Welcome to

ENEE236
Analog Electronics

Instructor

Mr. Nasser Ismail (Office ENG308)

nismail@birzeit.edu

Main Reference1 (~ text book) : **Electronic Devices and Circuit Theory , 10th Edition by R. Boylestad & L. Nashelsky**

Main Reference 2: **Electronic Devices, 8th edition, by Floyd**

Course Objectives

- Study diode construction, basic operating principles and modeling.
- To analyze and design diode based circuits for different applications such as ac-dc rectifiers, limiting and clamping, voltage multiplication.
- To Study zener diode operation and usage as voltage regulator.
- To Study construction, operation, biasing of Bipolar Junction Transistors and Field Effect Transistors.
- To design and analyze BJT and FET based amplifier circuits using small signal analysis techniques including their high and low frequency response
- To study operational amplifiers and how to use them in various applications such as amplification, summation, comparison, integration, differentiation
- To study different discrete and integrated circuit Voltage Regulators and be able to design them for different applications

Course Contents

1. **Introduction to Semiconductors and Semiconductor diodes**
   - **Atomic Structure; Semiconductors , Conductors And Insulators; Covalent Bonds;**
   - **Conduction in Semiconductors; N-Type and P-Type Semiconductors**
   - **The diode; biasing a Diode; V-I Characteristics of a Diode; Diode Models**

2. **Diode Applications**
   - **Load Line Analysis, Half-Wave and Full-Wave Rectifiers; Power supply Filters and Regulators; Diode Limiting and Clamping Circuits; Voltage Multipliers; The diode Data Sheet, Zener Diodes and their Applications**

3. **Bipolar Junction Transistors (BJT)**
   - **Transistor construction and operation, Transistor Characteristics and Parameters; The Transistor as an Amplifier; The Transistor as a Switch.**

4. **DC Biasing of BJTs**

   The DC Operating Point (Quiescent Operating Point); Voltage-Divider Bias; Other Bias Methods.

Course Contents

5. BJT AC Analysis

Amplifiers and small signal analysis, Transistor AC Equivalent Circuits- Hybrid Parameters, Common-Emitter Amplifier; Common-Collector Amplifier; Common-Base Amplifier; Multistage Amplifiers.

6. Field-Effect Transistors (FETs)

The JFET; JFET Characteristics and Parameters; JFET Biasing; The MOSFET Characteristics and Parameters; MOSFET Biasing

7. FET Amplifiers.

FET Amplification; Common-Source Amplifiers; Common- Drain Amplifiers and Common-Gate Amplifiers;

8. Operational Amplifiers and Applications

Introduction to Operational Amplifiers; Op-Amp Input Modes and Parameters Negative Feedback; Op-Amps with Negative Feedback ; Comparators; Summing Amplifiers; Integrators and Differentiators.

Instrumentation Amplifier; Converters and Other Op-Amp Circuits.

Course Contents

9. Amplifier Frequency Response
Basic Concepts; The Decibel; Low-Frequency Amplifier Response.
High- Frequency Amplifier Response; Total Amplifier Frequency Response.

10. Voltage Regulators
Voltage Regulation; Basic Series Regulator; Basic shunt Regulator; Integrated Circuit Voltage Regulators.

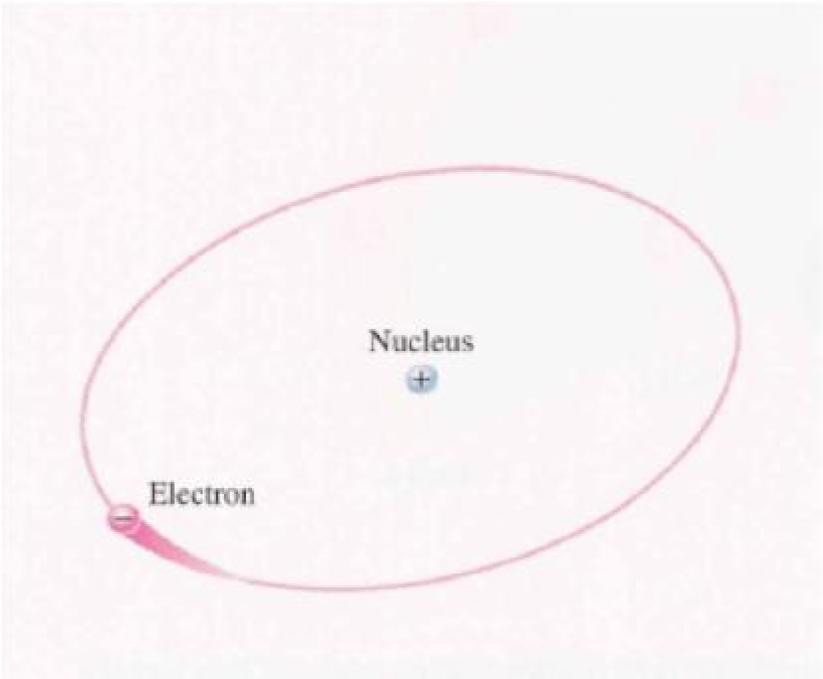
Grading Policy

Quizzes, assignments and participation:	15%
First and Second Exams:	40%
Final Exam:	45%

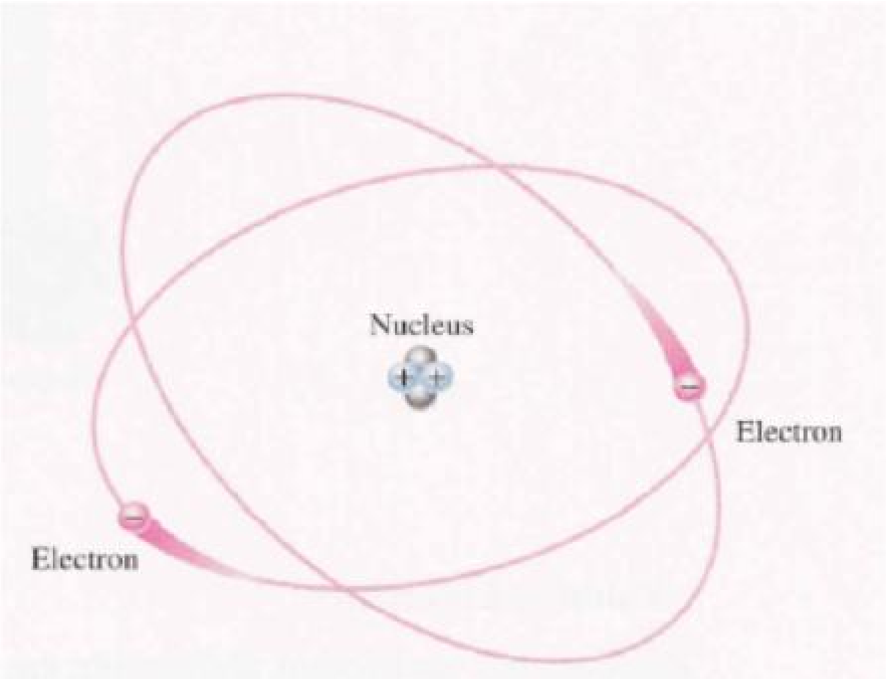
Introduction to Semiconductors and Semiconductor Diodes

Atomic Structure (1)

- An Atom is the smallest particle of an element that retains the characteristics of that element which is unique to each particular element
- Nucleus consists of positively charged protons and uncharged neutrons
- Each type of atom has a certain number of electrons and protons that distinguishes it from the atoms of all other elements
- For example, the simplest atom is that of hydrogen, which has one proton and one electron
- Also helium atom contains 2 protons and neutrons in the nucleus and 2 electrons orbiting the nucleus.



(a) Hydrogen atom



(b) Helium atom

Atomic Structure (2)

- <u>Bohr model of the atom:</u>

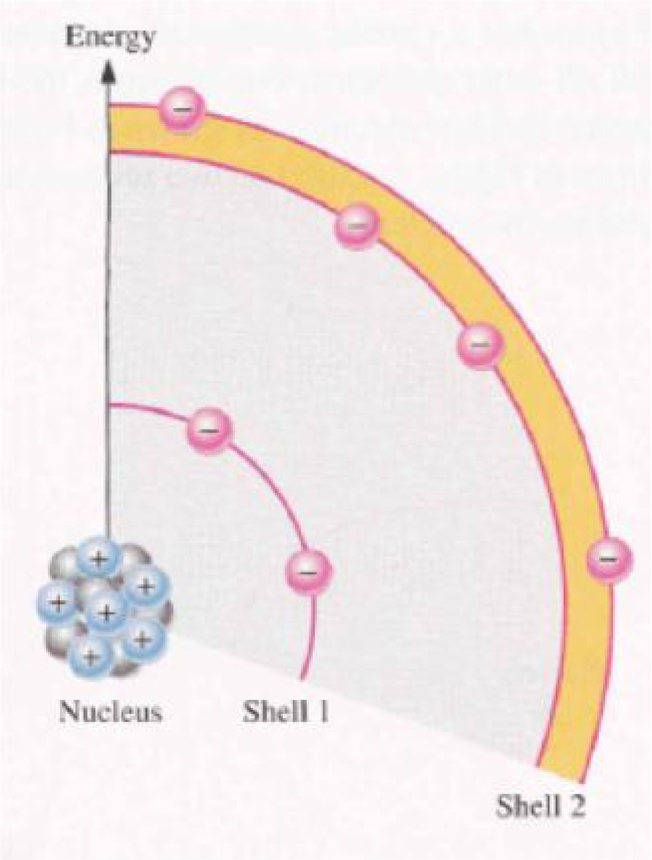
  an atom contains a fixed nucleus having a positive charge (protons) and electrons with negative charges that move around the nucleus in elliptical paths (orbits).
- These electrons distribute themselves in shells (quantistic energy levels).
- Electrons in the outermost shell are called valence electrons.

