# Semiconductor Devices And Applications (Unit 4)

# Outline

## ✓ Junction Diode Characteristics

- Intrinsic & Extrinsic Semiconductor
- PN junction diode
- Diode Characteristics
- Diode Applications

## ▪ Special Semiconductor Devices

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- Tunnel, Photodiode
- Shockley, SCR

## ✓ Rectifiers

- Half wave
- Full Wave
- Bridge

## ✓ Transistor

- Operation
- Characteristics
- Configuration

## ✓ Field Effect Transistor (FET)

- Operation
- Characteristics

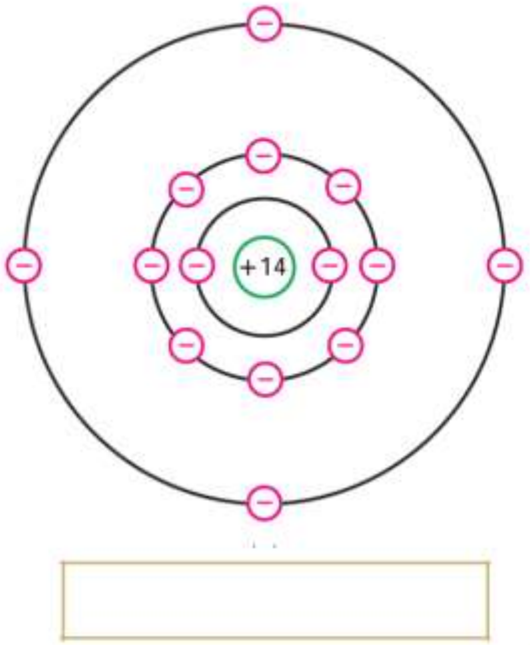
## ✓ Operational Amplifier

- Introduction
- Applications

# Junction Diode Characteristics

# Intrinsic Semiconductor

- ✓ A pure Silicon / Germanium crystal
- ✓ Not enough free electrons and holes to produce a current
- ✓ The electrical action can be modified by doping to increase either the number of free holes or number of free electrons

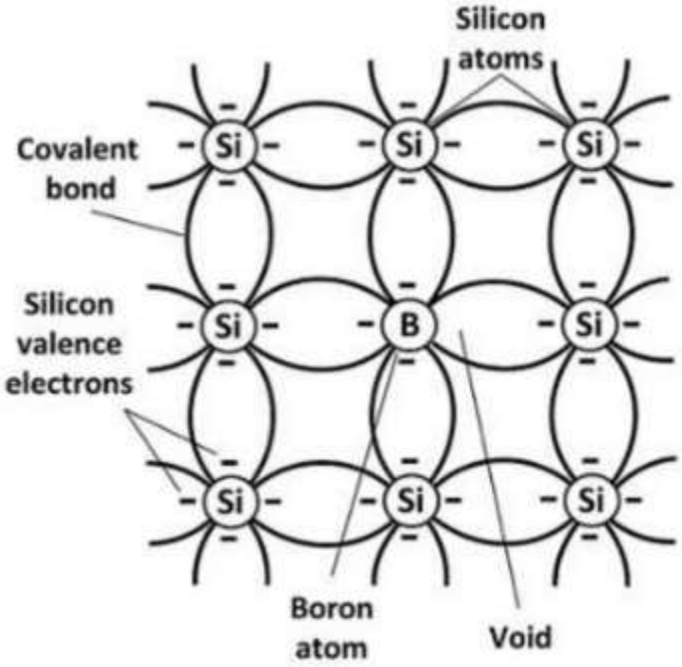



Silicon Atom

# Extrinsic Semiconductor

✓ When a crystal has been doped, it is called an **Extrinsic semi-conductor**

- N-type semiconductor having free electrons as majority carriers
- P-type semiconductor having free holes as majority carriers



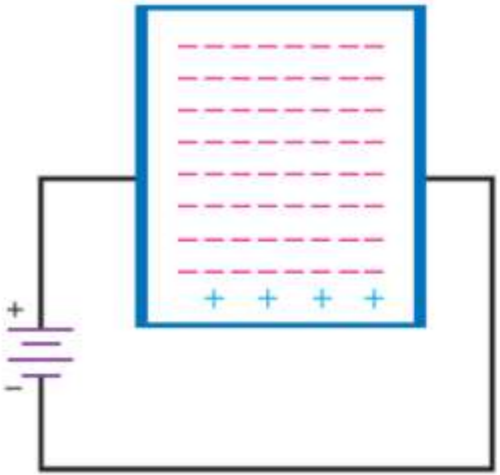

P – Type Semiconductor

# N-Type Semiconductor

✓ Silicon that has been doped with a **pentavalent impurity** is called an N-type semiconductor, where the n stands for negative.

