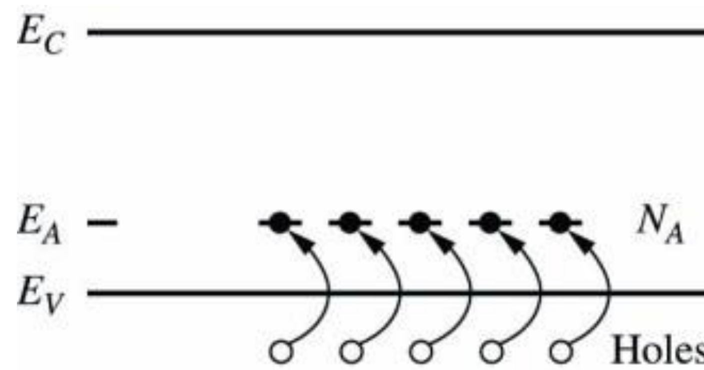


Semiconductor with donor or n-type dopants. The donor atoms have free electrons with energy E_D. Since E_D is close to E_C, (about 0.045 eV for phosphorous), it is easy for electrons in an n-type material to move up into the conduction band.

Energy Band Model for a Doped Semiconductor



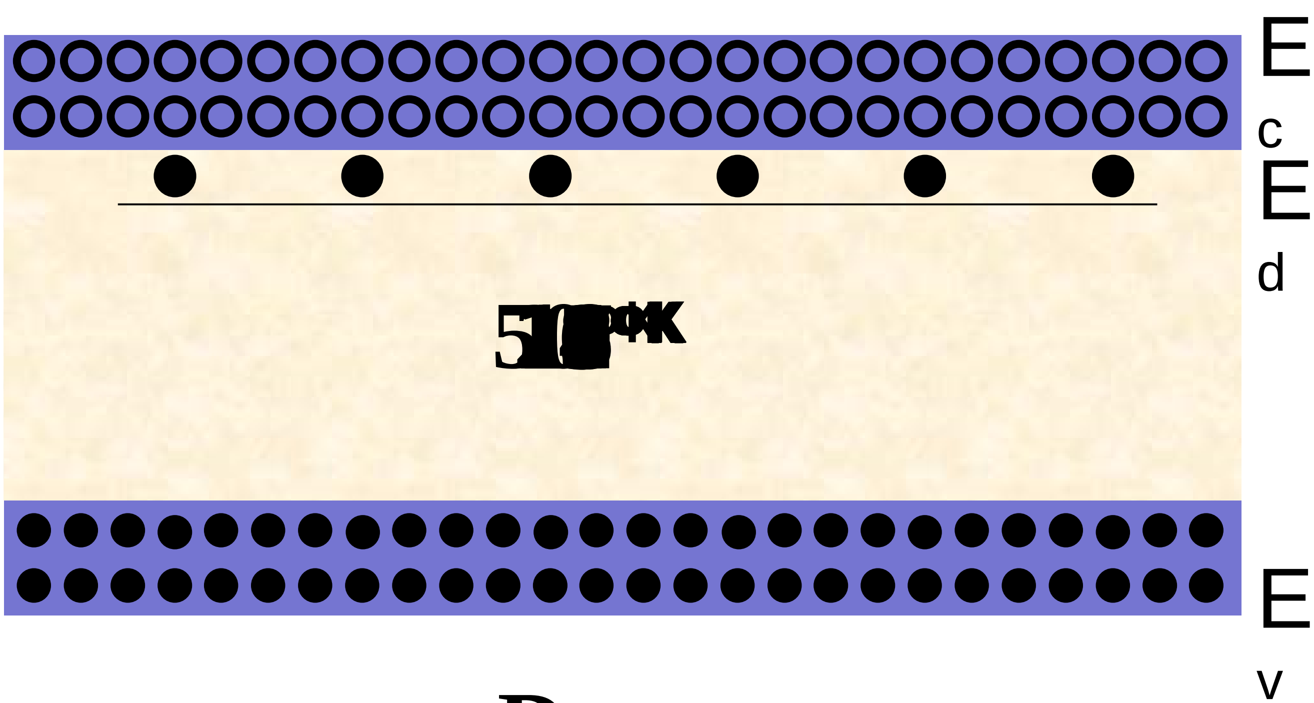
Semiconductor with donor or n-type dopants. The donor atoms have free electrons with energy E_D. Since E_D is close to E_C, (about 0.045 eV for phosphorous), it is easy for electrons in an n-type material to move up into the conduction band and create negative charge carriers.



Semiconductor with acceptor or p-type dopants. The acceptor atoms have unfilled covalent bonds with energy state E_A. Since E_A is close to E_V, (about 0.044 eV for boron), it is easy for electrons in the valence band to move up into the acceptor sites and complete covalent bond pairs, and create holes – positive charge carriers.

Extrinsic Material

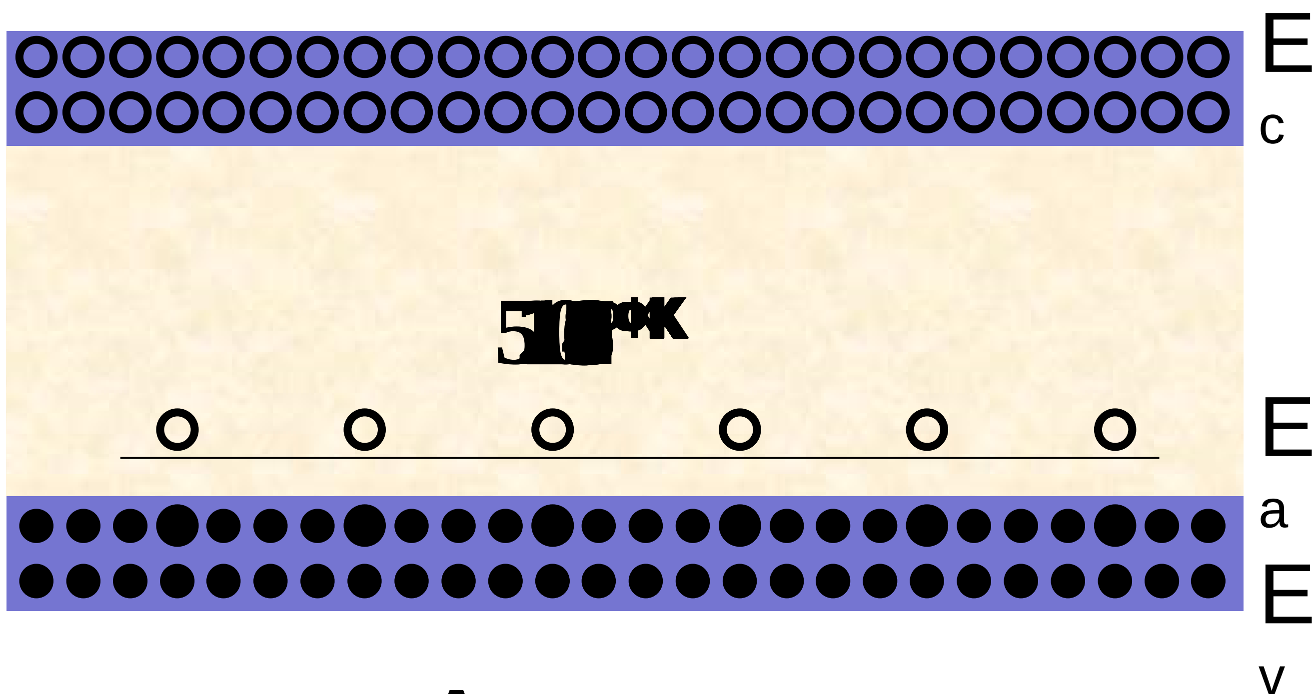
V
P
As
Sb



Donor

Extrinsic Material

III
B
Al
Ga
In



Acceptor

Hole and Electron Concentrations

- To produce reasonable levels of conduction doesn't require much doping
  - silicon has about 5 x 10^{22} atoms/cm^3
  - typical dopant levels are about 10^{15} atoms/cm^3
- In undoped (intrinsic) silicon, the number of holes and number of free electrons is equal, and their product equals a constant
  - actually, n_i increases with increasing temperature

$$np = n_i^2$$

- This equation holds true for doped silicon as well, so increasing the number of free electrons decreases the number of holes

If the concentration of donor atoms is N_D, where N_D, is usually much greater than n_i , the concentration of free electrons in the n-type silicon will be

$$n_n \approx\approx N_D$$

where the subscript n denotes n-type silicon. Thus n_n is determined by the doping concentration and not by temperature. This is not the case, however, for the hole concentration. All the holes in the n-type silicon are those generated by thermal ionization. Their concentration p_n can be found by noting that the relationship

$$np = n_i^2$$

applies equally well for doped silicon, provided thermal equilibrium is achieved. Thus for n-type silicon

$$p_n n_n = n_i^2$$

Substituting for n_n from Eq. (3.4), we obtain for p_n

$$p_n \simeq \frac{n_i^2}{N_D}$$

Thus p_n will have the same dependence on temperature as that of n_i^2.

Electron and Hole Densities

$$np = n_i^2$$

Majority Carriers : $p \approx N_A$

Minority Carriers : $n \approx \dfrac{n_i^2}{N_A}$

Majority Carriers : $n \approx N_D$

Minority Carriers : $p \approx \dfrac{n_i^2}{N_D}$

- The product of electron and hole densities is ALWAYS equal to the square of intrinsic electron density regardless of doping levels.

Questions ?

P-N JUNCTION FORMATION AND BEHAVIOR

- **IN THIS SECTION WE WILL LEARN:**
  - The structure and operation of the *pn* junction – a basic semiconductor structure that implements the diode and plays a dominant role in semiconductors.
  - The two mechanisms by which current flows in semiconductors – drift and diffusion charge carriers.

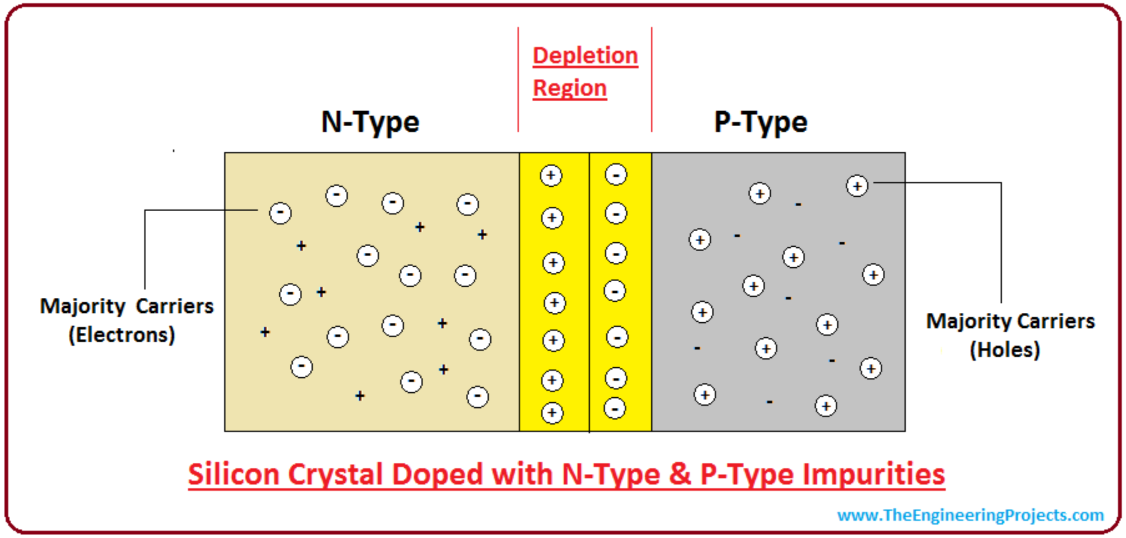
P-N Junction formation and behavior

- The *pn* junction under open-circuit condition
  - Diffusion and Drift currents
- The pn junction under closed circuit conditions
  - Forward bias
  - Reverse bias
- I-V characteristic of *pn* junction
  - Terminal characteristic of junction diode.

P-N Junction

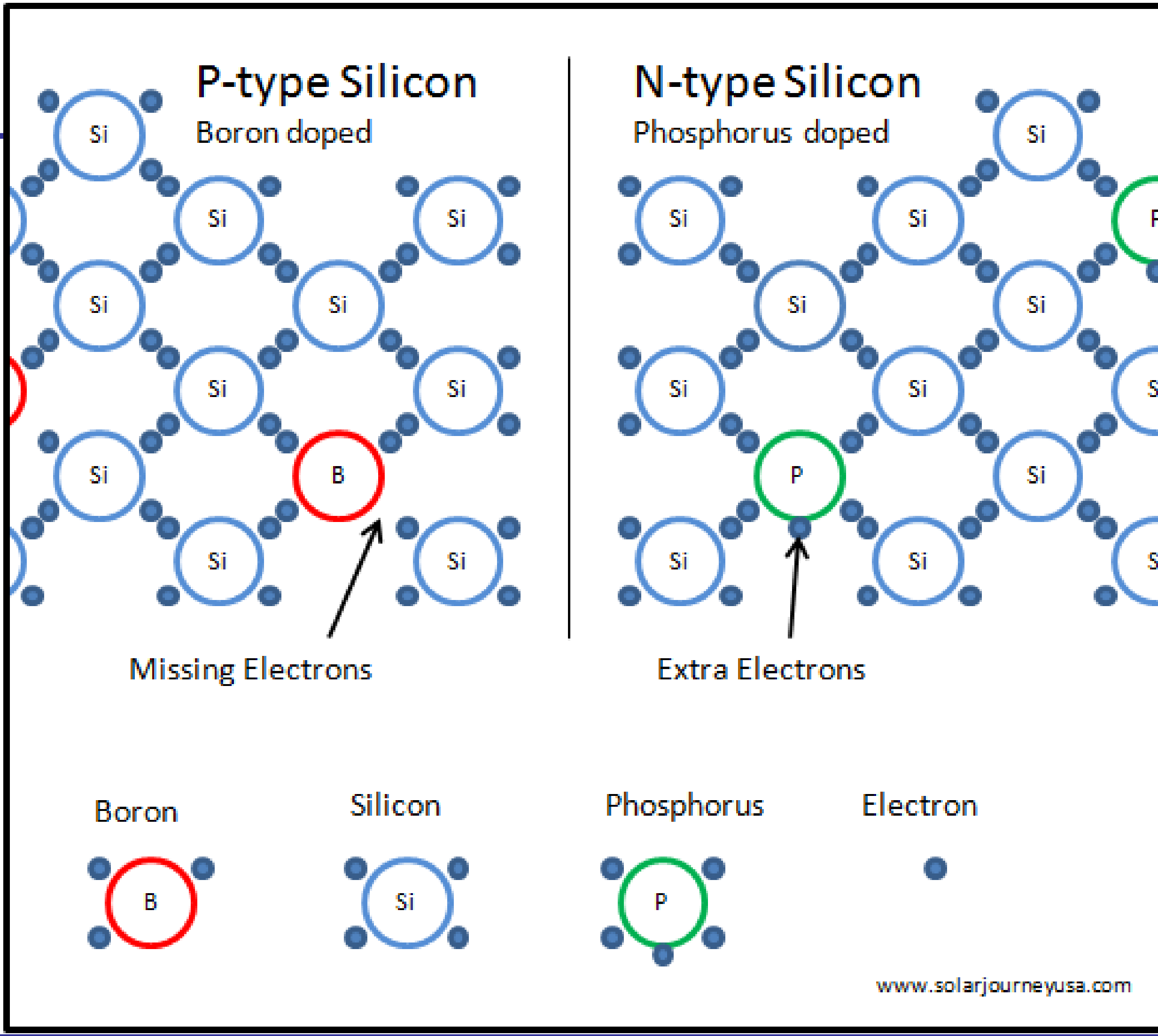
• Open circuit conditions

- The p-n junction possesses some interesting properties which have useful applications in modern electronics. Thus an understanding of the physical operations of p-n junctions is important to the understanding of the operation and terminal characteristics these electronic devices