Atomic Number (3)

- All elements are arranged in the periodic table according to their atomic number which equals to the number of protons or electrons in an electrically balanced atom which has a net charge of zero.
- Electron Shells and Orbits:
  - Electrons orbit the nucleus at certain distances. Electrons near the nucleus have less energy than those at distant orbits.
  - It is known that only discrete (separate and distinct) values of electron energies exist within atomic structures, Therefore, electrons must orbit at discrete distance from nucleus

Energy Levels (Shells)

- Each discrete distance (orbit) corresponds to certain energy level.
- In an atom energy levels are grouped into energy bands known as ***shells***, A given atom has a fixed number of shells.
- Each shell has a fixed maximum number of electrons at permissible energy levels.
- The differences in energy levels within a shell are much smaller than the differences in energy between shells,
- The energy band concept is illustrated next in next Figure , which shows the 1st shell with one energy level, the second with two energy levels. Additional shells may exist in other types of atoms depending on the element



Energy level increases as distance from nucleus increase

Valence Electrons

- Electrons that are farther from the nucleus have higher energy and are less tightly bound to thy nucleus, because the force of attraction between the nucleus and the electrons decrease with increasing distance from the nucleus
- Electrons with the highest energy exist in the outer-most shell of an atom and are relatively loosely bound to the atom
- The outer-most shell is known as valence shell and electrons in this shell are ***valence electrons***.
- These valence electrons contribute to chemical reactions and bounding within the structure of a material

and determine its electrical properties

Ionization

- When an atom absorbs energy from a heat source or light, the energies of electrons are raised. The valence electrons possess more energy and they are bound to the atom less and can easily jump to higher orbits within the same shell
- If a valence electron acquire enough energy, it can escape from the outer shell and from the atom's influence and it becomes a free electron
- The atom will have a positive charge and this process is called ionization and the atom is ***a positive ion.***
- If an electron losses energy and falls in the valence band of a neutral atom, this atom will have negative charge and it is known as ***a negative ion***

Semiconductors (2)

- In extremely pure elements, such as silicon, the atoms arrange themselves is orderly patterns called crystals
- The valence electrons determine the exact shape (= lattice structure) of the resulting crystal
- The atoms are bound in a lattice structure so that each atom “shares” its 4 valence electrons with neighboring atoms, these *covalent bonds* hold the lattice together.

$Maximum\ number\ of\ Electrons$ in a shell:

$$N_e = 2n^2$$

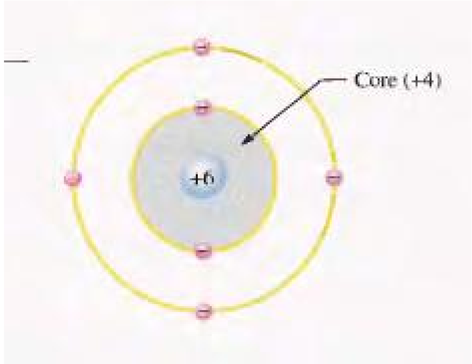
Where;
N_e is number of electrons
n is the shell number

Number of Electrons in each shell

- For example Si with atomic number=14
- $\boldsymbol{in\ shell\ 1\ \ N_e = 2.1^2}$=2
- $\boldsymbol{in\ shell\ 2\ \ N_e = 2.2^2}$=8
- $\boldsymbol{in\ shell\ 3\ \ N_e}$ = 4

Semiconductors, Conductors and Insulators

- All materials are made up of atoms. These atoms contribute to the electrical properties of a material including the ability to conduct electrical current
- For purposes of discussing electrical properties, an atom can be represented by the valence shell and a core that consists of all the inner shells and the nucleus
- For example carbon atom with atomic number of 6 is shown, it has a net charge of +4 (+6 for the nucleus and -2 for the for the inner shell electrons



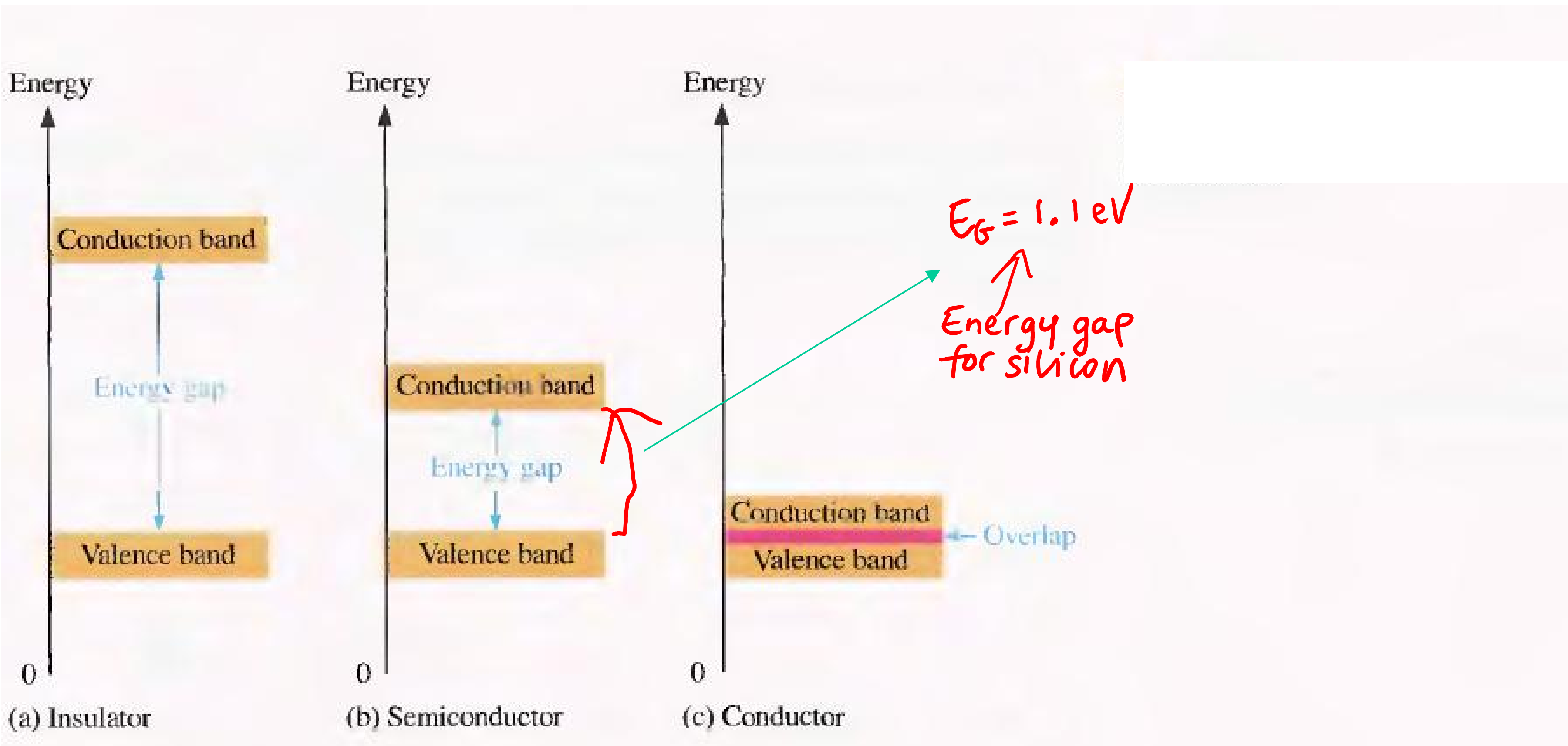
Conduction in materials

- Materials can be classified based on their conduction characteristics in:
- **Insulators** – does not conduct current un der normal conditions, valence electrons are tightly bound to the atoms and there are very few free electrons
- **Conductors**- easily conducts current and is characterized by one valence electron loosely tied to the atom and can easily break away and become free electron
- **Semiconductors**- A pure (intrinsic) semiconductor is neither a good conductor nor a good insulator , they are characterized by 4 valence electrons such as single element Si (14), Ge (32)
- Also compounded semiconductors exist such as :Gallium Arsenide, Silicon Carbide

Energy Bands and Energy Gap

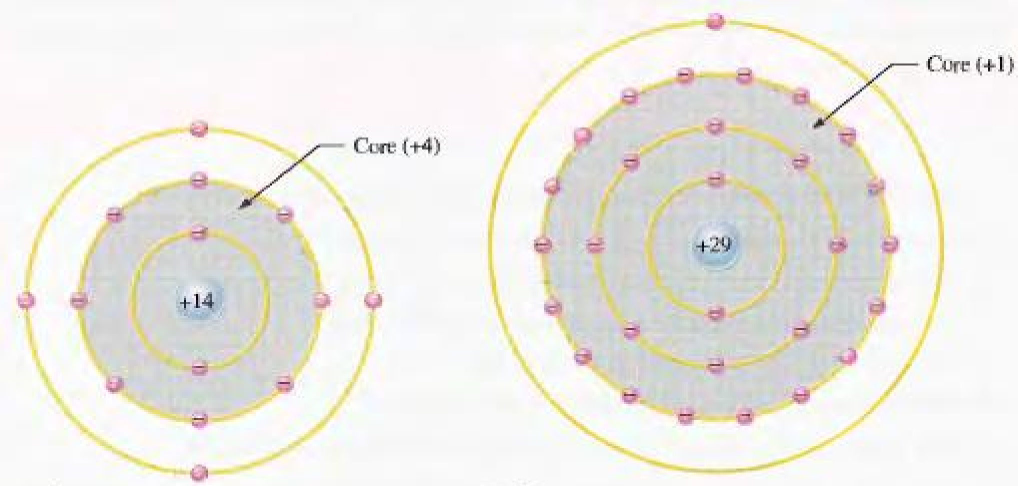
- Energy Bands: the valence shell of an atom represents an energy band in which the valence electrons exist
- When an electron acquires enough additional energy it can move to conduction band and become a free electron
- Energy Gap: is the difference in energy between valence band and conduction band of material , this is the energy a valence electron must acquire in order to move to conduction band and become free electron and move through out the material without being tied to any atom

Energy Gap


Energy
Conduction band
Energy gap
Valence band
0
(a) Insulator
Energy
Conduction band
Energy gap
Valence band
0
(b) Semiconductor
Energy
Conduction band
Overlap
Valence band
0
(c) Conductor
$E_G = 1.1\,eV$
Energy gap for silicon