✓ Since the free electrons outnumber the holes in an n-type semiconductor, the **free electrons** are called the **majority carriers** and the **holes** are called the **minority carriers.**

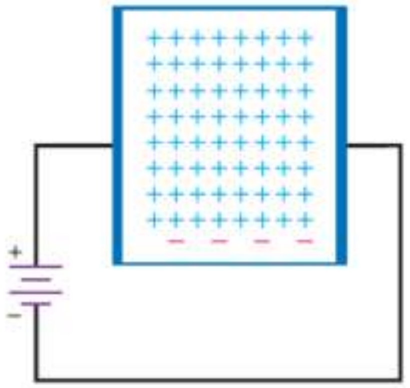
✓ Because of the applied voltage, the free electrons move to the left and the holes move to the right.




N-type semiconductor has many free electrons

# P-Type Semiconductor

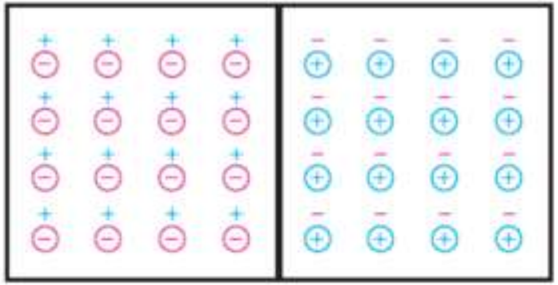
- ✓ Silicon that has been doped with a **trivalent impurity** is called a P-type semiconductor, where the p stands for positive.
- ✓ Since holes outnumber free electrons, the **holes** are referred to as the **majority carriers** and the **free electrons** are known as the **minority carriers.**
- ✓ Because of the applied voltage, the free electrons move to the left and the holes move to the right.



P-type semiconductor has many holes

# PN Junction Diode

- ✓ When a manufacturer dopes a crystal so that one-half of it is P-type and the other half is N-type, something new comes into existence.
- ✓ The border between P-type and N-type is called the PN junction.
- ✓ The PN junction has led to all kinds of inventions, including diodes, transistors, and integrated circuits.



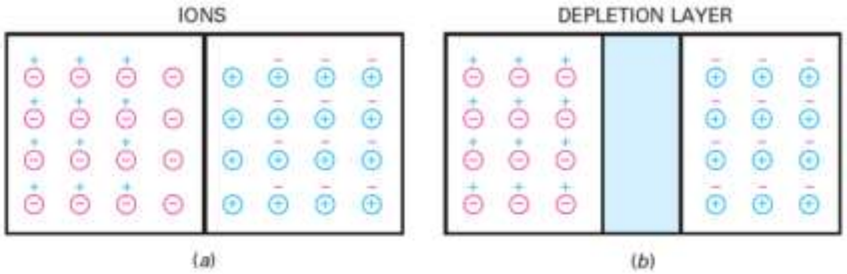
PN Junction

- ✓ Each circled minus sign is the trivalent atom, and each plus sign is the hole in its valence orbit.
- ✓ Each circled plus sign represents a pentavalent atom, and each minus sign is the free electron it contributes to the semiconductor.

# The Depletion Layer

✓ Because of their repulsion for each other, the free electrons on the n side of Fig. tend to diffuse (spread) in all directions. Some of the free electrons diffuse across the junction.