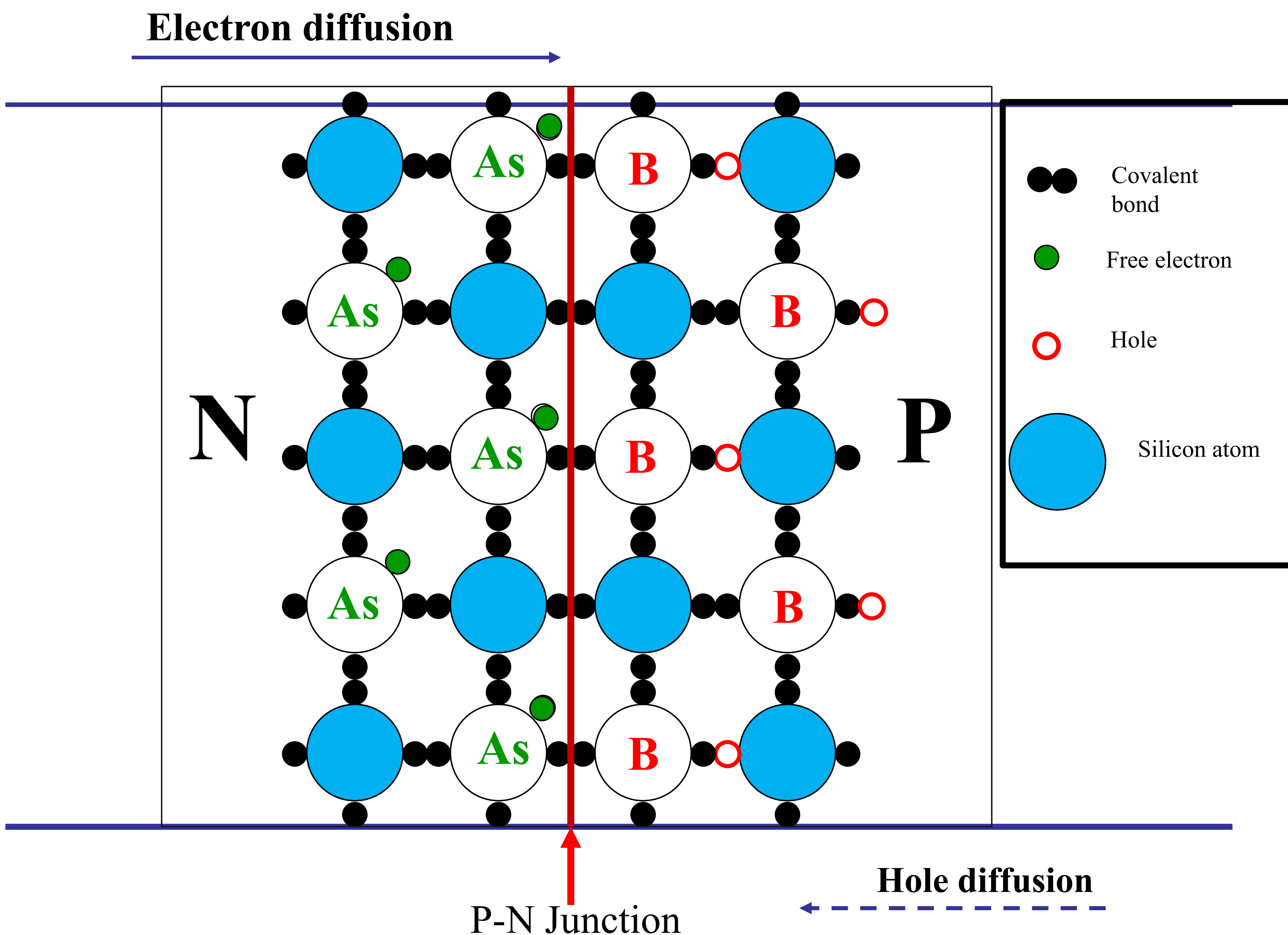


P-N JUNCTION FORMATION

- Three important phenomena occur during the formation of a P-N Junction namely;
- Diffusion
- Space charge
- Drift

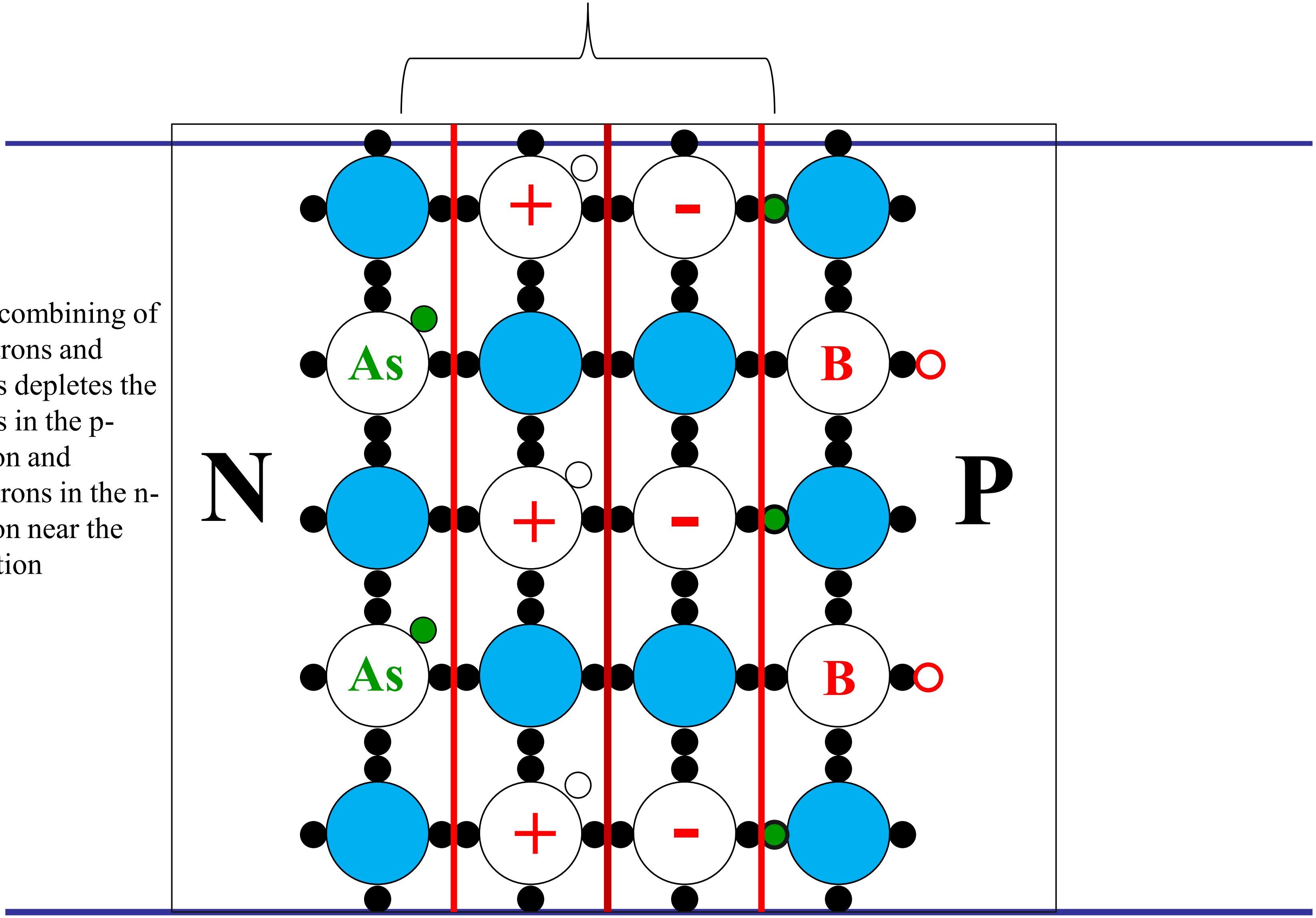

P-type Silicon
Boron doped
N-type Silicon
Phosphorus doped
Si
B
P
Missing Electrons
Extra Electrons
Boron
Silicon
Phosphorus
Electron
www.solarjourneyusa.com

Formation of the P-N Junction

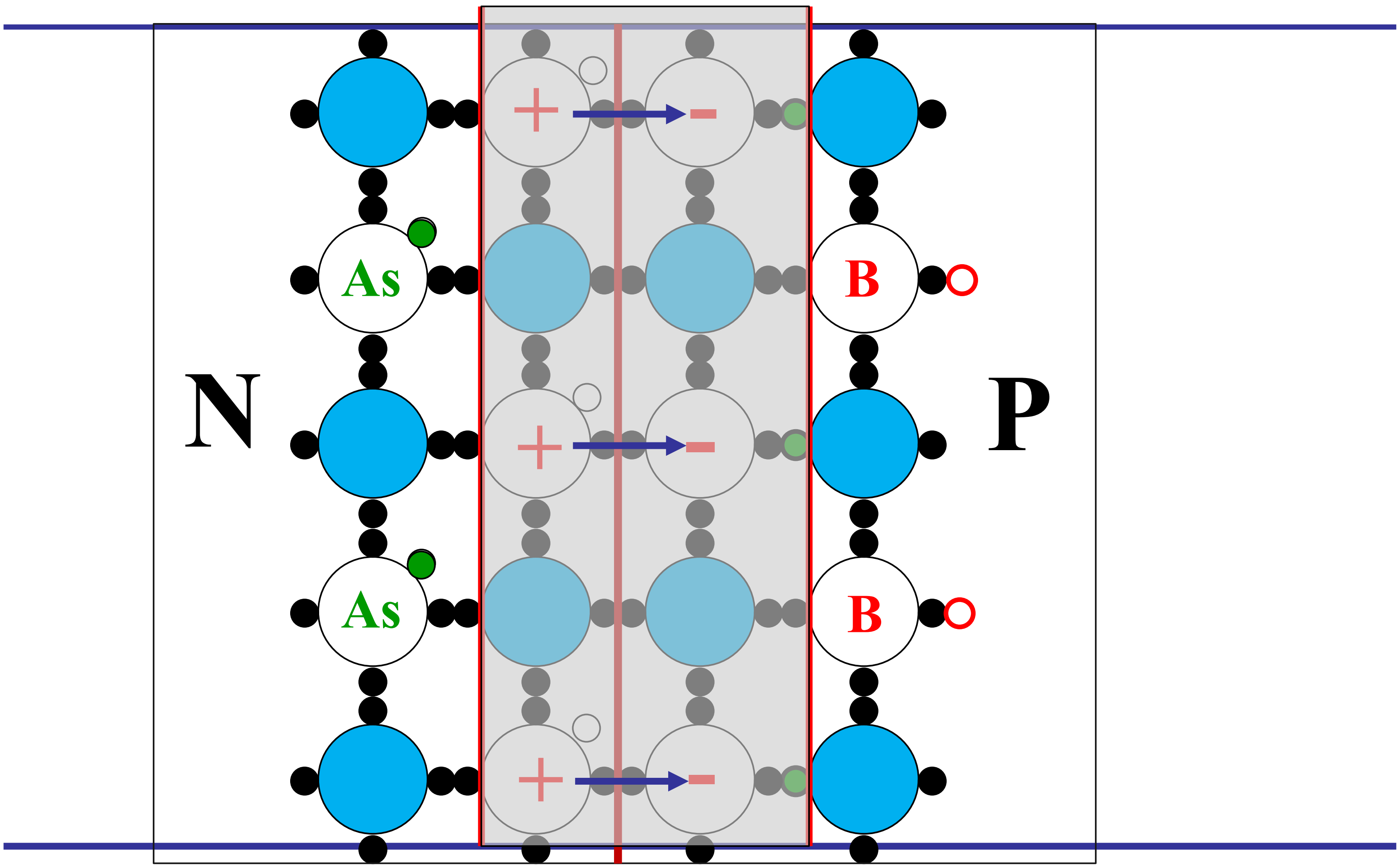


Depletion Region/Space Charged Region

The combining of electrons and holes depletes the holes in the p-region and electrons in the n-region near the junction



As a result of the barrier pd, an electric field is set up in the depletion region, and it prevent further diffusion of charge carriers across the junction.