Examples

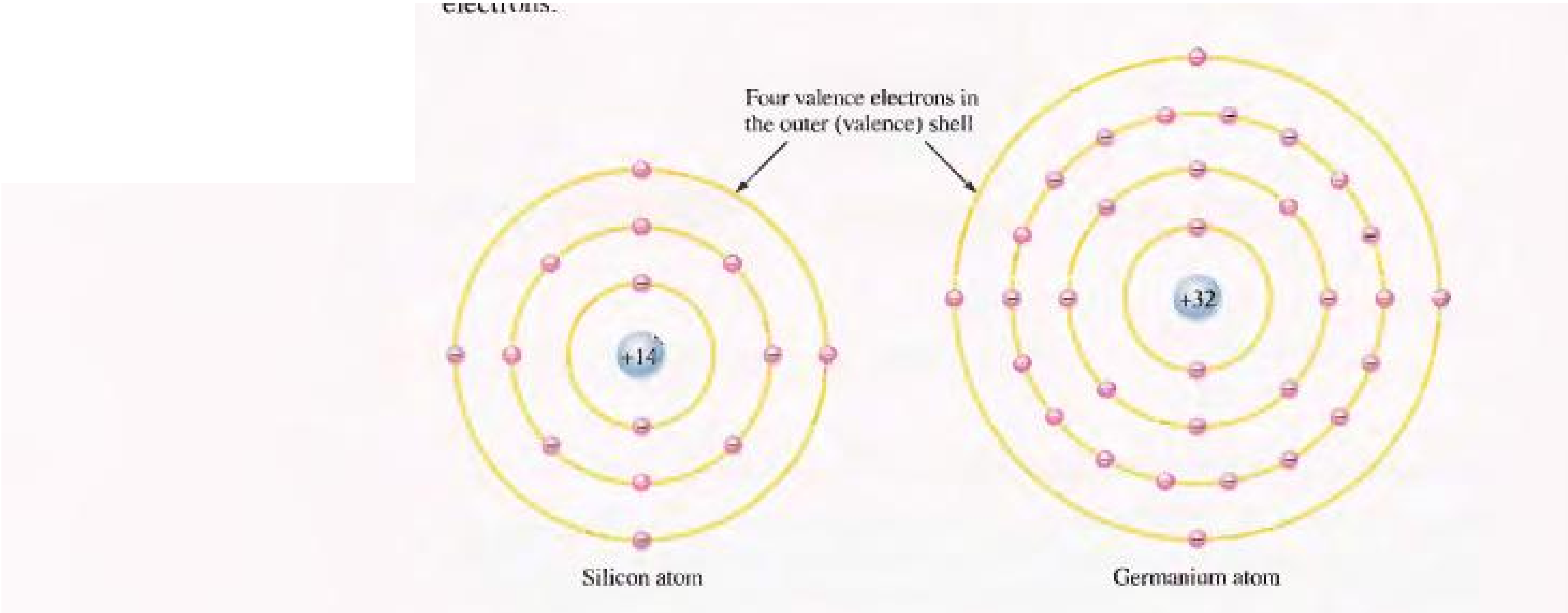
- Silicon with atomic number +14 and copper with atomic number +29



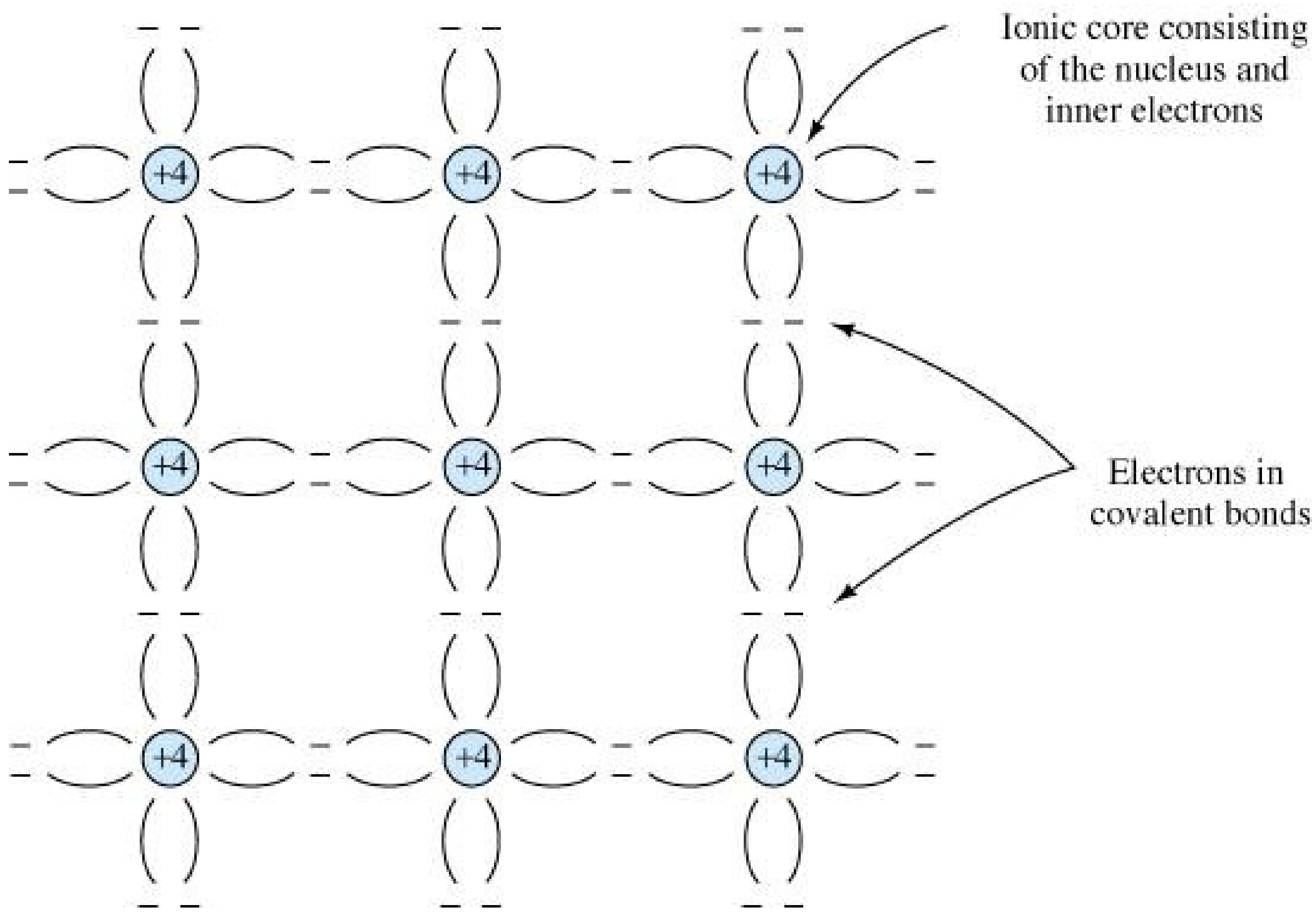
(a) Silicon atom (b) Copper atom

- Silicon atom has 4 times the attraction force of the copper, and thus copper electrons are less tied to the nucleus

Silicon and Germanium atoms

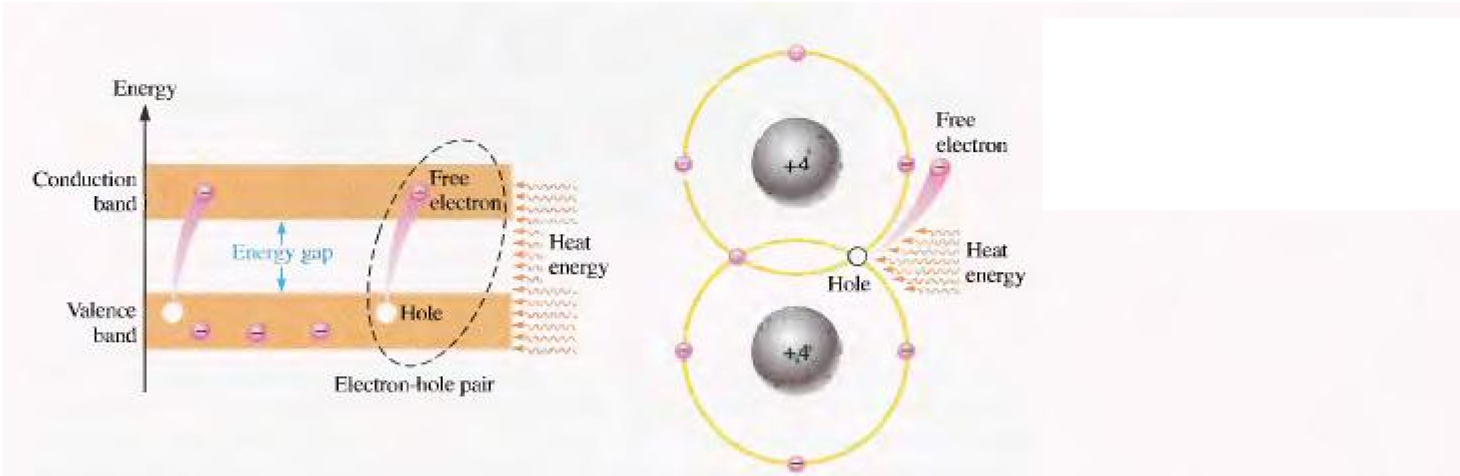


Silicon Intrinsic Crystal



Intrinsic silicon crystal.

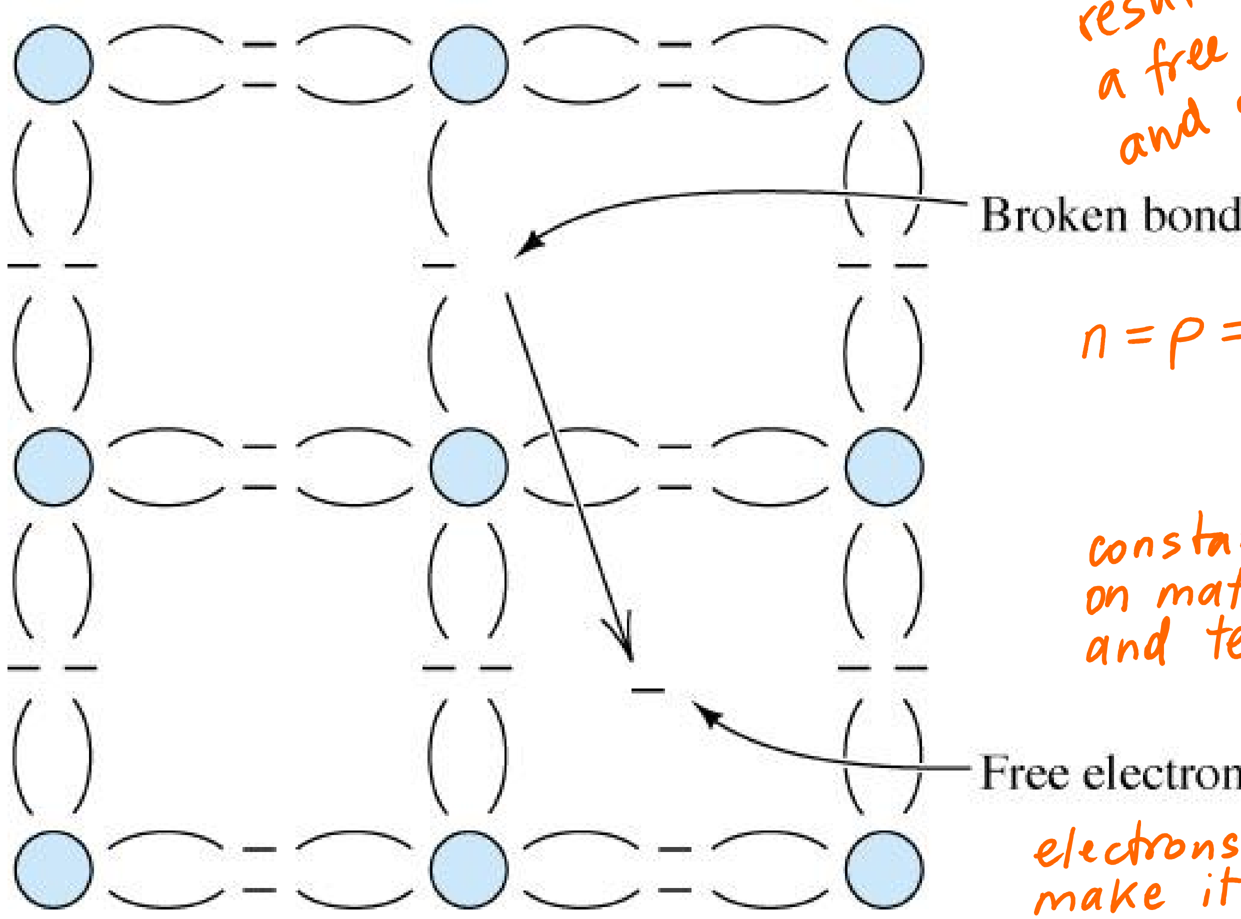
- An intrinsic (pure) silicon crystal at room temperature has sufficient heat energy for some valence electrons to jump the gap from valence band into the conduction band becoming free electrons ***(conduction electrons)***