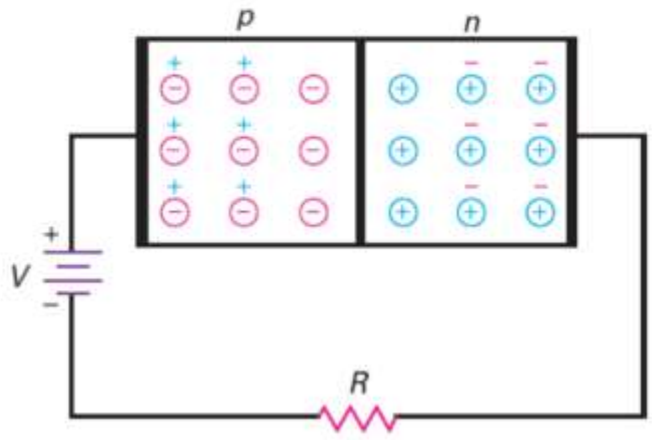
✓ When a free electron enters the p region, it becomes a minority carrier. With so many holes around it, this minority carrier has a short lifetime. Soon after entering the p region, the free electron recombines with a hole. When this happens, the hole disappears and the free electron becomes a valence electron.




(a) Creation of ions at junction; (b) depletion layer.

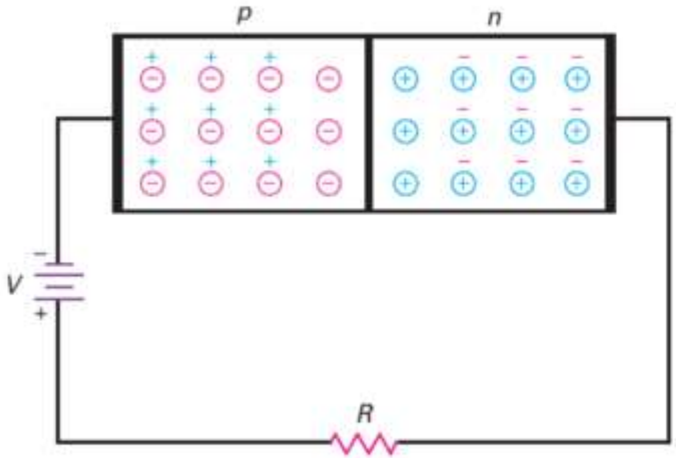
# Forward Bias

- ✓ Figure shows a dc source across a diode.
- ✓ The negative source terminal is connected to the n-type material, and the positive terminal is connected to the p-type material.
- ✓ This connection produces what is called **forward bias**.

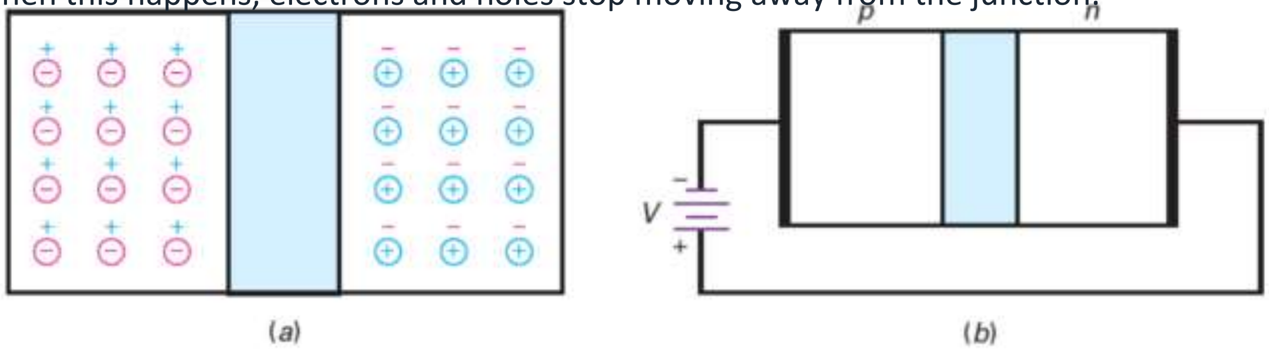


# Reverse Bias

- ✓ The negative battery terminal is connected to the p side and the positive battery terminal to the n side.
- ✓ This connection produces what is called **reverse bias.**
- ✓ The negative battery terminal attracts the holes, and the positive battery terminal attracts the free electrons. Because of this, holes and free electrons flow away from the junction. Therefore, the depletion layer gets **wider**.