Summary of Procedure for Forming *pn* Junction

The procedure of forming *pn* the dynamic equilibrium of drift and diffusion movements for carriers in the silicon. In detail, there are 4 steps:

a) Diffusion

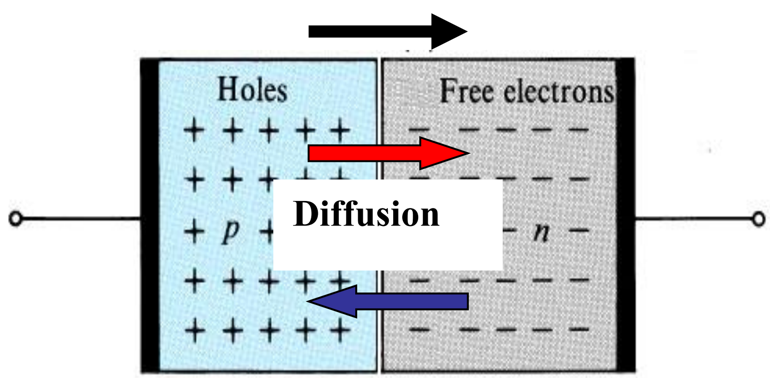
b) Space charge region

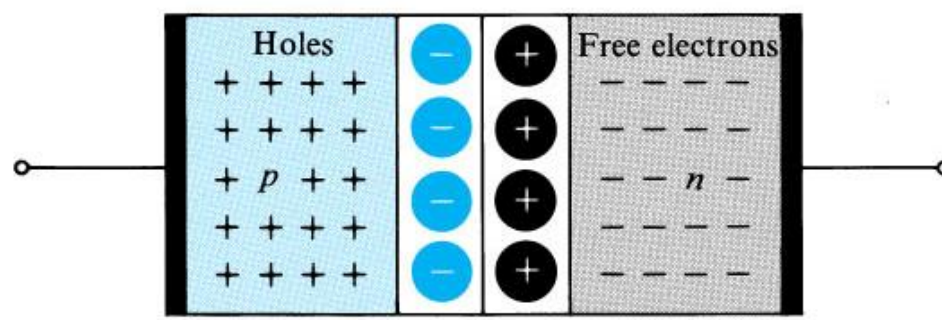
c) Drift

d) Equilibrium

Summary of P-N Junction formation

- As the free electrons move across the junction from n-type to p-type, +ve donor ions are uncovered. Hence a +ve charge is built on the n-side of the junction. At the same time, the free electrons cross the junction and uncover the –ve acceptor ions by filling in the holes. Therefore a net –ve charge is established on p-side of the junction.



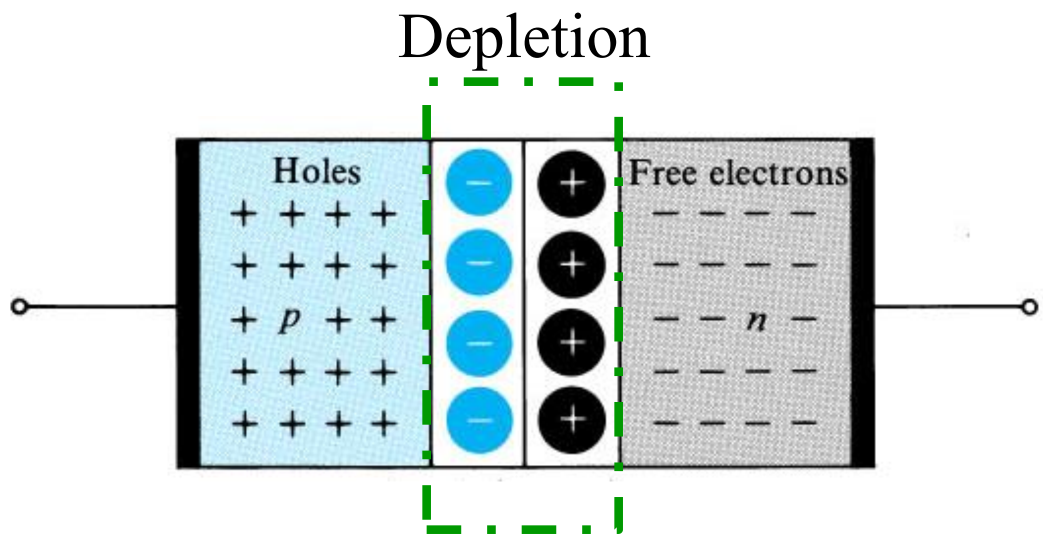


Procedure of Forming *pn* Junction

- diffusion
  - Both the majority carriers diffuse across the boundary between *p*-type and *n*-type semiconductor.
  - The direction of diffusion current is from p side to *n* side.

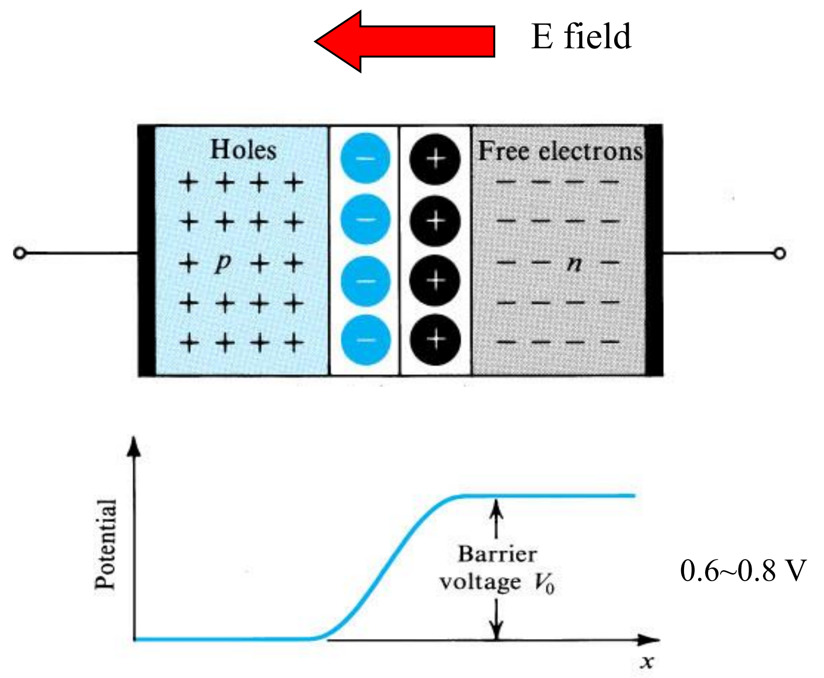
Summary of P-N Junction formation

- **Note:** outside this barrier on each side of the junction, the material is still neutral. Only inside the barrier, there is a +ve charge on n-side and –ve charge on p-side. This region is called depletion region.



Summary of P-N Junction formation

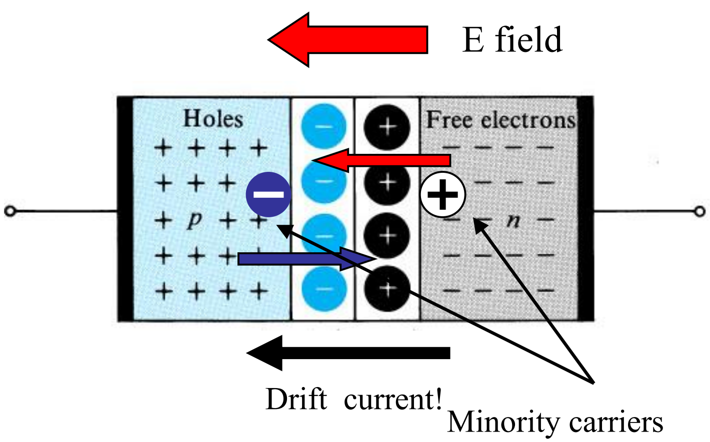
- When a sufficient number of donor and acceptor ions are uncovered further diffusion is prevented.
- Thus a barrier is set up against further movement of charge carriers. This is called potential barrier or junction barrier Vo. The potential barrier is of the order of 0.1 to 0.3V.

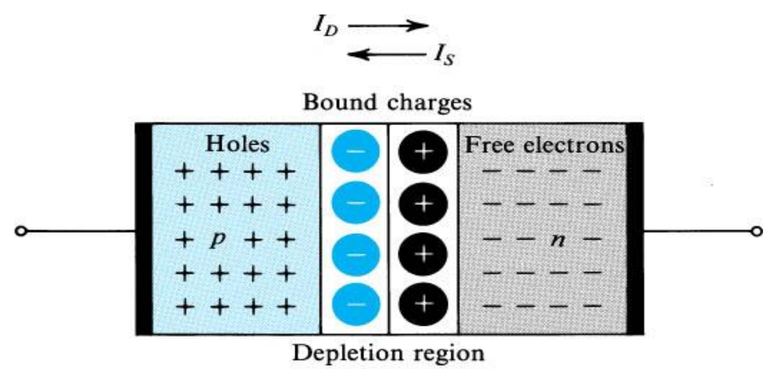


(b)

Equilibrium

- If for some reason, I_D exceeds I_s, then more bound charge will be uncovered on both sides of the junction, the depletion layer will widen and the voltage across it V_o will increase. This in turn causes I_D to decrease until equilibrium is achieved with I_D = Is.



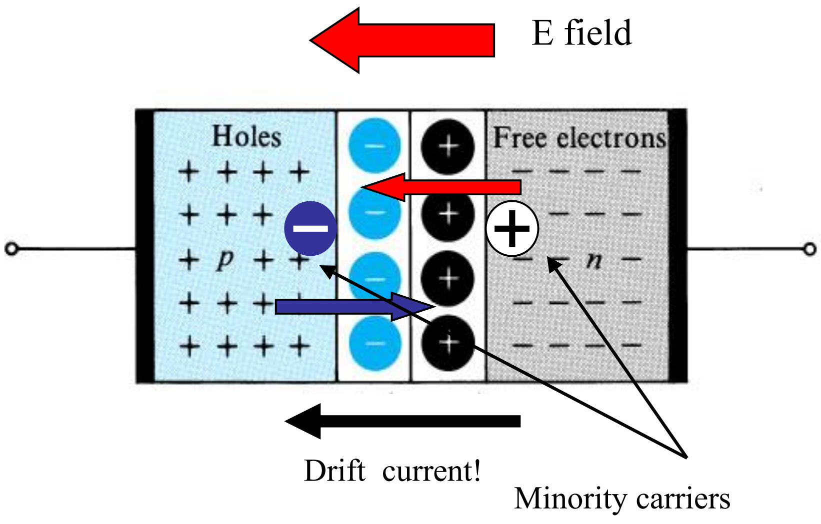


(a)

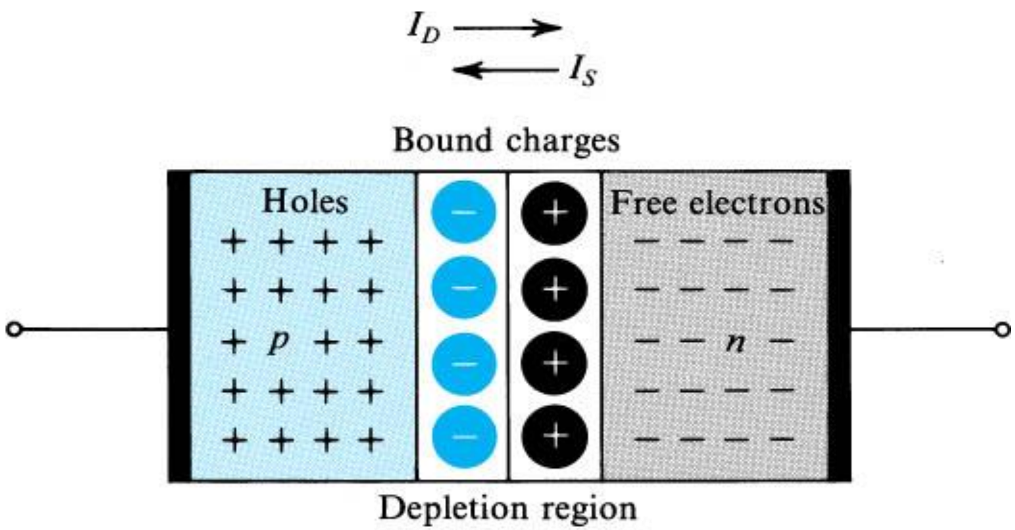
$$W_{dep} = x_n + x_p = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)V_0} \qquad (3.50)$$

Equilibrium

- On the other hand, if I_s exceeds I_D, then the amount of uncovered charge will decrease, the depletion layer will narrow and the voltage across it will decrease. This causes I_D to increase until equilibrium is achieved with $I_D = I_s$



pn Junction Under Open-Circuit Condition

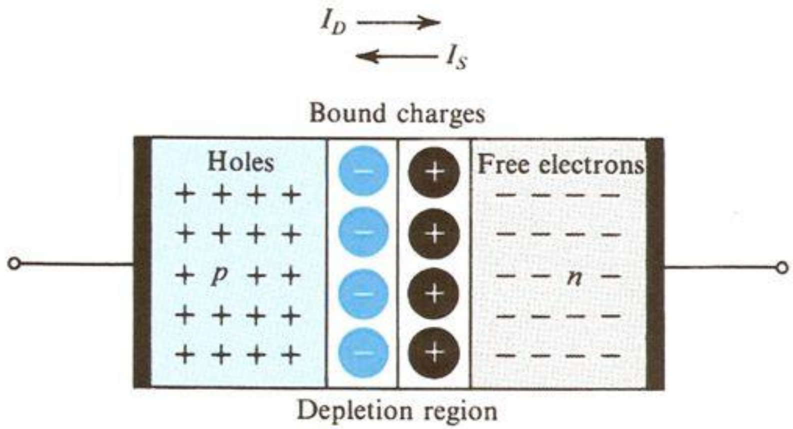


(a)

Fig **(a)** shows the *pn* junction with no applied voltage (open-circuited terminals).

Under open circuit conditions, no external current exists; thus the two opposite currents across the junction should be equal in magnitude i.e., $I_D = I_s$..