(a) Energy diagram (b) Bonding diagram

- When an electron jumps the conduction band, a vacancy is left in the valence band within the crystal. ***This vacancy is called a hole***.
- For every electron raised to the conduction band by external energy, there is one hole left in the valence band ***creating what is called an electron-hole pair***
- Recombination occurs when the conduction band electron losses energy and it falls back into a hole in the valence band

Free electrons & Holes



breaking a bond results in both a free electron and a hole

$n = p = n_i$

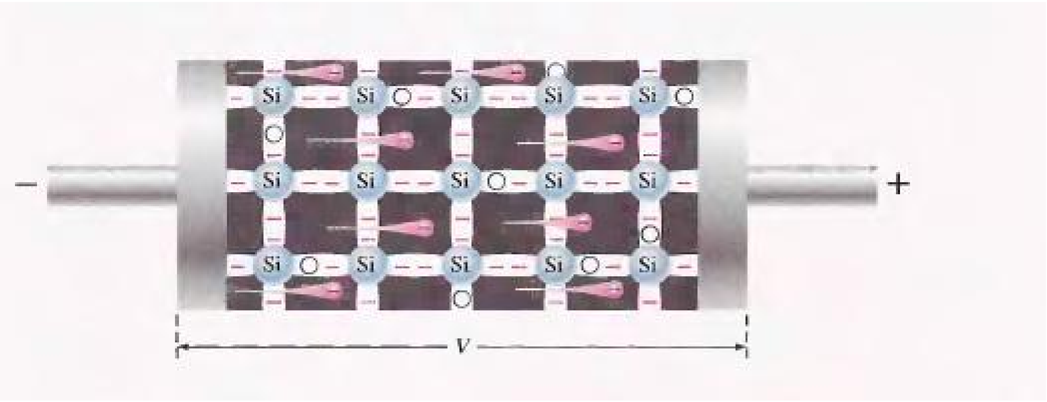
constant depending on material and temperature

electrons that make it through the "GAP".

Thermal energy can break a bond, creating a vacancy and a free electron, both of which can move freely through the crystal.

Electron and Hole Current

- When voltage is applied across a piece of silicon, the thermally generated free electrons in the conduction band, which are free to move randomly in the crystal structure, are now easily attracted toward the positive end è ***this movement is called electron current***



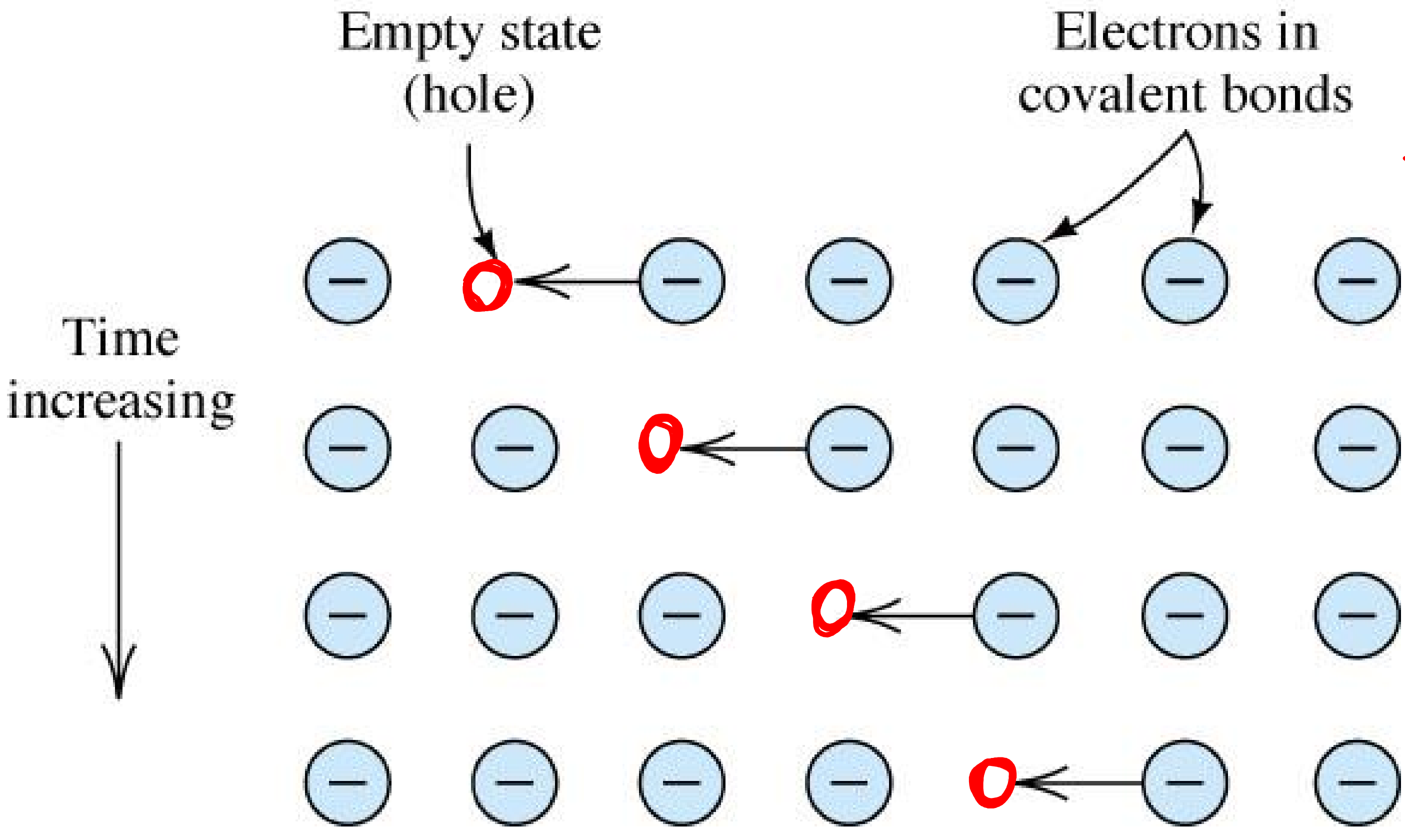
Hole Current

- Another type of current occurs in the valence band, where the holes created by free electrons exist. Electrons remaining in the valence band are still attached to their atoms and are not free to move randomly as are free electrons,
- ***However, a valence electron can move into a nearby hole with little change in its energy level, thus leaving another hole where it came from***. Effectively the hole has moved from one place to another in the crystal structure
- ***This is called hole current***

Holes movement

Holes move slower than electrons !!

it has to do with the probability that a hole gets filled



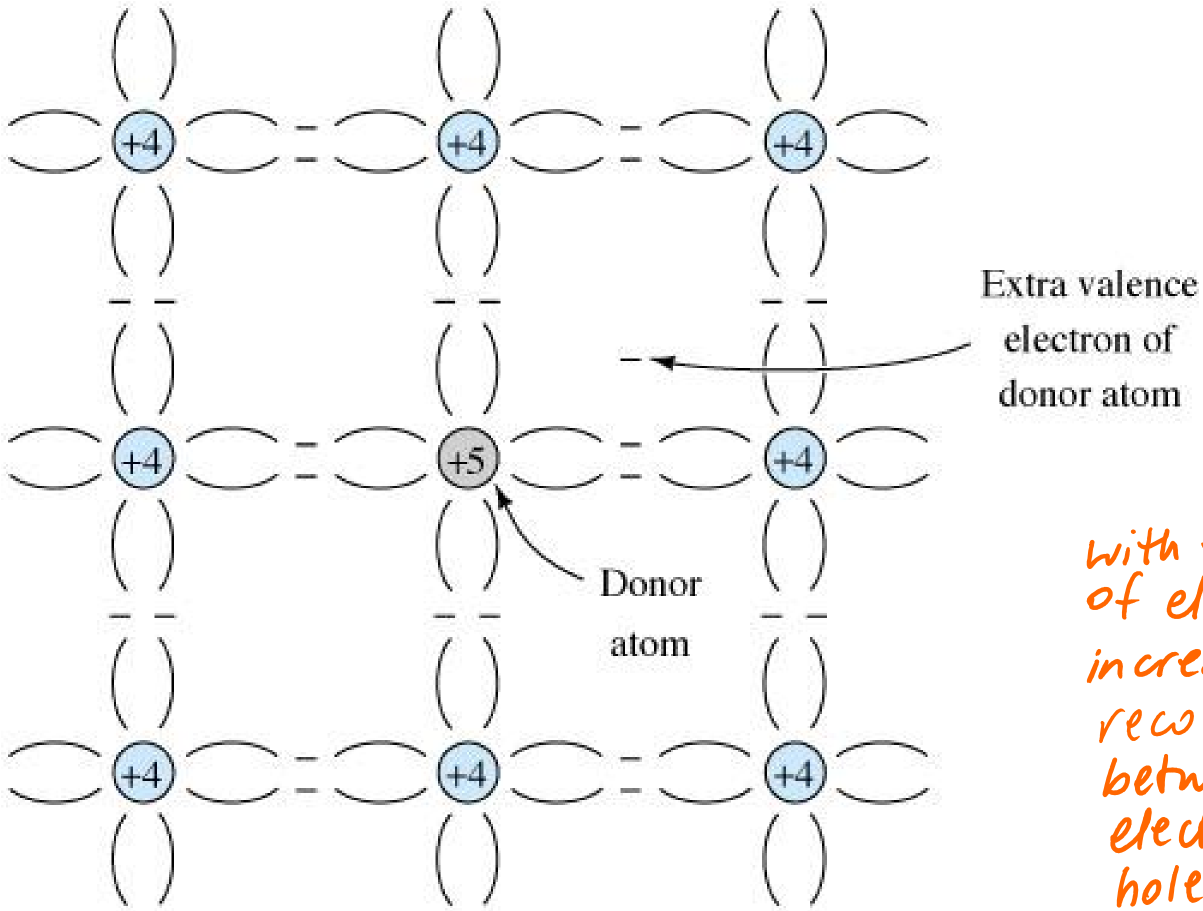
As electrons move to the left to fill a hole, the hole moves to the right.