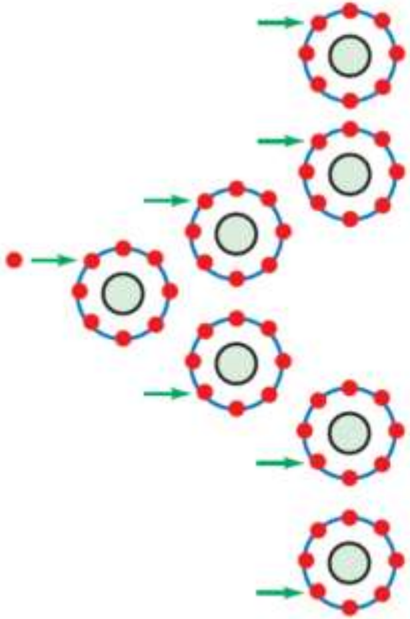
- When the holes and electrons move away from the junction, the newly created ions increase the difference of potential across the depletion layer.
- The wider the depletion layer, the greater the difference of potential.
- The depletion layer stops growing when its difference of potential equals the applied reverse voltage.
- When this happens, electrons and holes stop moving away from the junction.




(a) Depletion layer; (b) increasing reverse bias widens depletion layer.

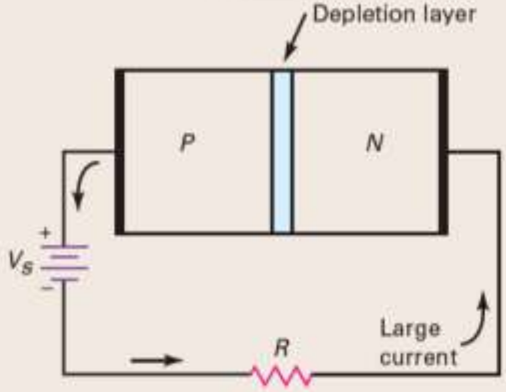
# Breakdown

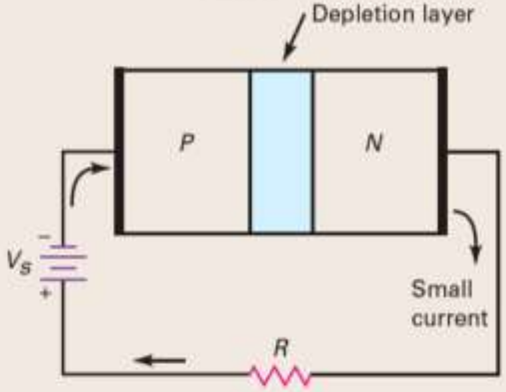
- ✓ Diodes have maximum voltage ratings.
- ✓ There is a limit to how much reverse voltage a diode can withstand before it is destroyed.
- ✓ If you continue increasing the reverse voltage, you will eventually reach the breakdown voltage of the diode.
- ✓ Once the breakdown voltage is reached, a large number of the minority carriers suddenly appears in the depletion layer and the diode conducts heavily.



The process of avalanche is a geometric progression: 1, 2, 4, 8, . .

## Summary Table 2-1 Diode Bias




| | Forward bias | Reverse bias |
|---|---|---|
| $V_s$ polarity | (+) to *P* material<br>(−) to *N* material | (−) to *P* materials<br>(+) to *N* material |
| Current flow | Large forward current if $V_s > 0.7$ V | Small reverse current (saturation current and surface leakage current) if $V_s <$ breakdown voltage |
| Depletion layer | Narrow | Wide |