3.7.2 The *pn Junction Under Open-Circuit Conditions*



(a)

Barrier Voltage:

$$V_0 = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

$V_T = \dfrac{kT}{q}$ (thermal voltage)

N_A : doping concentration of the p side

N_D : doping concentration of the n side

n_i : concentration of free electron or hole in intrinsic silicon

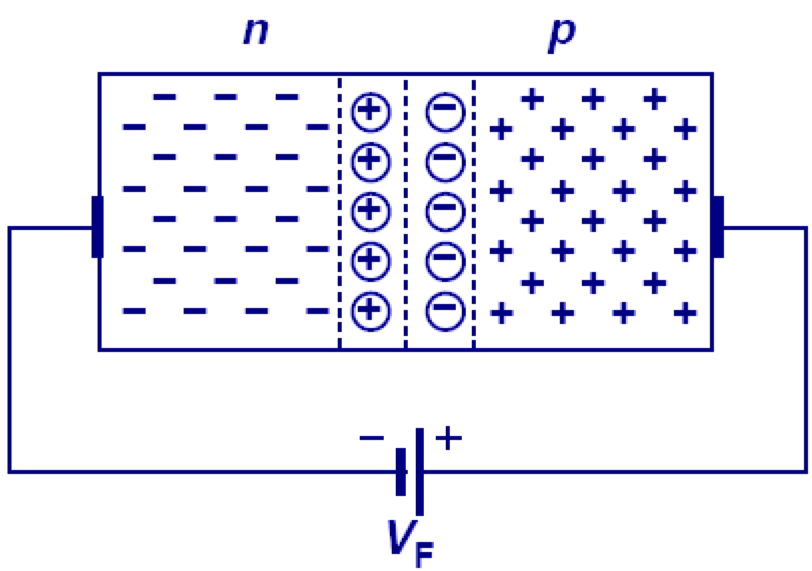
49

P-N Junction

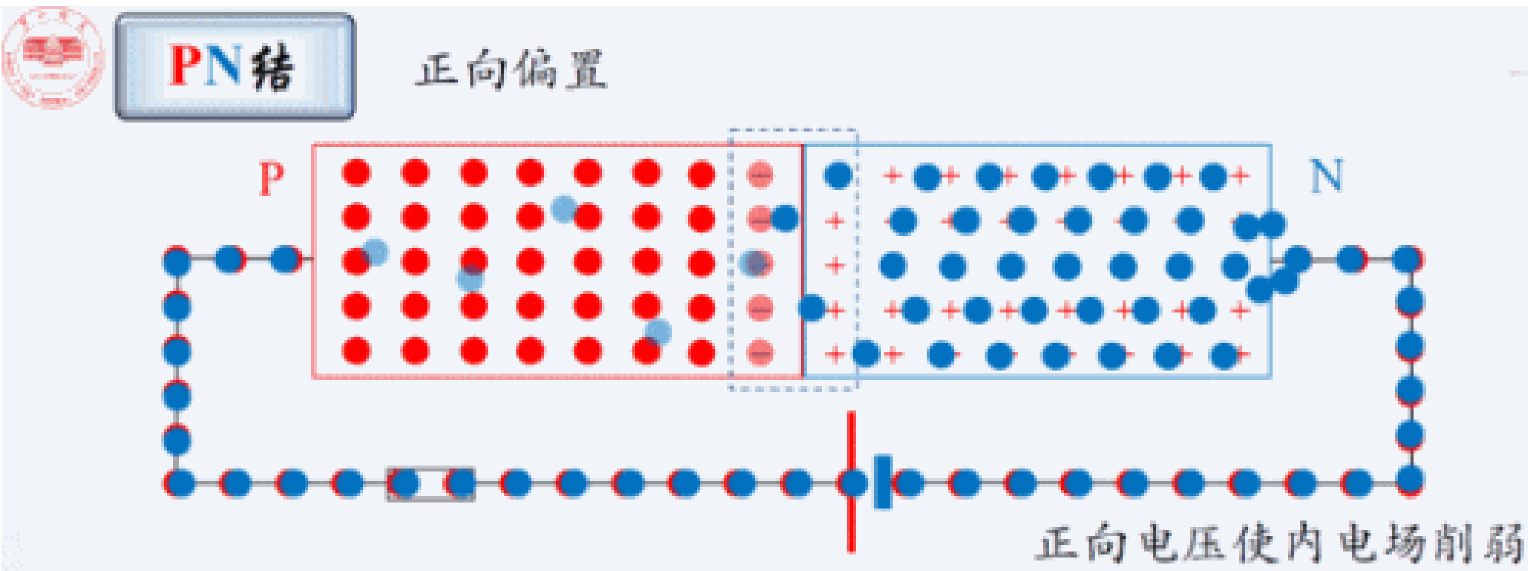
- **Closed circuit conditions**

Forward Biased Junction

- An external source can either oppose or aid the barrier potential.
- If the positive side of the voltage is connected to the p-type material, and the negative side to the n-type material, then the junction is said to be *forward biased*.
- Or When the N-type region of a pn junction is at a lower potential than the P-type region, the pn junction is in forward bias.
- The depletion width is shortened and the built-in electric field decreased.

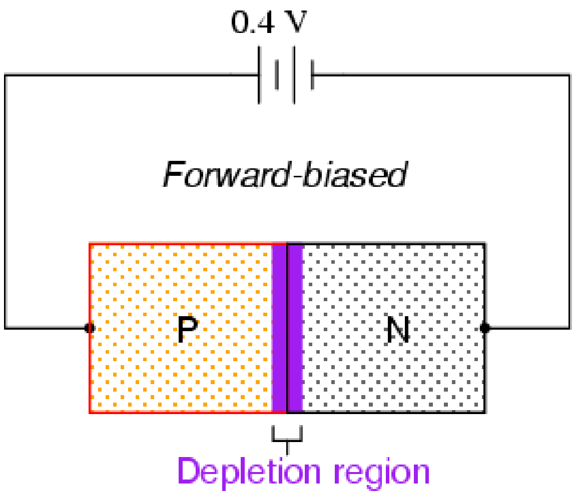


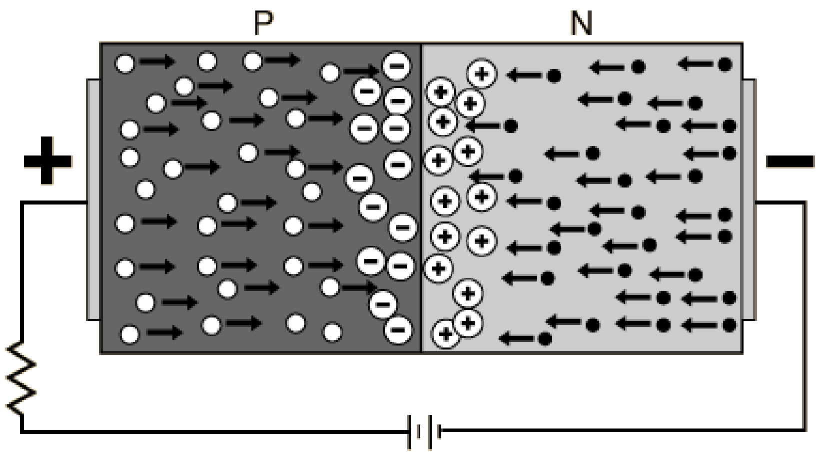
Biasing the Junction (forward)

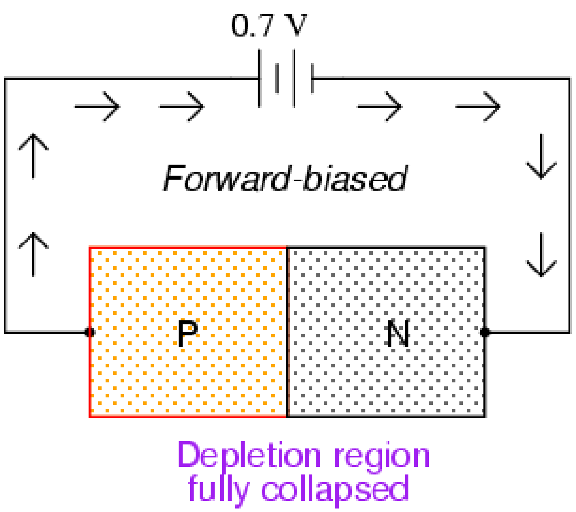


Now the negative charges are driven toward the junction in the N material and the positive charges also are driven toward the junction in the P material. The depletion zone shrinks and will disappear if the voltage exceeds a threshold. This is called **forward bias**.

P-N junction (closed circuit) forward bias



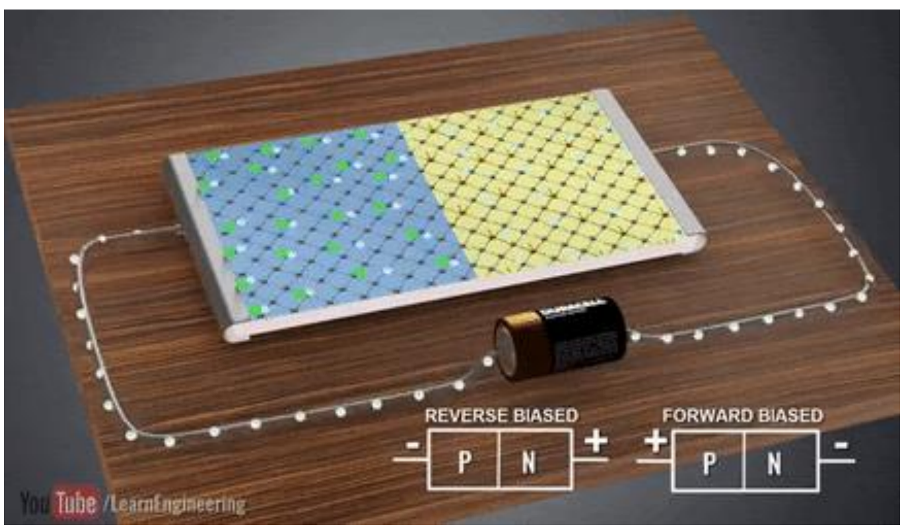


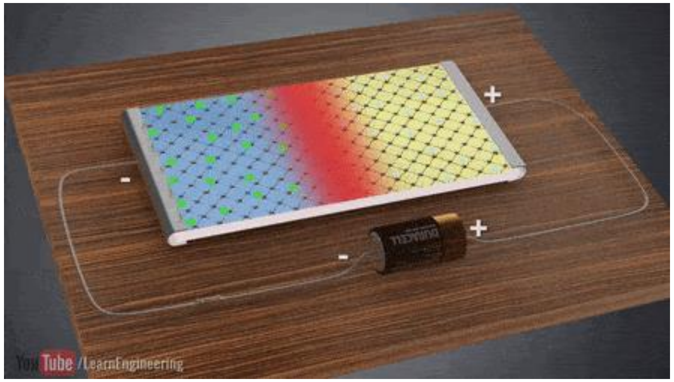


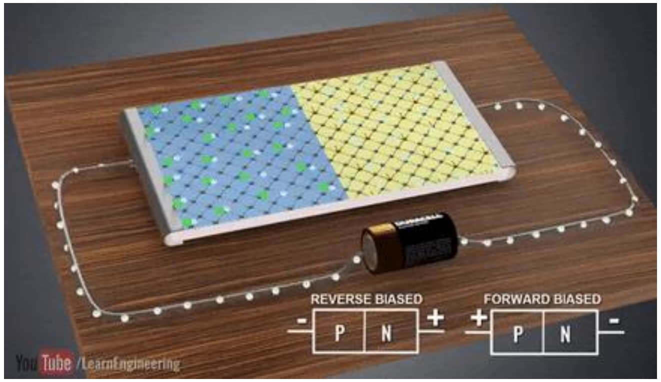
Note that for a forward biased pn junction there is a threshold voltage, below which no current flows across the junction

Forward Biased Junction

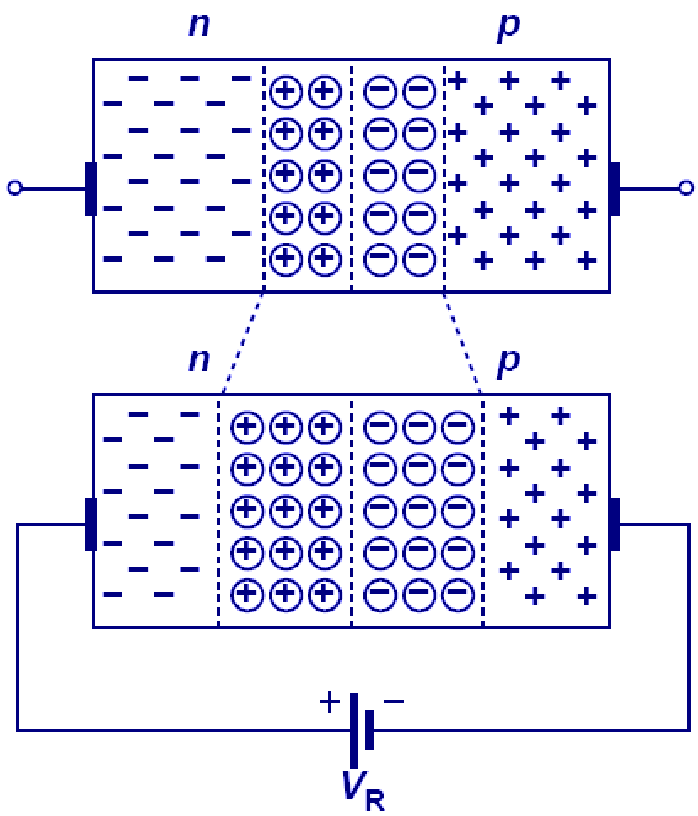
- In a forward biased junction, the following conditions exist:
  - Forward bias overcomes barrier potential.
  - Forward bias narrows the depletion region.
  - There is maximum current flow with forward bias.