Doping

- Adding impurities to the pure (intrinsic) semiconductor material is termed doping, which increases the number of current carriers (holes or electrons).
- There is two categories of impurities: n-type or p-type

- **N-Type Semiconductor**
- Pentavalent impurity (one which has 5 valence electrons) atom is added such as phosphorus
- This atom forms covalent bonds with 4 adjacent silicon atoms, while the fifth becomes a conduction electron since it is not attached to any atom

n-type silicon



with the number of electrons increasing the rate of recombination between free electrons and holes also increase

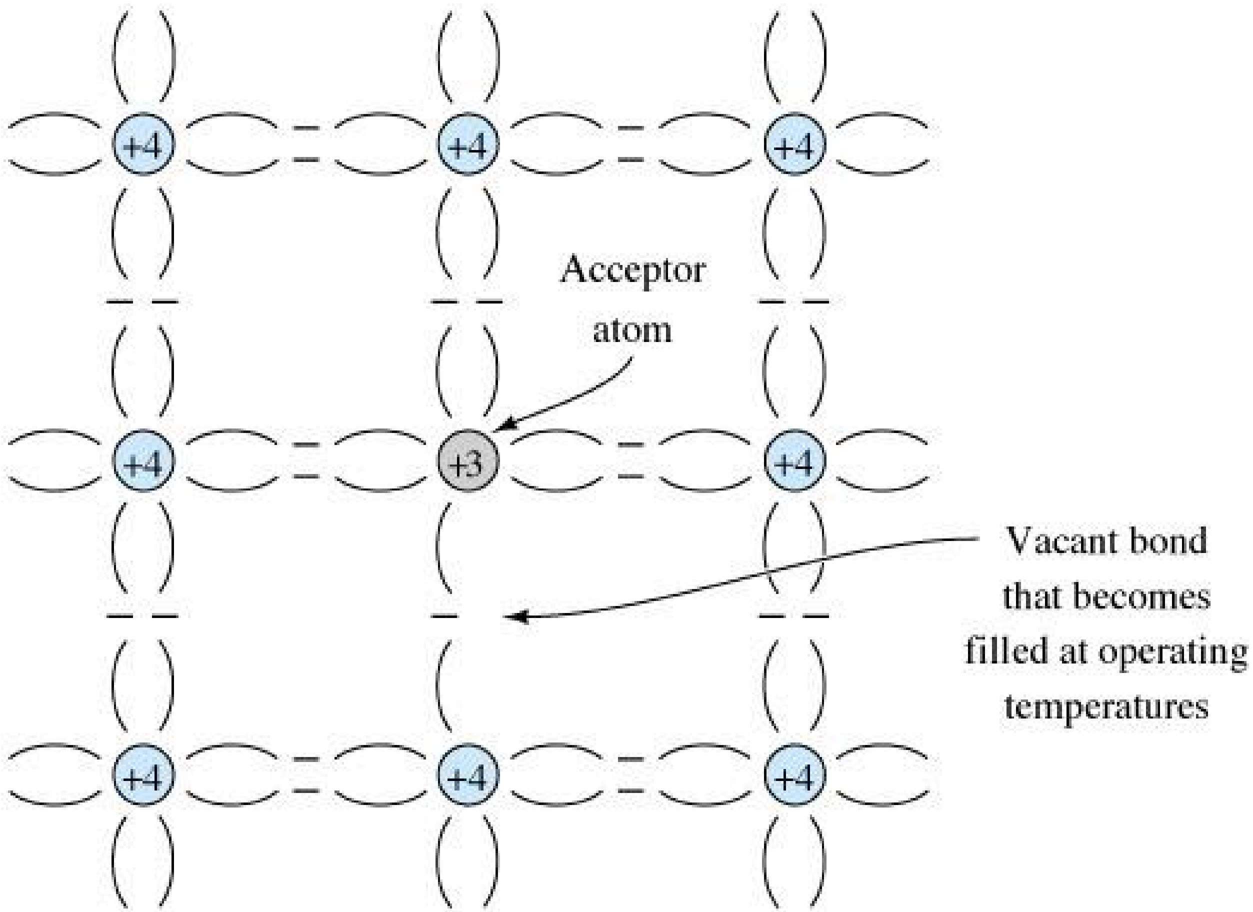
***n*-type silicon is created by adding valence five impurity atoms.**

- Number of conduction electrons can be carefully controlled by the number of impurities added
- Since most of the current carriers are electrons, this type of material doped with pentavalent impurities is an n-type semiconductor
- The majority current carriers in n-type material is electrons, but there are few holes created when electron-hole pair are thermally generated, these holes are minority carriers

P-Type Semiconductor

- To increase number of holes in intrinsic silicon, trivalent impurity atoms are added (atoms with three valence electrons) such as boron (B) or gallium (Ga)
- Valence electrons (3) of the impurity atom create covalent bonds with three adjacent atoms of silicon and a fourth electron is missing, creating a hole with each added impurity atom
- Majority carriers in P-type material are holes
- Also there are few free electrons that are created when electron-hole pair are thermally generated, these electrons are minority carriers

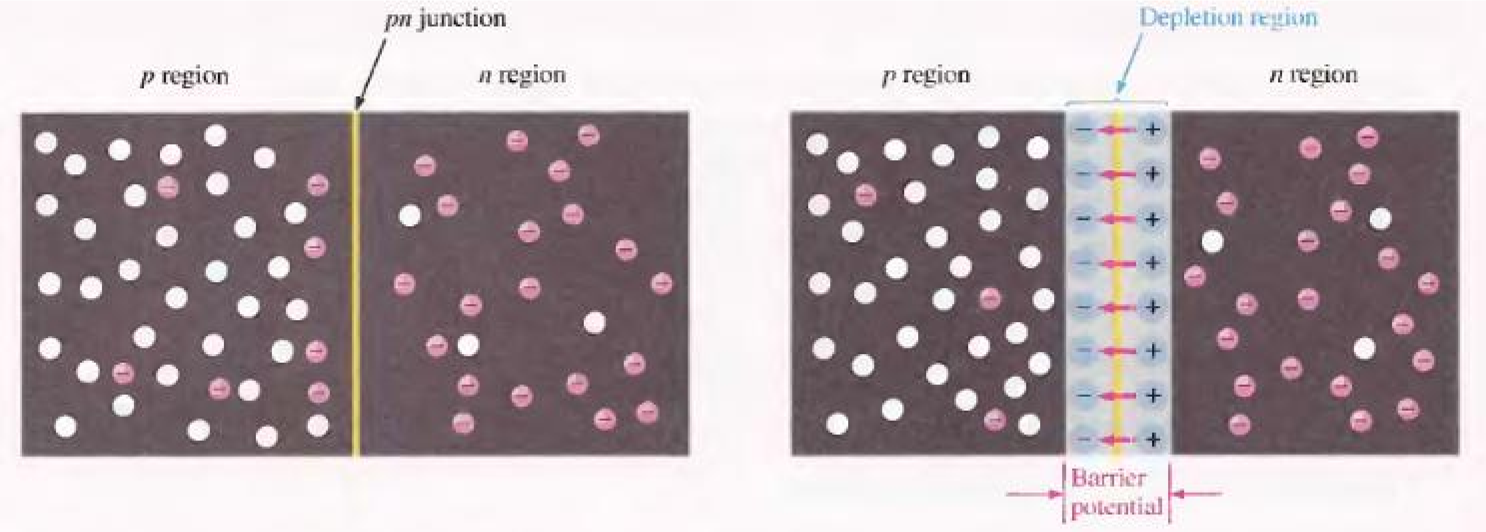
p-type silicon



***p*-type silicon is created by adding valence three impurity atoms.**

Formation of Depletion Region

- Free electrons in n- region are randomly drifting in all directions.
- ***At the instant of pn junction formation, free electrons near the junction in the n-region begin to diffuse across the junction into p-region where they combine with holes near the junction***



(a) At the instant of junction formation, free electrons in the *n* region near the *pn* junction begin to diffuse across the junction and fall into holes near the junction in the *p* region.

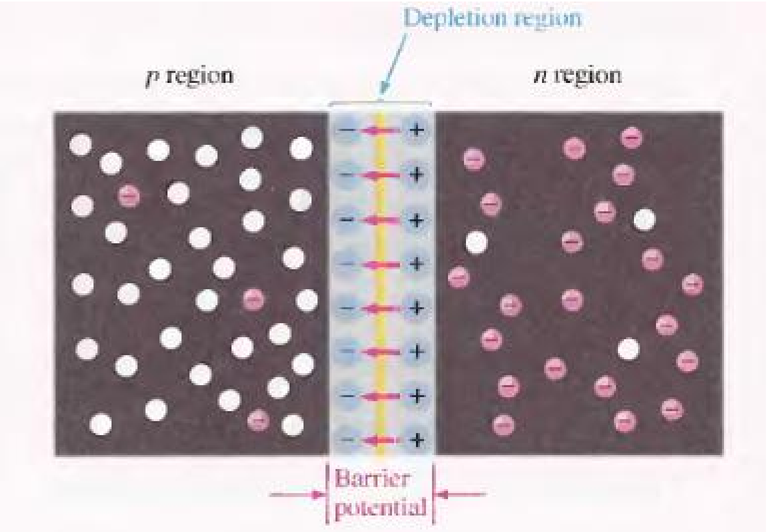
(b) For every electron that diffuses across the junction and combines with a hole, a positive charge is left in the *n* region and a negative charge is created in the *p* region, forming a barrier potential. This action continues until the voltage of the barrier repels further diffusion.