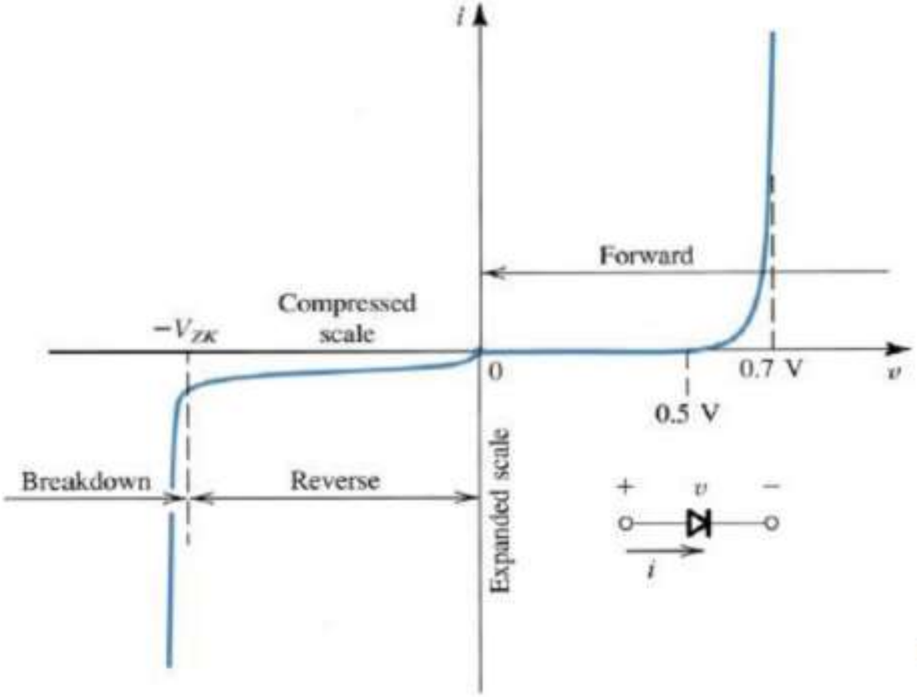
# V-I Characteristic of PN Junction Diode

✓ **Knee Voltage (Cut-in Voltage):** The applied forward voltage at which the PN junction diode start conducting.

- Silicon Diode: 0.7 V
- Germanium Diode: 0.3 V

✓ **Reverse Saturation Current:** In reverse bias condition there will be negligible amount of current that will flow through the device due to minority carrier.

- This current is very small.
- It’s of the order of nA in Si diode and A in Ge diode.



# Simplified equivalent circuit

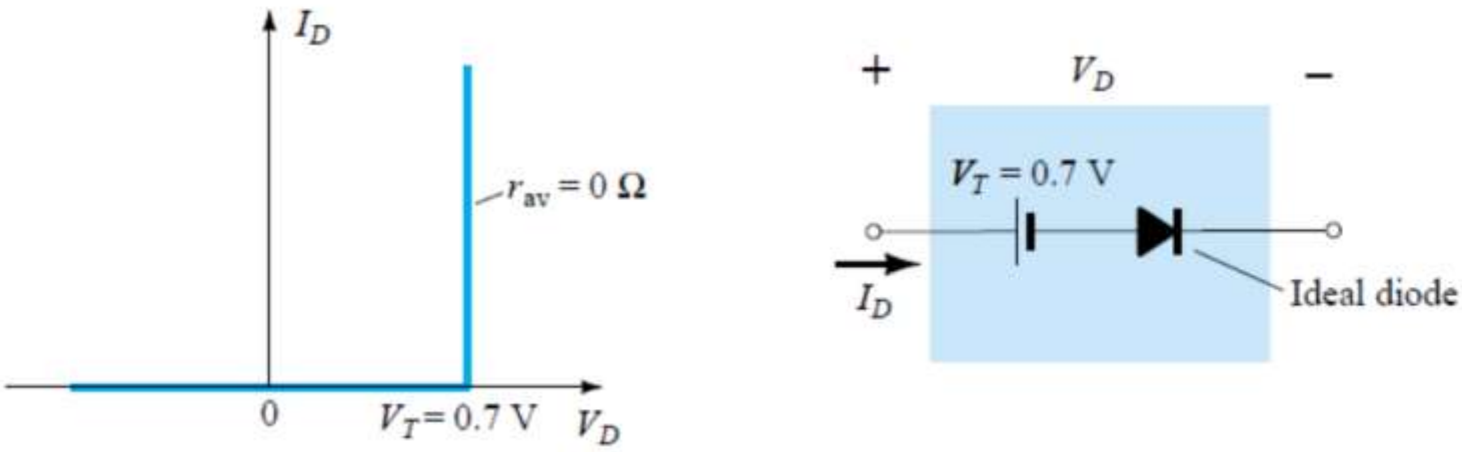



**Figure 1.33** Simplified equivalent circuit for the silicon semiconductor diode.

- It states that a forward-biased silicon diode in an electronic system under dc conditions has a **drop of 0.7 V** across it in the conduction state at any level of diode current.