+
-
+
-
YouTube /LearnEngineering


REVERSE BIASED
- P N +
FORWARD BIASED
+ P N -
YouTube /LearnEngineering

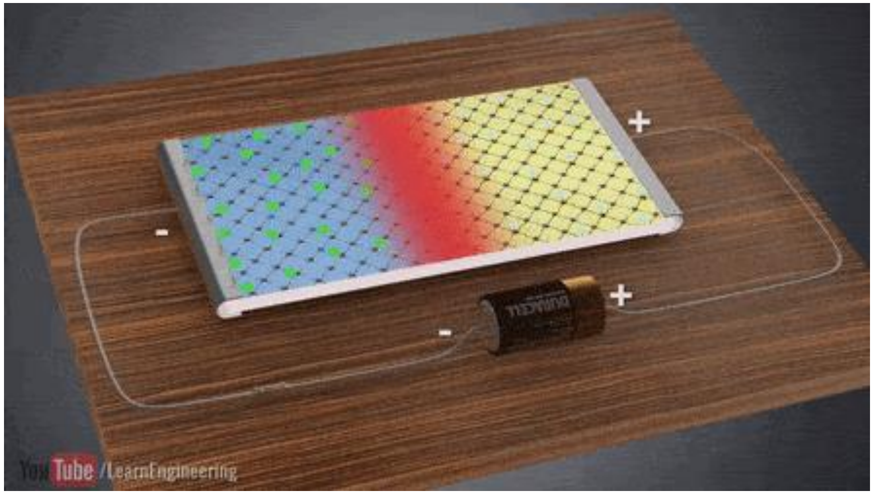
P-N Junction in Reverse Bias



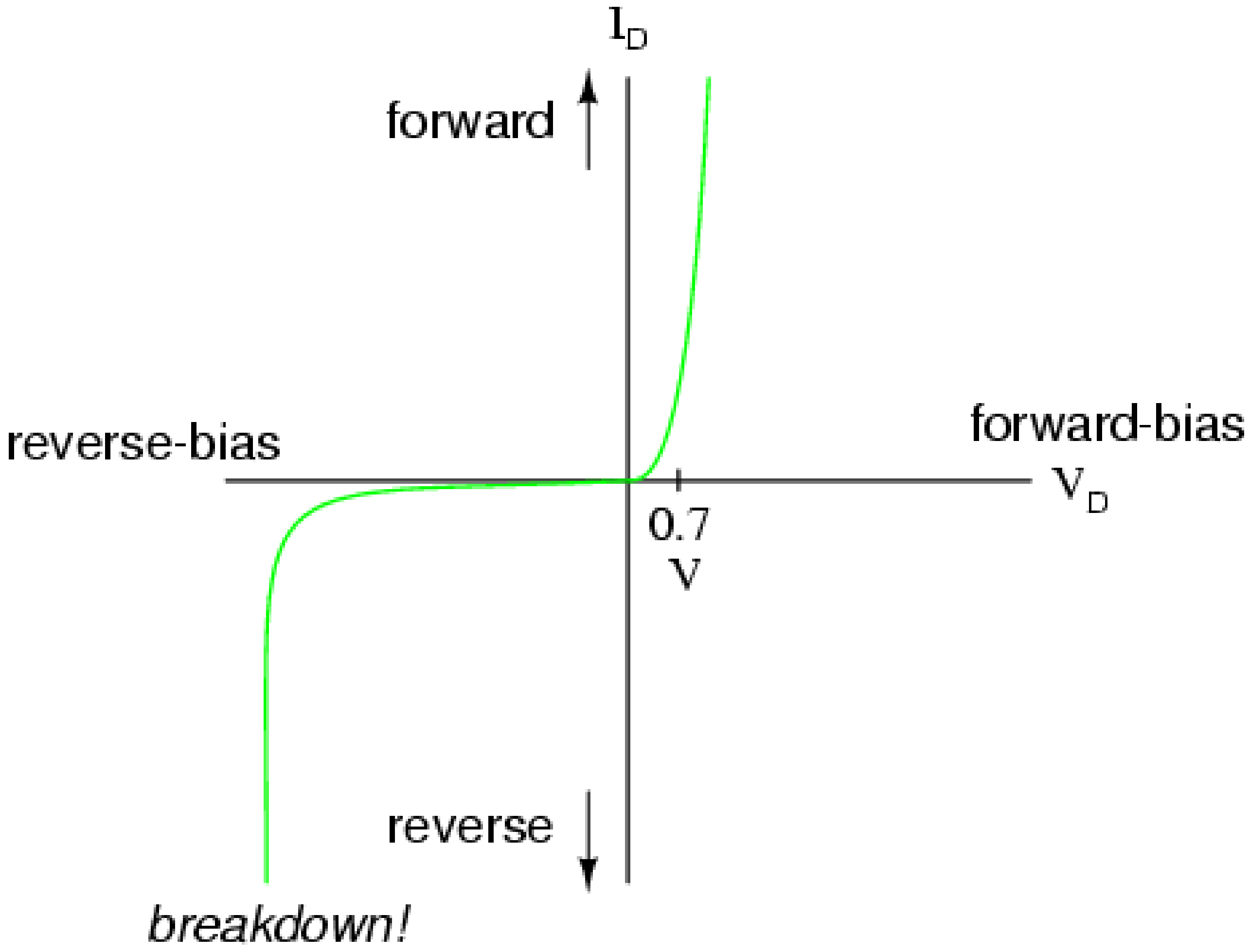
- When the N-type region of a pn junction is connected to a higher potential than the P-type region, the pn junction is under reverse bias, which results in wider depletion region and larger built-in electric field across the junction.

Reverse Biased Junction

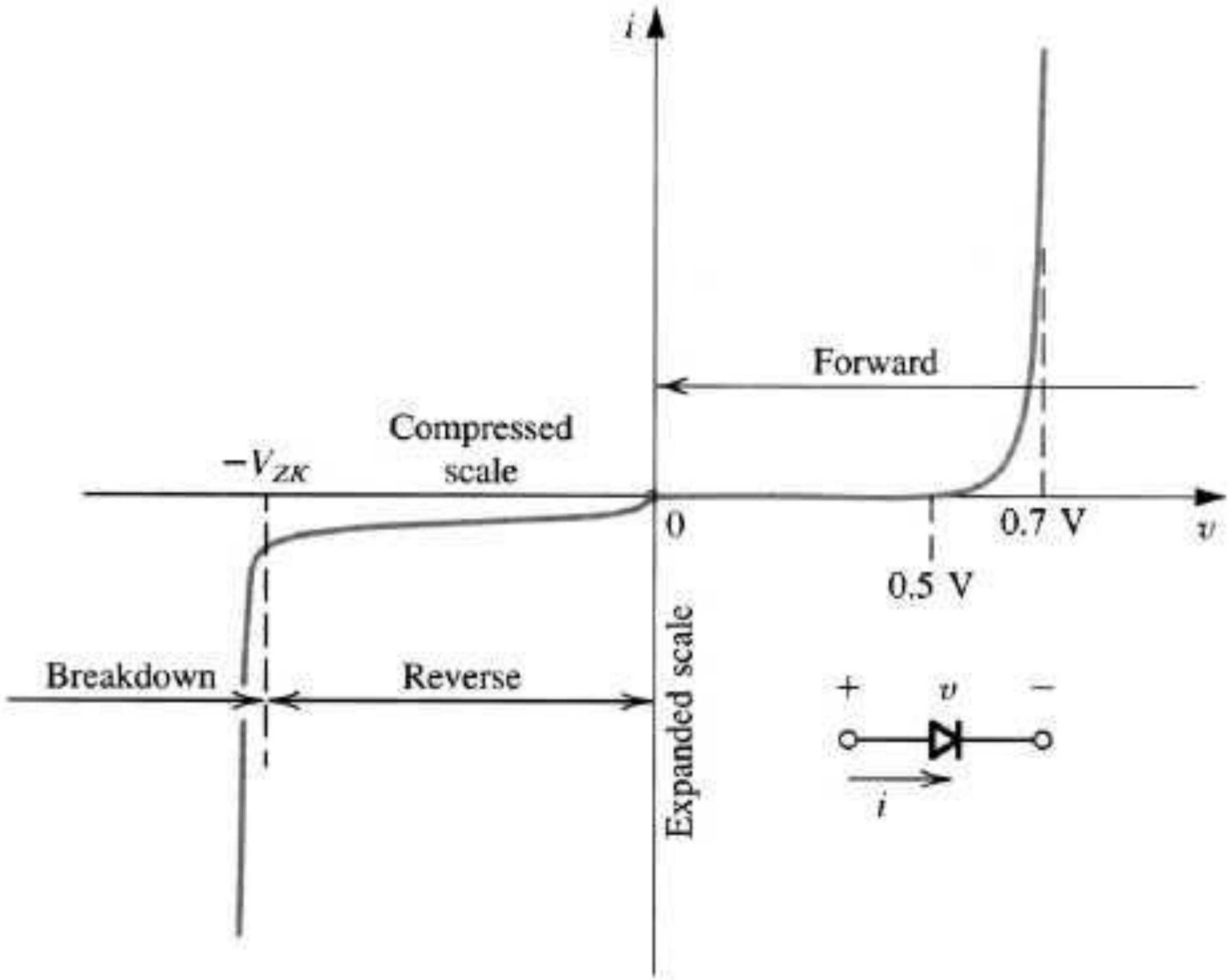
- Reverse bias strengthens the barrier potential.
- Reverse bias widens the depletion region.
- Current flow is minimum.



I-V characteristics of the P-N Junction

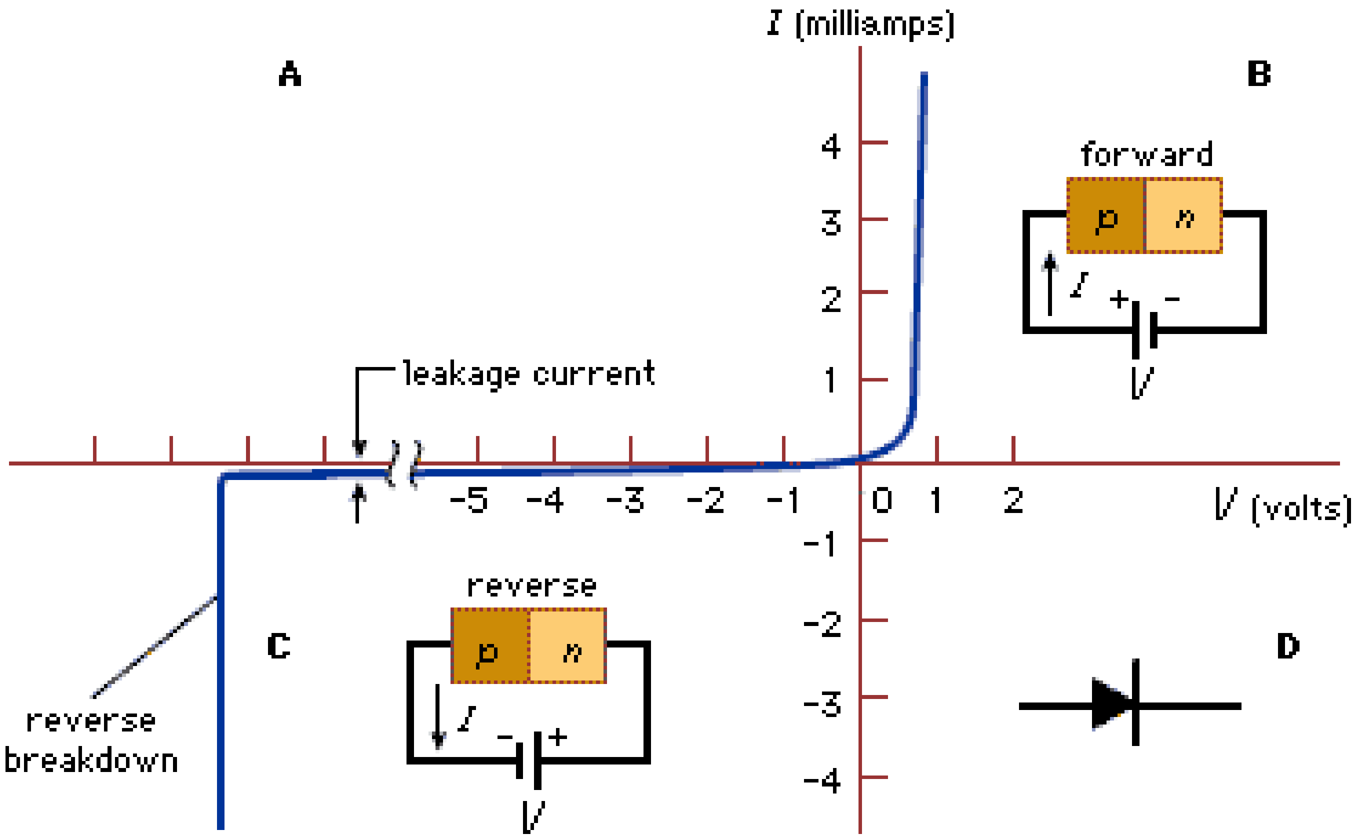


The experimental I-V characteristic of a Si diode



The diode i–v relationship with some scales expanded and others compressed in order to reveal details.

I-V characteristics of the P-N Junction



Reverse Biased Junction

- A reversed biased junction has zero current flow (ideally).
- Reverse current is temperature dependent.
- If reverse biased is increased enough, the reverse current increases dramatically.
- This breakdown is called *junction breakdown*. The voltage required to reach this point is the *reverse breakdown voltage*.
- As the breakdown occurs, *avalanche* may occur and destroy the device if uncontrolled.

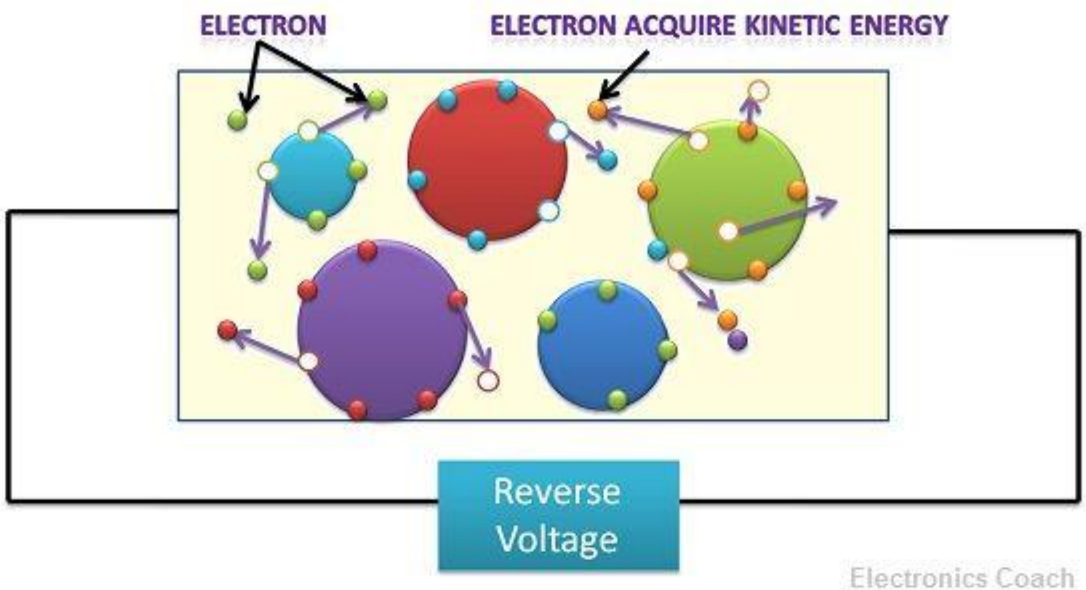
BREAKDOWN REGION

- Breakdown occurs when p–n junctions are operated in the reverse-bias mode.
- This breakdown occurs at a critical reverse-bias voltage (V_z). At this critical voltage the reverse current through the diode increases sharply, and relatively large currents flow with little increase in voltage.
- The following two mechanisms can cause reverse breakdown in a junction diode.