Formation of Depletion Region*

- ***When the pn junction is formed, the n- region loses free electrons as they diffuse across the junction. This creates a layer of positive charges near the junction*.**
- As the electrons move across the junction, the p region loses holes as the electrons and holes combine. This creates a layer of ***negative*** charges near the junction
- These two layers of positive and negative charges form the depletion region (which is depleted of charge carriers, i.e. electrons and holes due to diffusion across the junction)
- The depletion region is formed quickly and is very thin compared to p and n regions, diffusion continues until a point is reached where the total negative charge in the depletion region repels any further diffusion of electrons into the p region and the diffusion stops
- i.e. the depletion region acts as a barrier to the further movement of electrons across the junction

Barrier Potential

- *The barrier potential of a pn junction depends on several factors, including the type of semiconductor material, amount of doping, and the temperature*
- *Typical at 25 deg C it is ~ 0.7 for silicon and ~ 0.3 for germanium*



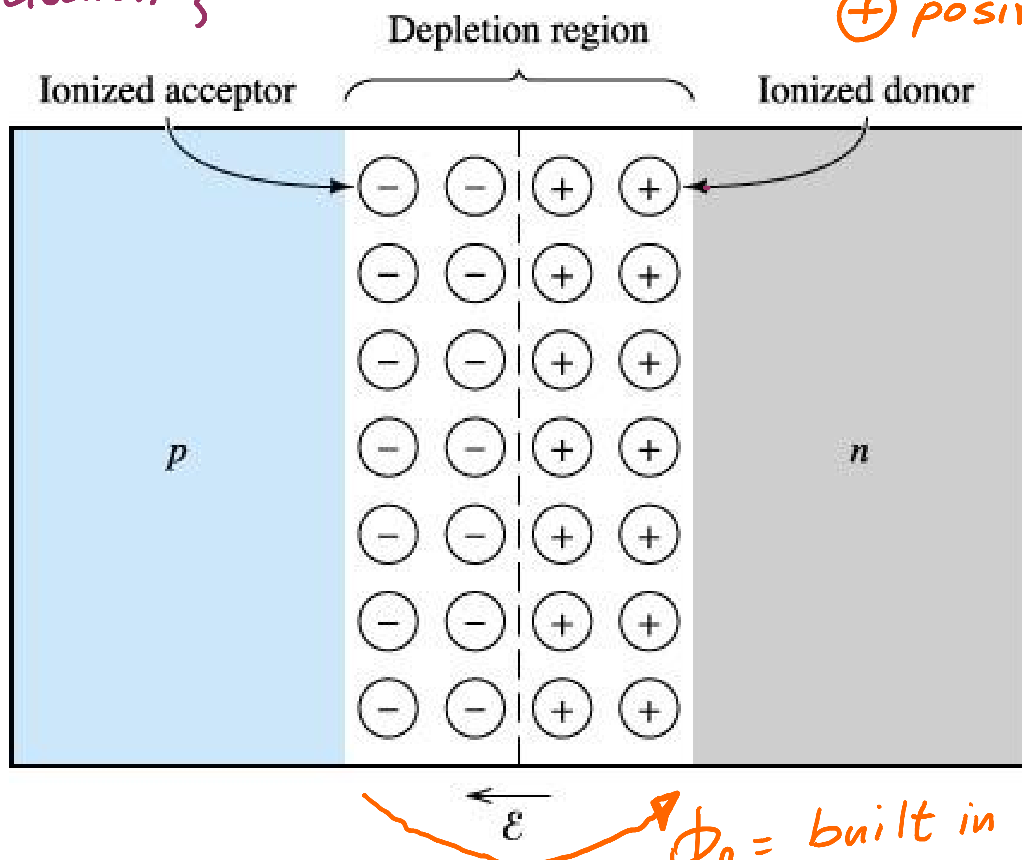
(b) For every electron that diffuses across the junction and combines with a hole, a positive charge is left in the *n* region and a negative charge is created in the *p* region, forming a barrier potential. This action continues until the voltage of

Unbiased PN junction

+ hole
− free electron } ← mobile charge

⊖ negative ion
⊕ positive ion } fixed charge

It's like a barrier that makes hard for electrons in the N-region to reach the P-region (and analogously for the holes in the N-region)



ϕ_B = built in voltage

(a) *pn* junction

Diffusion of majority carriers into the opposite sides causes a depletion region to appear at the junction.

Biasing the Diode

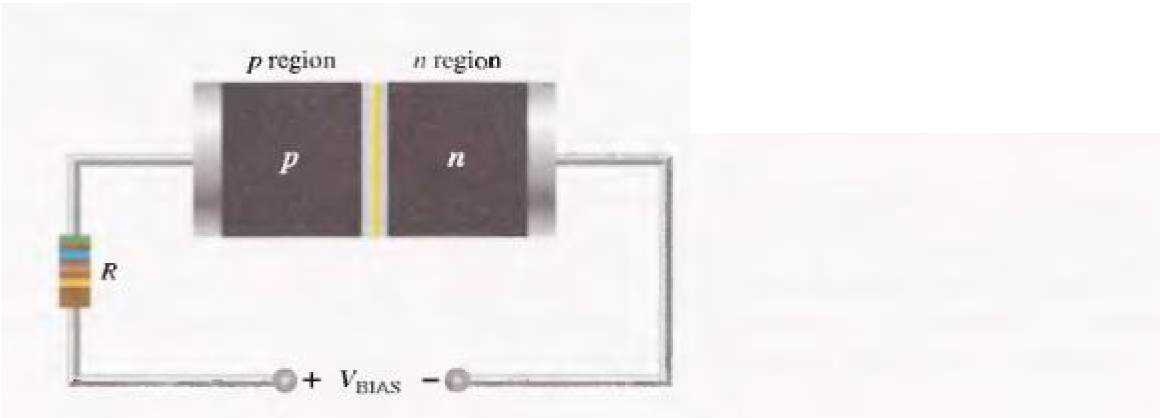
Bias: is the use of dc voltage source to establish certain operating conditions for an electronic device

For the diode, there is two bias conditions: ***forward and reverse***

Forward Bias

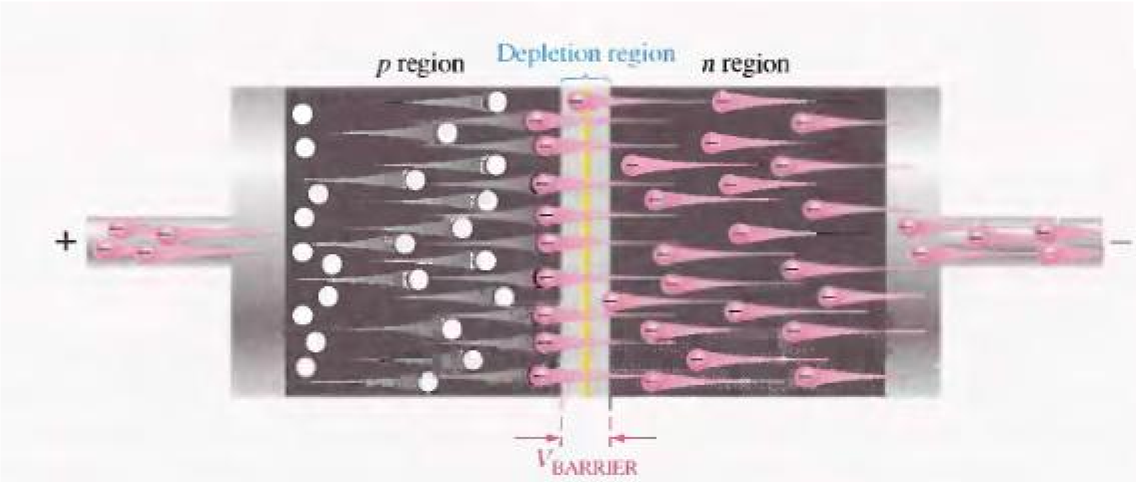
To Apply dc voltage to allow forward current through the pn junction

R limits current to a safe value that will not damage the diode



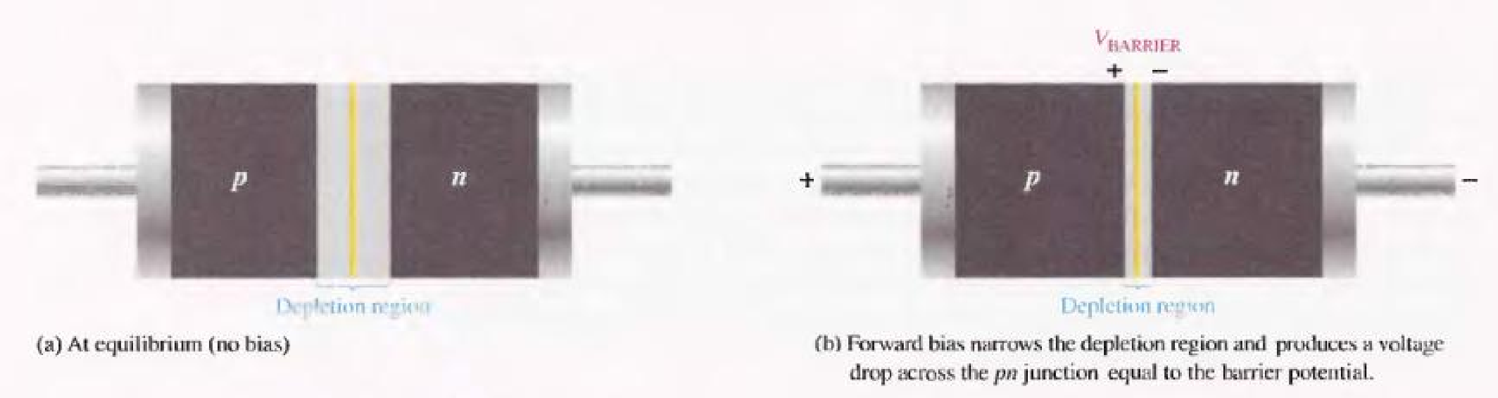
Forward Bias

- **Conditions for forward bias:** 1) Anode must be more positive than cathode and 2) Vbias must be greater than barrier potential (0.7 for Silicon and 0.3 for Germanium)
- The negative side of Vbias, pushes free electrons toward the pn junction. This is electron current
- The negative side of Vbias also provides continuous flow of electrons through the external connection and into the n-region as shown



A forward-biased diode showing the flow of majority carriers and the voltage due to the barrier potential across the depletion region.