# Ideal equivalent circuit

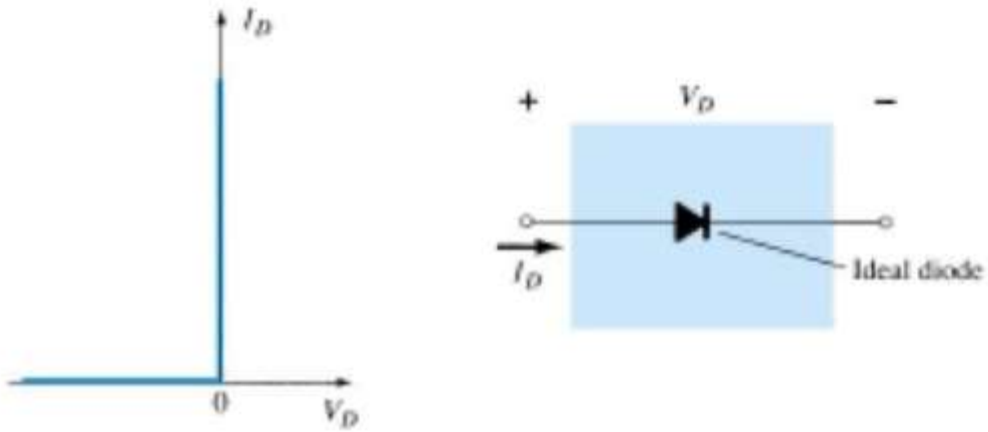
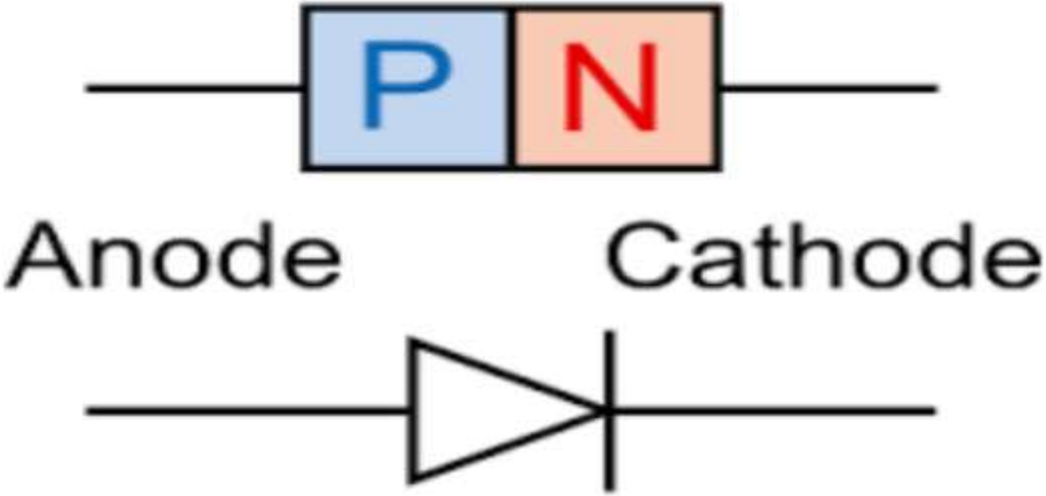


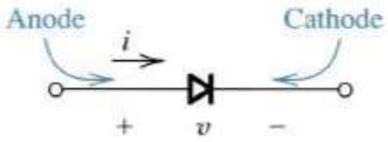

Figure 1.34 Ideal diode and its characteristics.

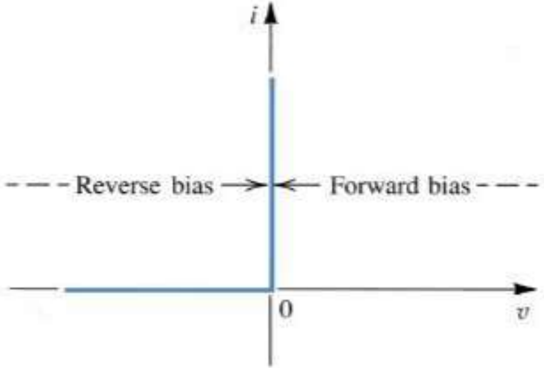
- A 0.7 V level can often be ignored in comparison to the applied voltage level.
- In this case the equivalent circuit will be reduced to that of an ideal diode as shown in Fig. 1.34 with its characteristics.