BREAKDOWN REGION

Zener Breakdown

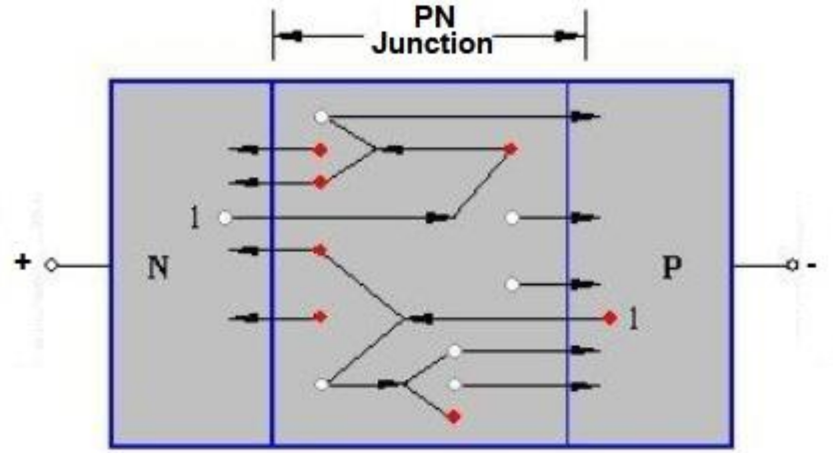
- Zener breakdown occurs when a sufficiently large reverse-bias is applied across a *p–n junction (diode)*. *The resulting* electric field at the junction imparts a very large force on a bound electron, enough to dislodge it from its covalent bond.
-



BREAKDOWN REGION

Zener Breakdown

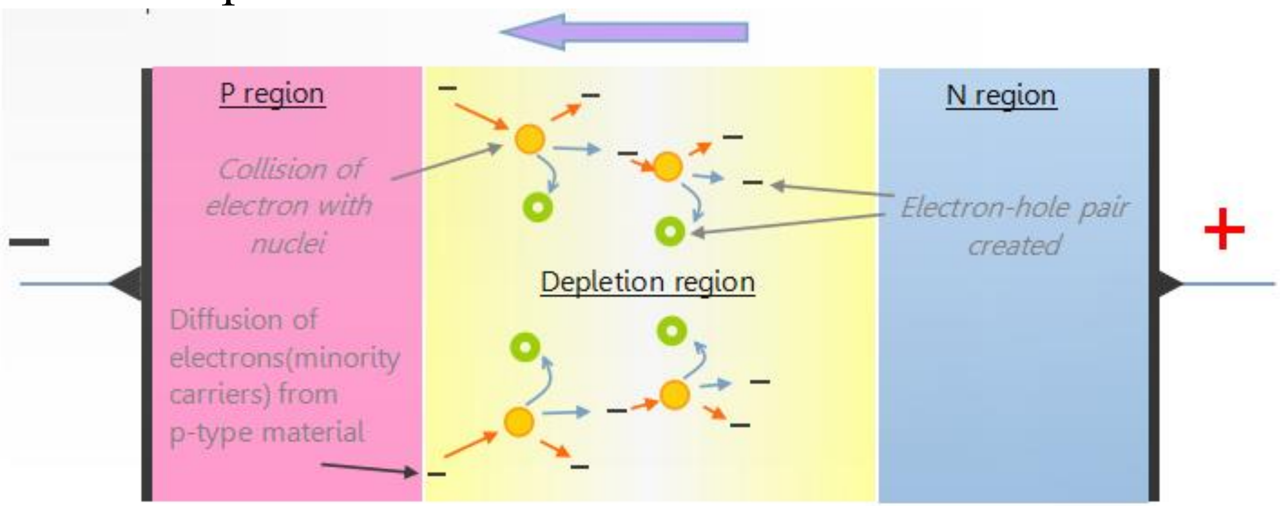
- The breaking of the covalent bonds produces a large number of EHP (electron–hole pairs). Consequently the reverse current becomes very large. This type of breakdown phenomena is known as ***Zener breakdown***.



BREAKDOWN REGION

❖ Avalanche Breakdown

- In a reverse-biased junction, the minority-carriers drift across the depletion region. On their way across this region, they occasionally have collisions with atoms in the lattice.
- With a large enough field, a carrier drifting across the depletion region is accelerated to the point where it has enough energy to knock a valance electron free from its host atom during a collision.
- The field then separates the electron and hole of this newly created EHP and we now have three mobile carriers instead of one. This process is called avalanche multiplication.
-

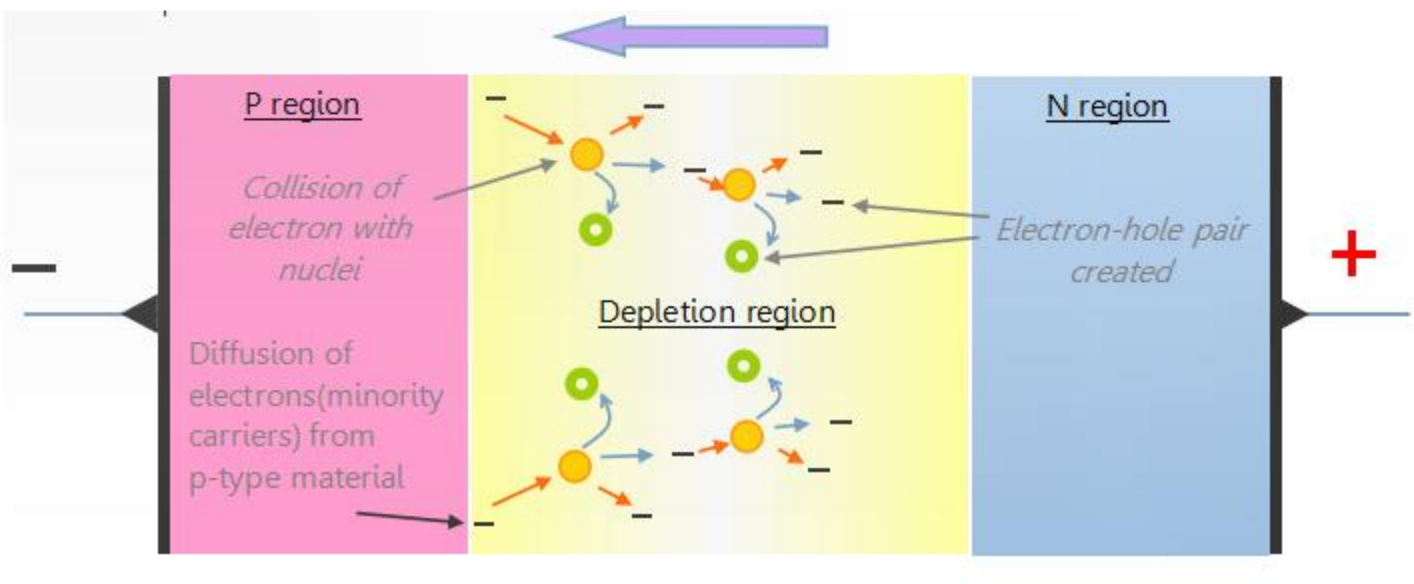


Avalanche breakdown

BREAKDOWN REGION

Avalanche Breakdown

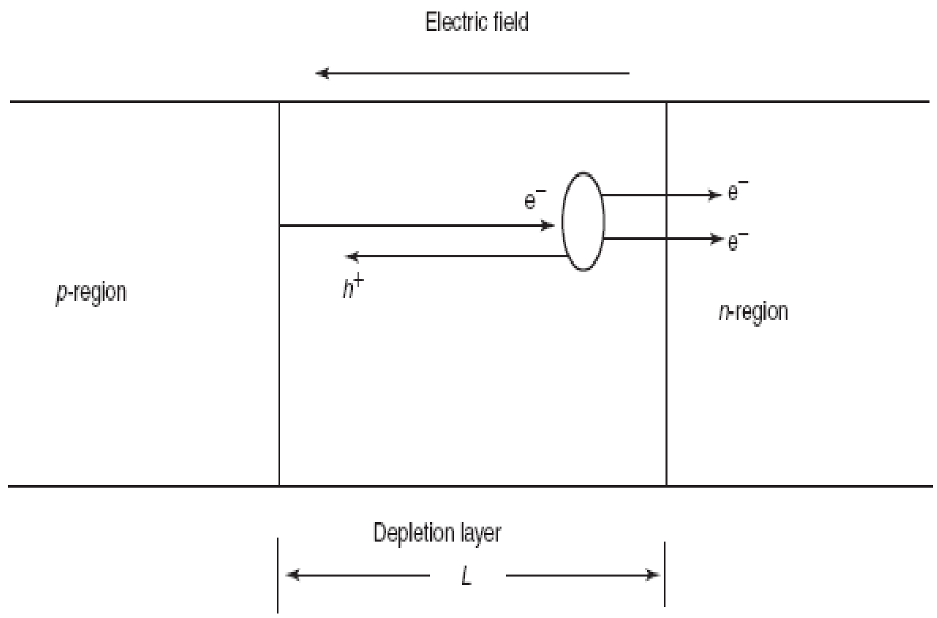
- The multiplication can become quite large if the carriers generated by this collision also acquire to create more carriers, thereby initiating a chain reaction.
- Once the process starts, the number of multiplication that can occur from a single collision increases rapidly with further increase in the reverse-bias, so the terminal current grows rapidly, and we say that the junction breaks down. This is called *avalanche breakdown.*



Avalanche breakdown

BREAKDOWN REGION

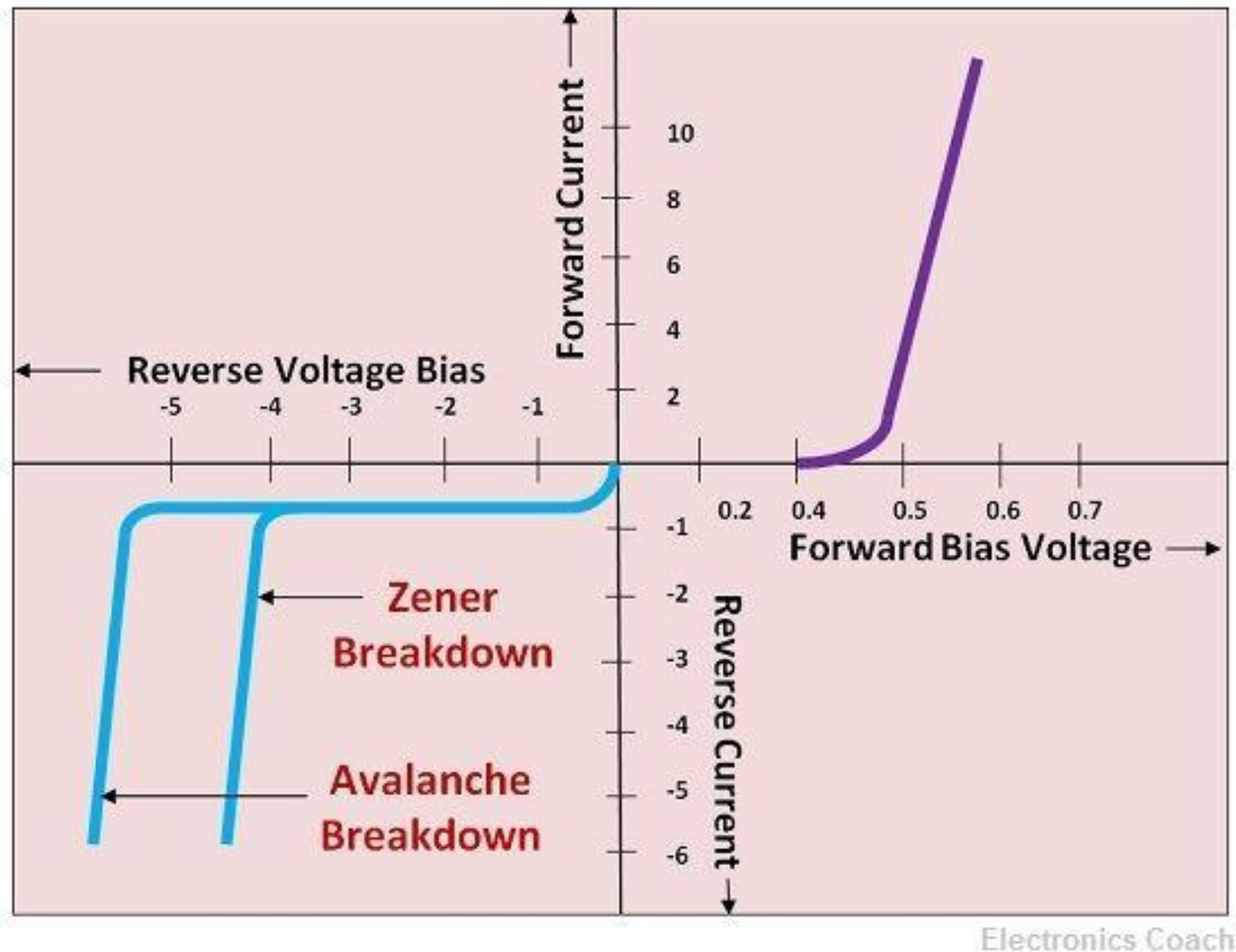
- A single such event results in multiplication of carriers; the original electron as well as the secondary electron are swept to the *n-type semiconductor, while,* the generated hole is swept to the *p-type semiconductors.*



Carrier multiplications in the depletion region due to impact ionization

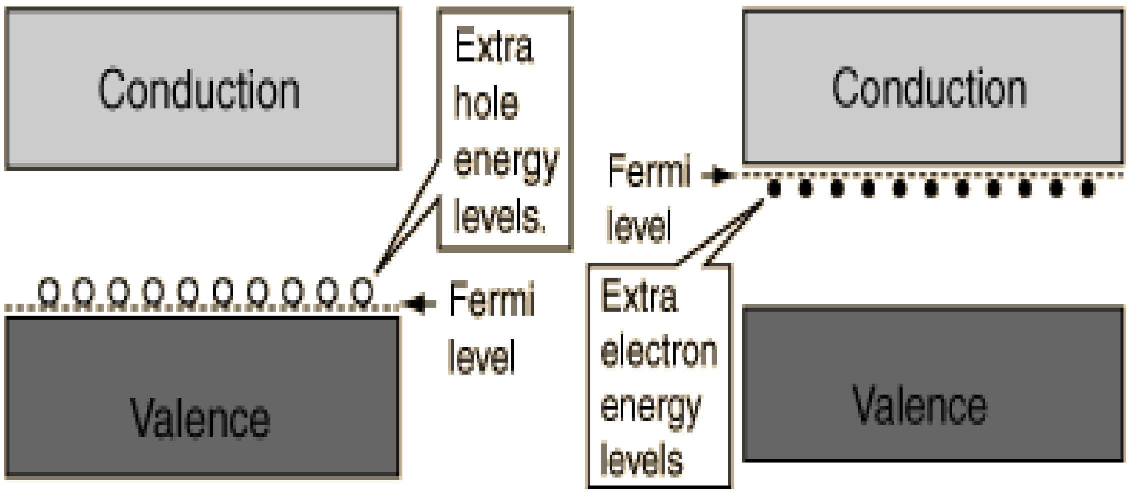
Breakdown region

- *If a pn junction breaks down with Vz < 5 V, the breakdown mechanism is usually the zener effect. Avalanche breakdown occurs when Vz > 7 V.*


Forward Current
10
8
6
4
2
Reverse Voltage Bias
-5
-4
-3
-2
-1
0.2
0.4
0.5
0.6
0.7
-1
Forward Bias Voltage
-2
-3
-4
-5
-6
Zener
Breakdown
Avalanche
Breakdown
Reverse Current
Electronics Coach