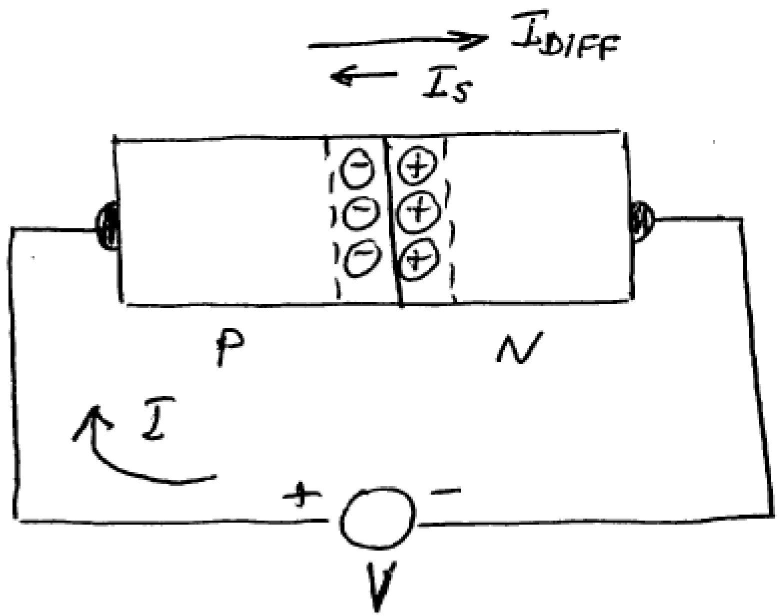
- As the electrons flow out of the p region to the positive side of Vbias, they leave holes behind in the p region.
- So, there is continuous availability of holes moving toward the pn junction and combine with electrons as they come through the junction
- ***What does Forward Bias do to the depletion region?***
- As more electrons flow into the depletion region, the number of positive ions is reduced
- As more holes flow into the depletion region on the other side of pn region, the number of negative ions is reduced
- This reduction in positive and negative ions during forward bias causes the depletion region to narrow



(a) At equilibrium (no bias)

(b) Forward bias narrows the depletion region and produces a voltage drop across the *pn* junction equal to the barrier potential.

Forward biased PN junction

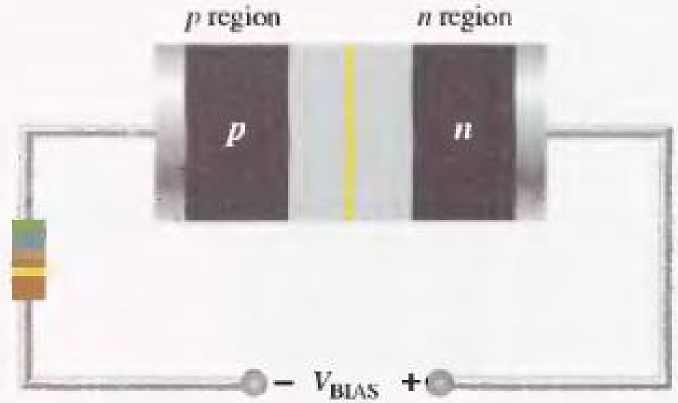


The depletion region shrink

it will be easier for the majority carriers to overcome the barrier and therefore cross the junction

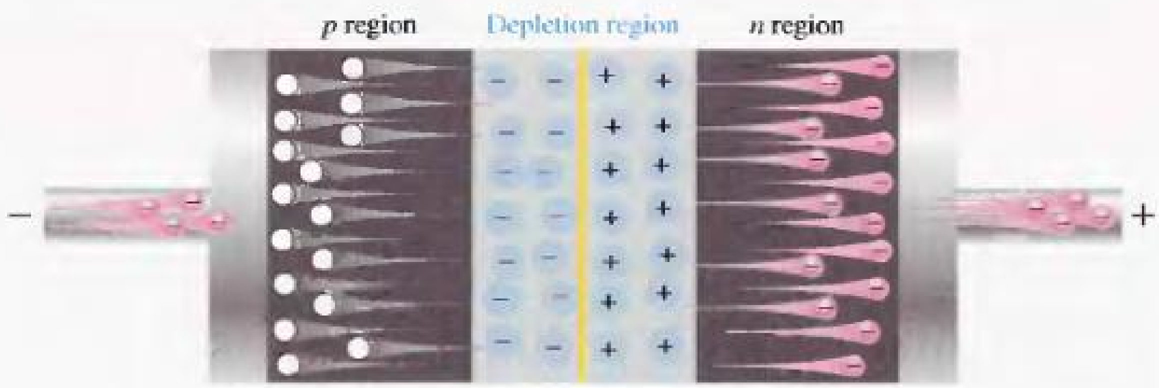
but il will be tougher for the minority carriers to be drifted all the way from one side to the other.

Reverse Bias



A diode connected for reverse bias. A limiting resistor is shown although it is not important in reverse bias because there is essentially no current.

- The positive side of Vbias pulls the free electrons, which are the majority carriers in n-region, away from pn



The diode during the short transition time immediately after reverse-bias voltage is applied.

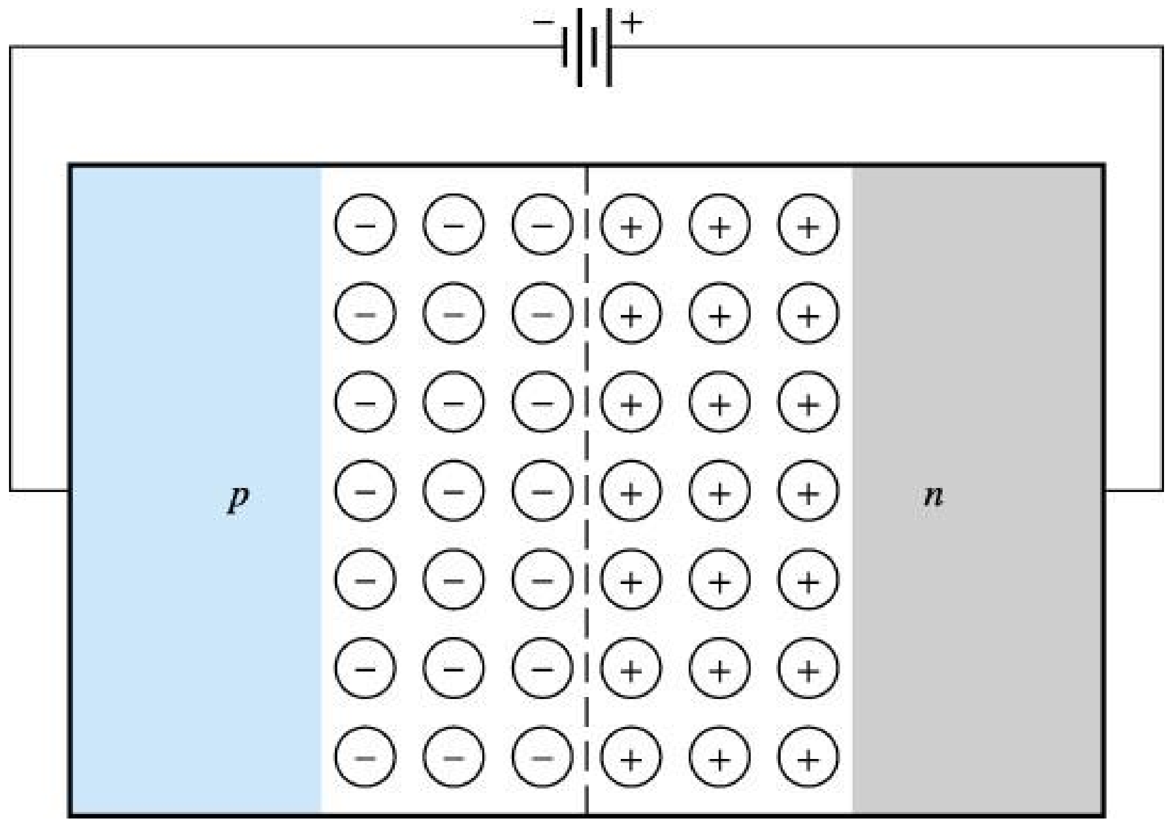
Reverse Bias

- Also in the p-region, electrons from negative side of Vbias enter as valence electrons and move from hole to hole toward the depletion region creating additional negative ions, thus widening the depletion region
- The initial flow of charge carriers is transitional and last for very short duration after reverse bias voltage is applied
- As the depletion region widens, the electric field between positive and negative ions increase until the potential across the depletion region equals the Vbias
- At this point transition current stops except for very small reverse current which is usually neglected

Reverse biased PN junction (1)

-n side more positive than p side

- Depletion region becomes wider



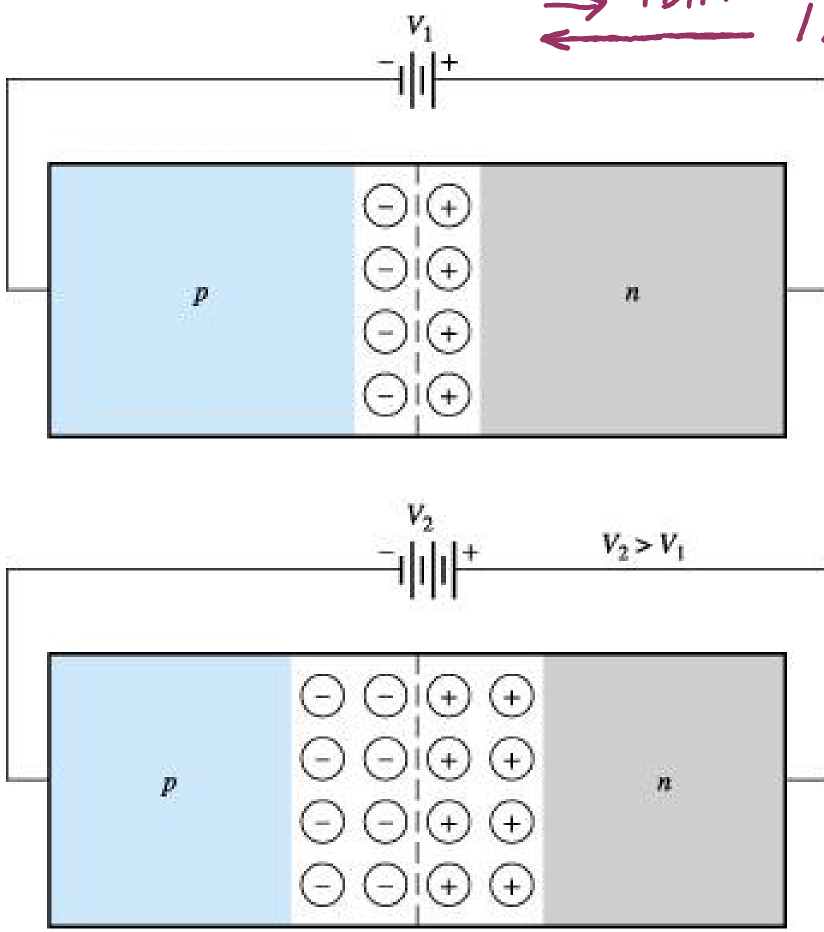
Under reverse bias, the depletion region becomes wider.