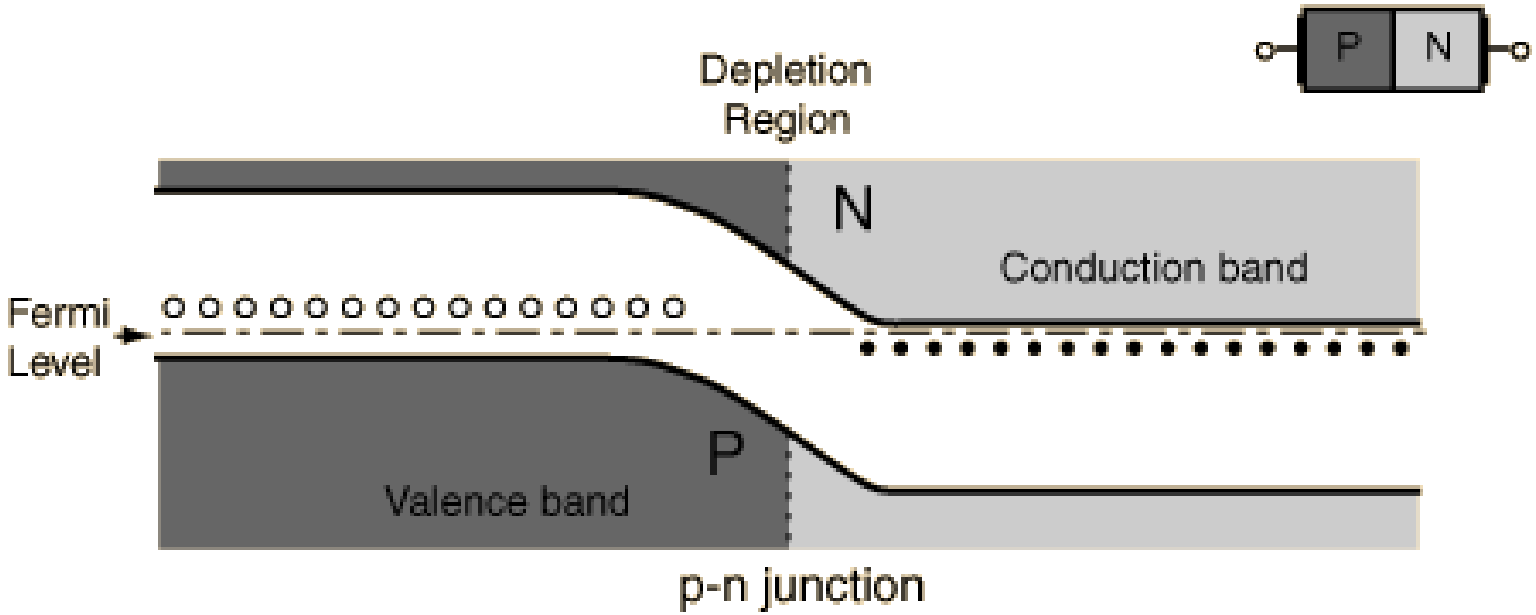
EXPLAINING PN JUNCTION FORMATION WITH THE ENERGY BAND DIAGRAM

PN junction formation



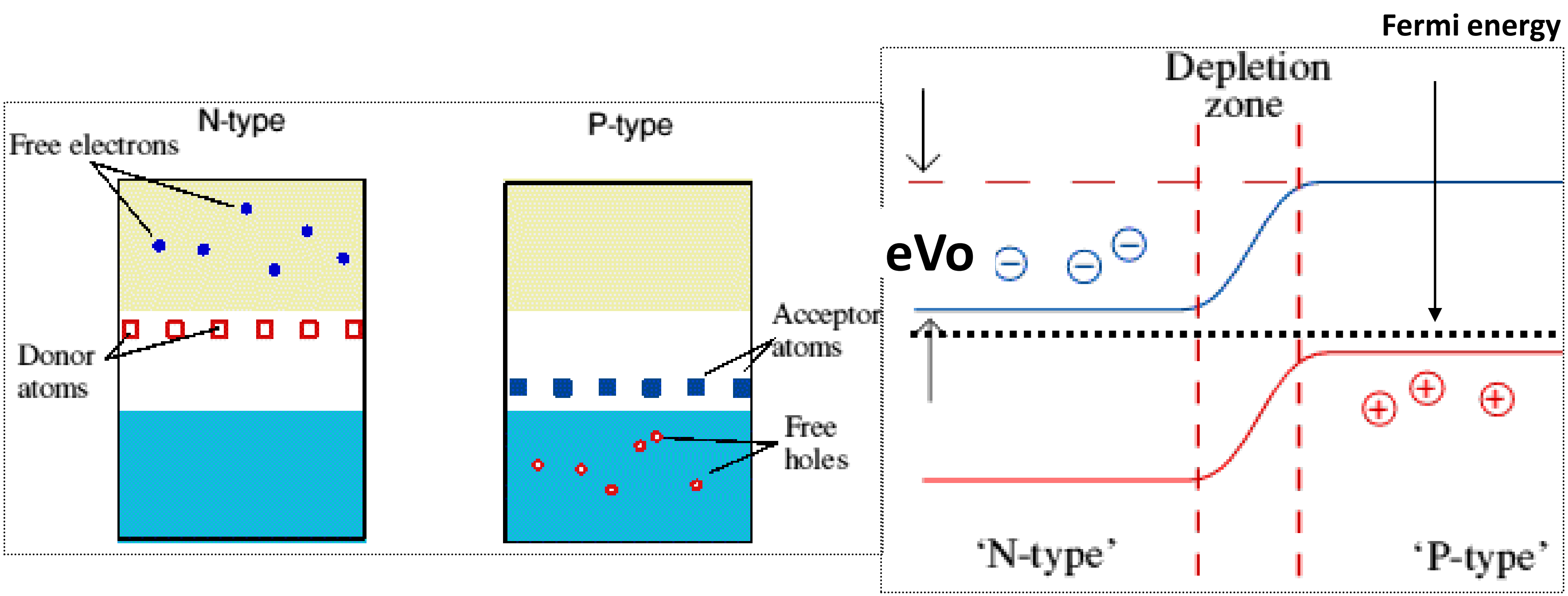
The Fermi energy in a p-type and n-type semiconductor before they are brought together to form a p-n junction

PN junction formation



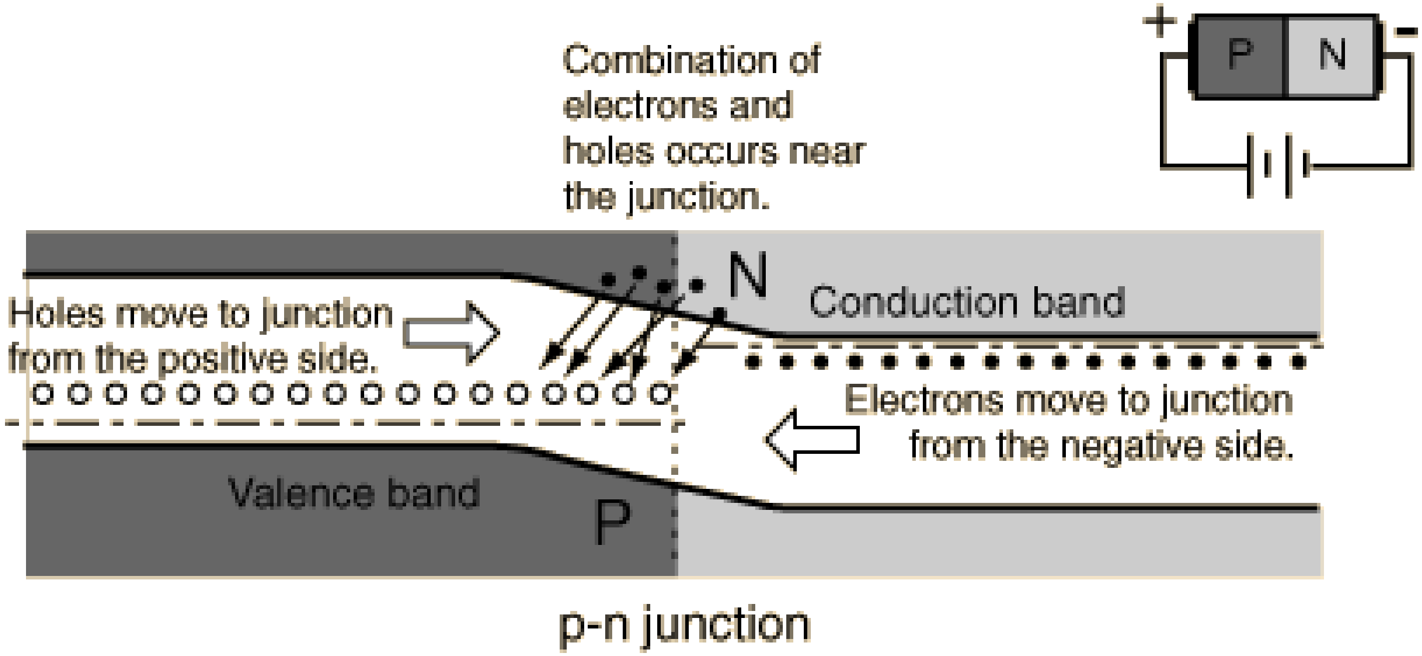
The Fermi energy has the same value throughout a system in equilibrium – in the absence of external potentials and in thermodynamic equilibrium, there is no net flow of charge or energy across the

PN junction formation



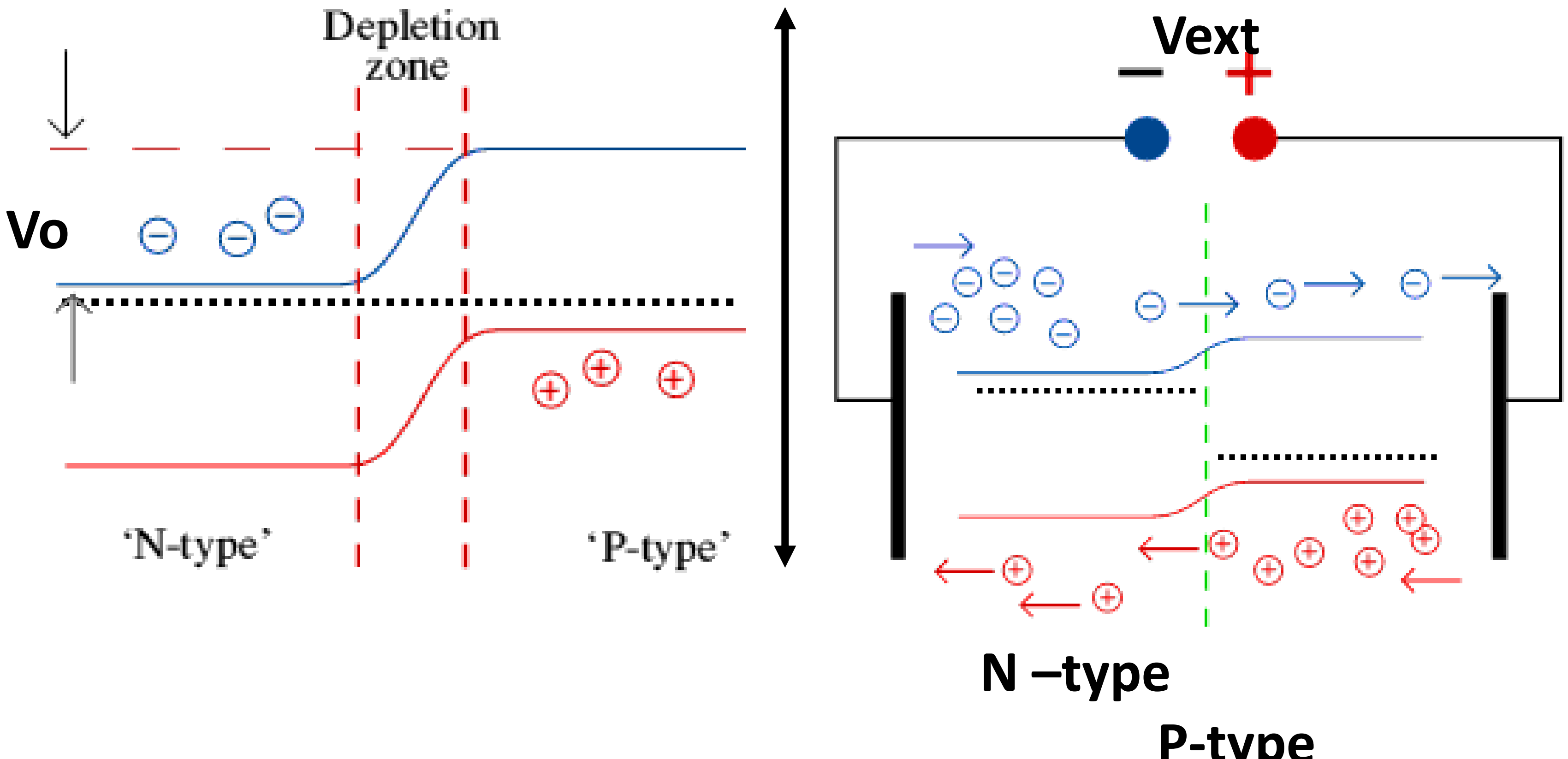
The junction potential Vo is what brings the Fermi energies to the same level.

Forward bias



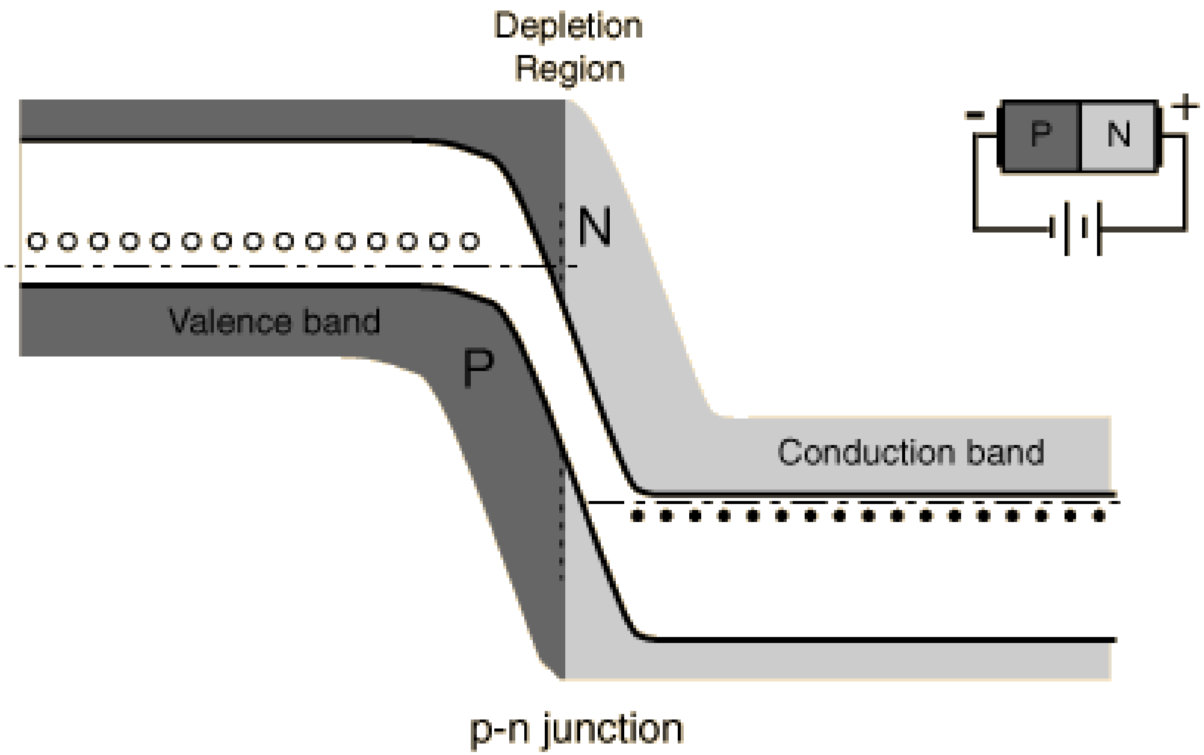
When an external potential, V_{ext}, is applied across a pn junction, the junction is said to be biased. In that case there can be a net flow of charge and energy and the Fermi energies no longer need be the same,

Forward bias



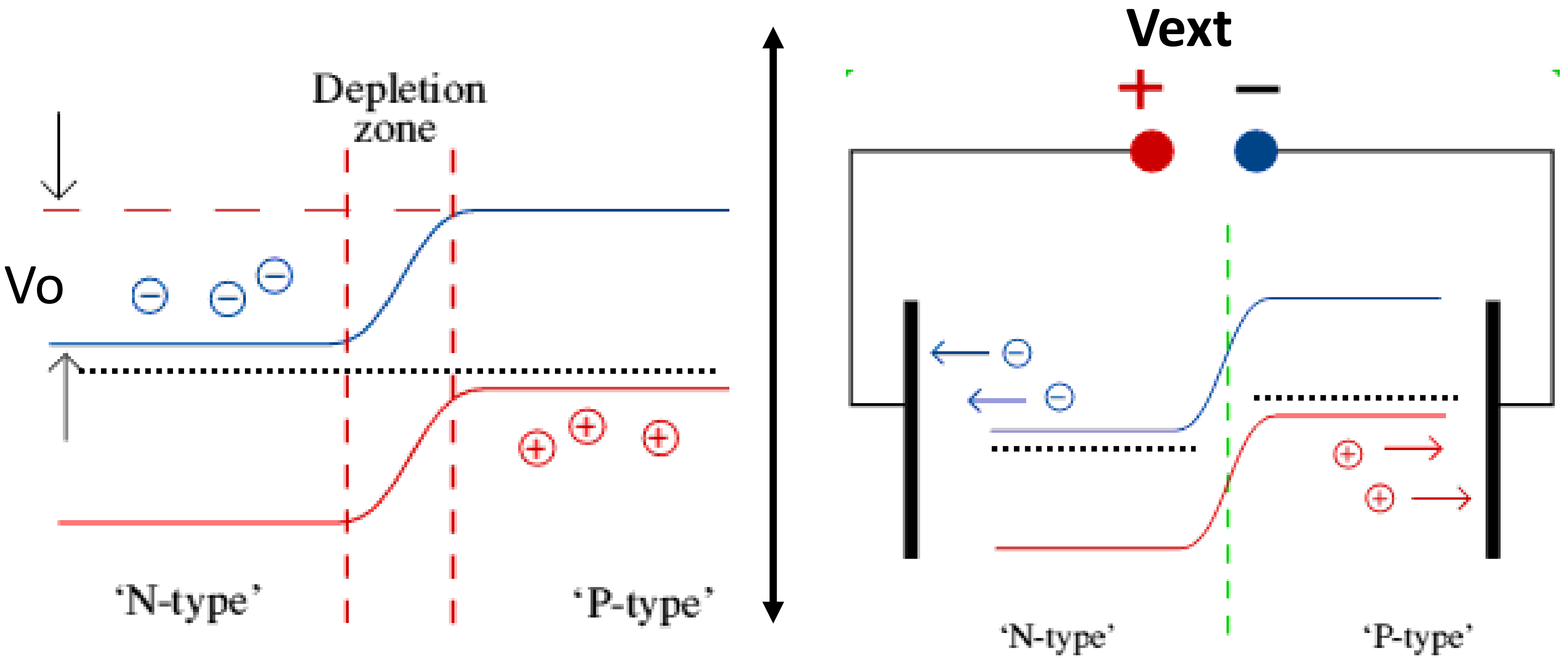
Contact potential is reduced from |Vo| to |Vo| - |Vext|. In that case there can be a net flow of charge and energy and the Fermi energies no longer need be the same,

Reverse bias



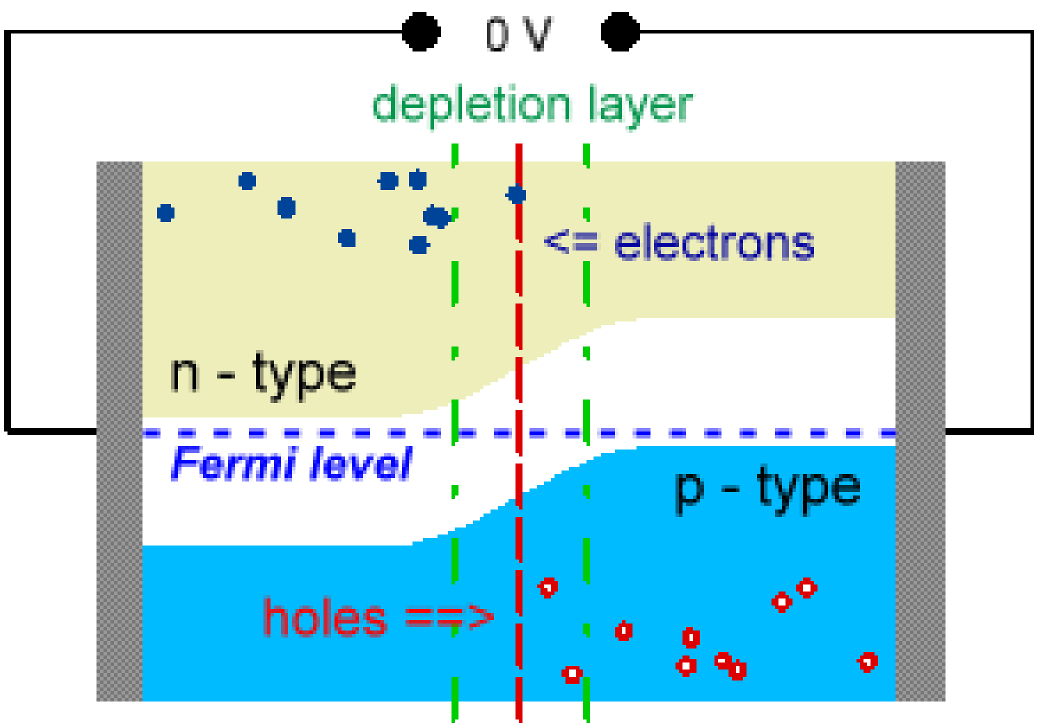
The magnitude of the junction potential is increased from |Vo| to |Vo| + |Vext|. Thus, both electrons from the n-side and holes from the p-side have an even harder time

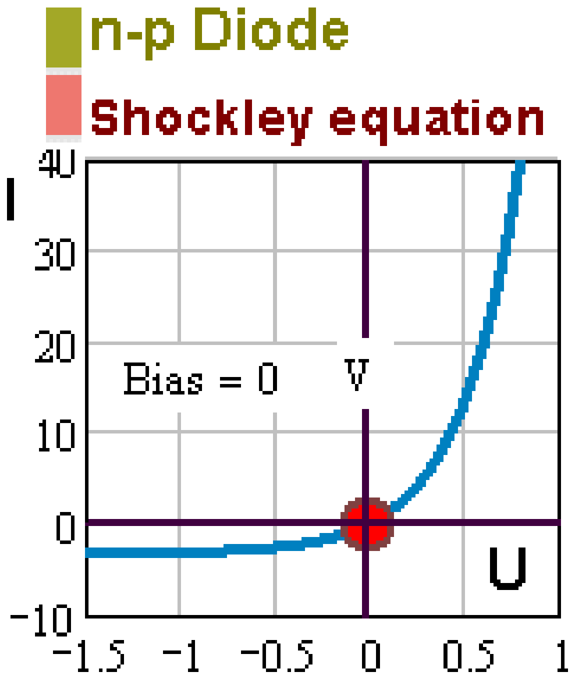
Reverse bias

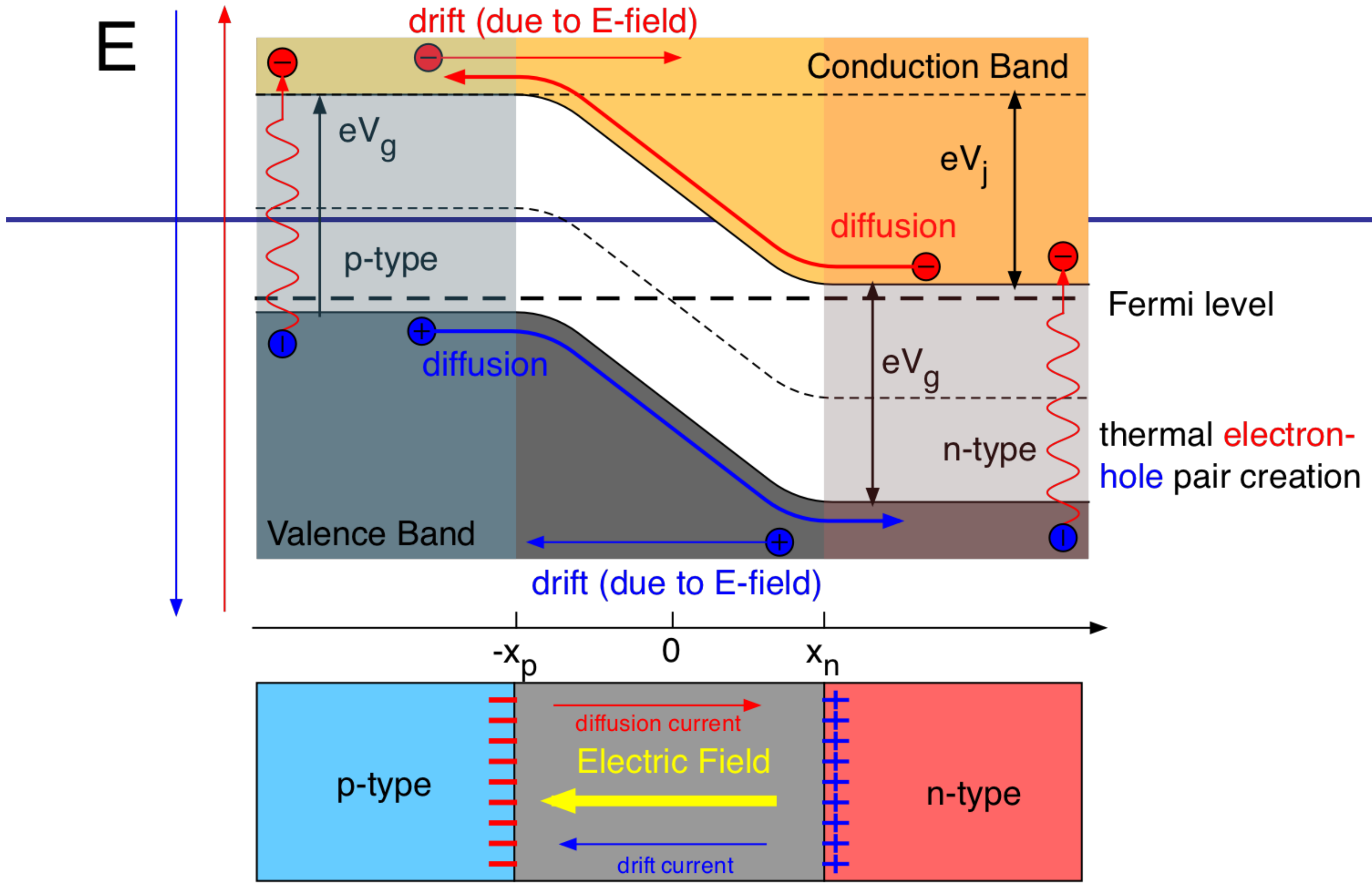


the magnitude of the junction potential is increased from |Vo| to |Vo| + |Vext|. Thus, both electrons from the n-side and holes from the p-side have an even harder time overcoming the additional

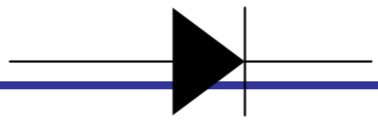
I-V characteristics



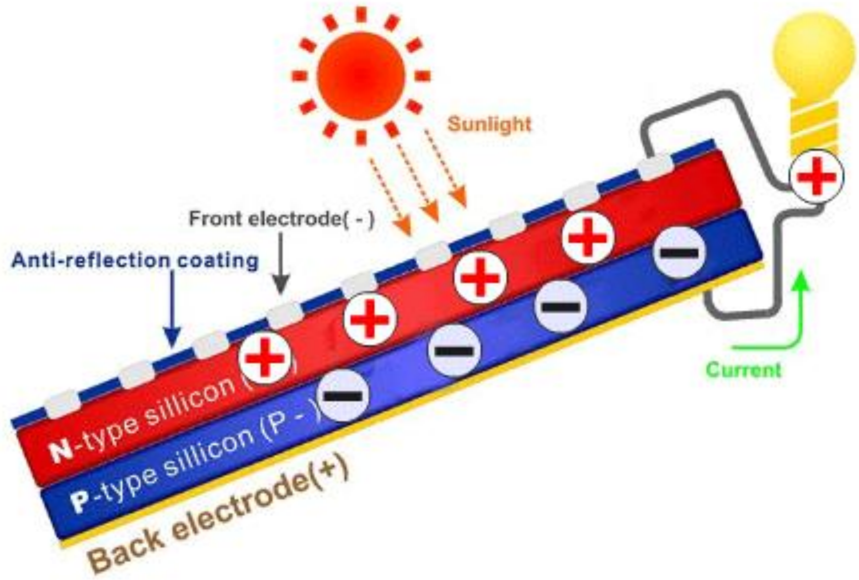




Schematic of pn-junction



Questions ?


Sunlight
Front electrode(-)
Anti-reflection coating
N-type sillicon
P-type sillicon (P -)
Back electrode(+)
Current