Reverse biased PN junction (2)

$\xrightarrow{} I_{DIFF}$

$\xleftarrow{} I_{DRIFT} = I_S$

$I = I_{DIFF} + I_{DRIFT}$

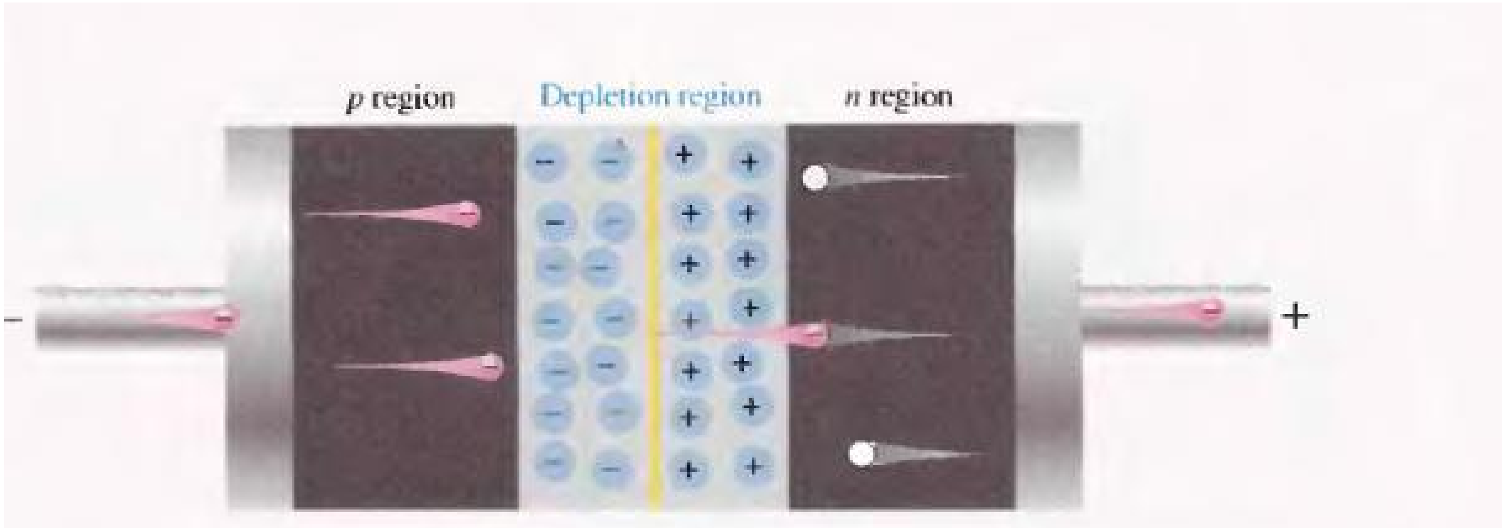


It gets easier for the minority carriers to be swept (drifted) from one side to another

As the reverse bias voltage becomes greater, the charge stored in the depletion region increases.

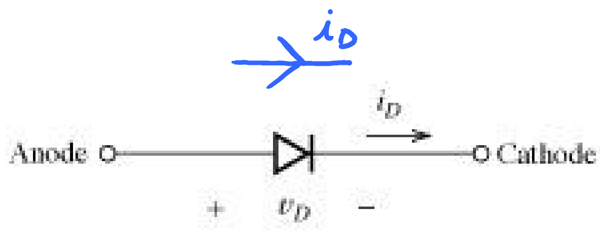
- **Reverse Current (Is)**: an extremely small current during reverse bias is caused by minority carriers in p and n regions that are produced by thermally generated electron-hole pairs (reverse current is ignored in further discussions)
- **Reverse Breakdown:** the reverse current is small in value but can increase if the reverse is increased and reaches a value called breakdown voltage, then the current will increase and might cause permanent damage to the diode unless heat-sink is provided to limit the temperature rise

Reverse Breakdown



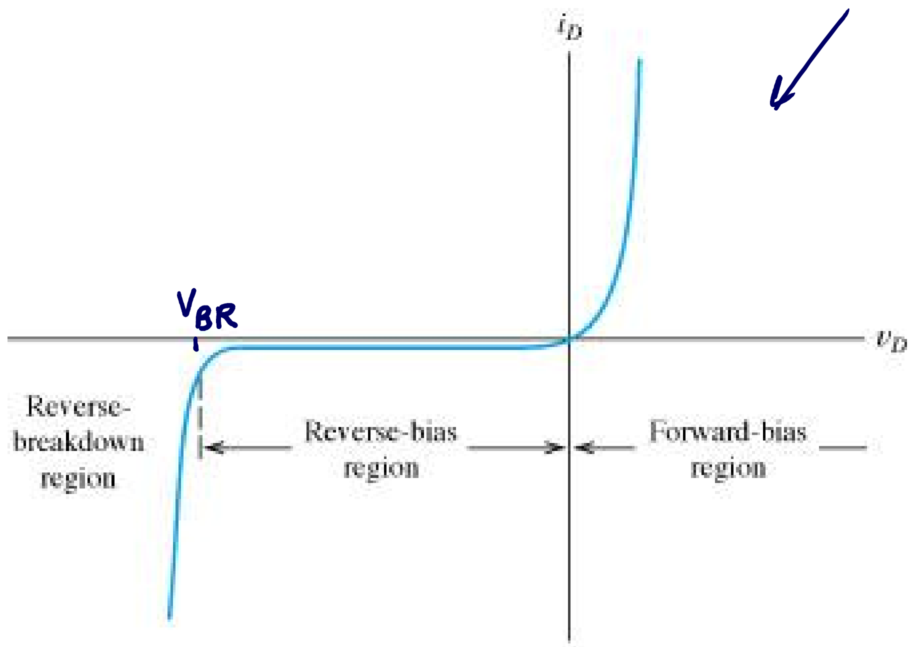
- The high reverse bias impacts energy to the free minority electrons so that as they speed through the p region, they collide with atoms with enough energy to knock electrons out of orbit and into conduction band
- The newly created conduction electrons are also high in energy and repeat the process
- If each electrons knocks only two others out of their valence orbit during its travel through p region, the number quickly multiply. As these high energy electrons go through the depletion region, they have enough energy to go through the n region as conduction electrons, rather than combining with holes
- This multiplication of conduction electrons just discussed is known as avalanche and results in a very high reverse current that can damage the diode because of excessive heat dissipation

Semiconductor Diode



(a) Circuit symbol

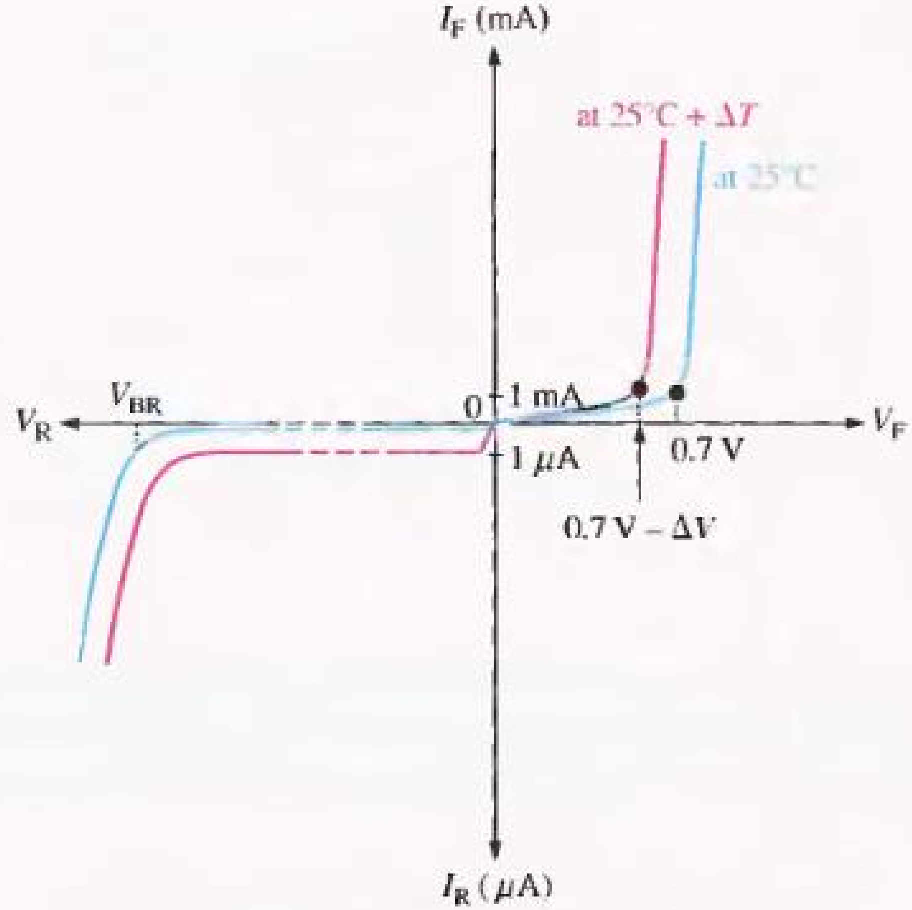
3 operating regions :



(b) Volt-ampere characteristic

FIGURE 1–30

Temperature effect on the diode *V-I* characteristic. The 1 mA and 1 μA marks on the vertical axis are given as a basis for a relative comparison of the current scales.



The diode equation (1)

For forward and reverse bias region:

$$i_D = I_S \left(e^{v_D / \eta V_T} - 1 \right)$$

Analytical i-v relationship valid in forward & reverse region

I_S = saturation current (sometime called scale factor because it is proportional to the cross-section area A of the diode → doubling the junction area A results in a diode with double I_S and as a consequence double i_D). → I_S is strongly dependent on the temperature. (doubles every 5°C for silicon).

V_T = thermal voltage = $\frac{KT}{q}$ ($\simeq$ 26mV at 27°C)

The diode equation (2)

η = empirical scaling constant = exponential ideality factor

has value between $0.5 \div 2$
it depends on the type of semiconductor and the doping.

K = Boltzman constant = 1.38×10^{-23} J/K

q = charge of the electron = 1.69×10^{-19} Coulomb

T = temperature in Kelvin (= 273 + temperature in °C)

Forward & Reverse regions (2)

FORWARD DYNAMIC RESISTANCE:

$$r_D = \frac{\eta V_T}{i_D + I_S} \underset{i_D \gg I_S}{\approx} \frac{\eta V_T}{i_D}$$

typically a very small value !!

≈ A SHORT

REVERSE DYNAMIC RESISTANCE:

$$r_D = \frac{\eta V_T}{i_D + I_S} \underset{i_D \approx -I_S}{\approx} \infty$$

AN OPEN

Breakdown region

- The breakdown region is entered when the magnitude of the reverse voltage exceed a threshold called "breakdown voltage" or the "zener knee voltage".
- In the breakdown region the current increase rapidly with a very small increase in the associated voltage.
- There is an avalanche of electrons flowing across the junction with the result that the diode overheat.
- Provided that the power dissipated in the diode is limited by external circuitry to a safe level (typically specified in the data sheets) breakdown won't be destructive.