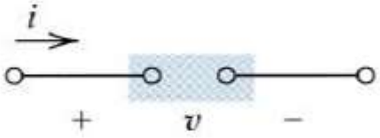
# PN JUNCTIONDIODE



# Diodes approximation (Ideal Diode)

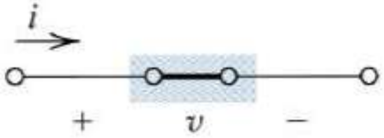



$v < 0 \Rightarrow i = 0$

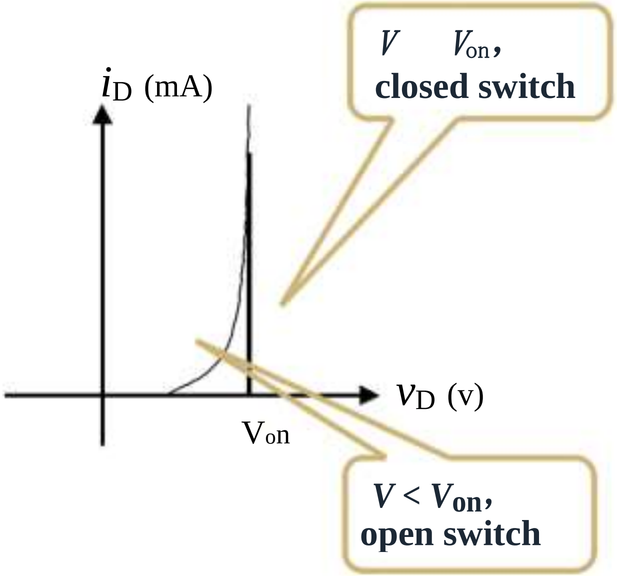
Open Circuit

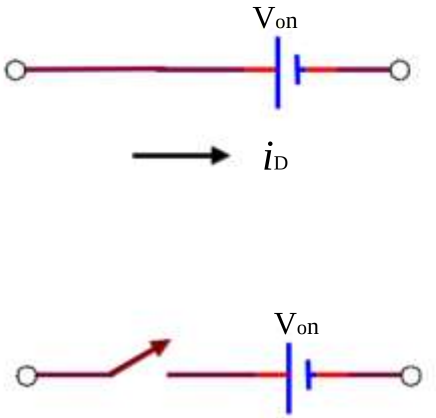



$i > 0 \Rightarrow v = 0$

Short Circuit

# Second Approximation Model



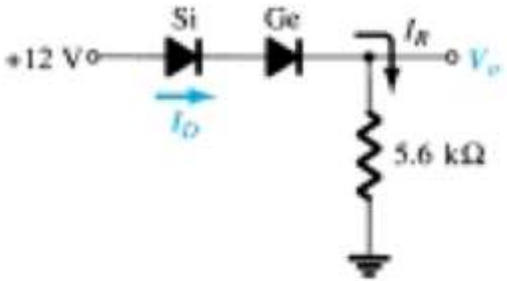




**Si diode**: $V_{on} \approx 0.7(V)$（0.6～0.8）

**Ge diode**: $V_{on} \approx 0.2$（V）

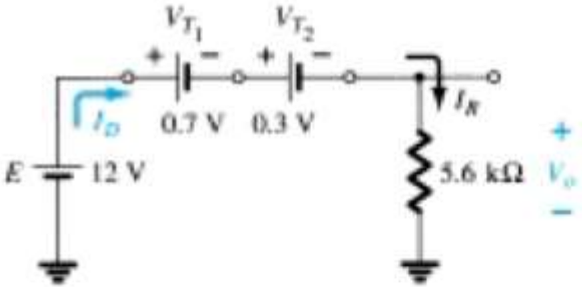
# Diode Example

Determine $V_o$ and $I_D$ for the series circuit of Fig. 2.21.




$$V_o = E - V_{T_1} - V_{T_2} = 12\text{ V} - 0.7\text{ V} - 0.3\text{ V} = \mathbf{11\text{ V}}$$

$$I_D = I_R = \frac{V_R}{R} = \frac{V_o}{R} = \frac{11\text{ V}}{5.6\text{ k}\Omega} \cong \mathbf{1.96\text{ mA}}$$



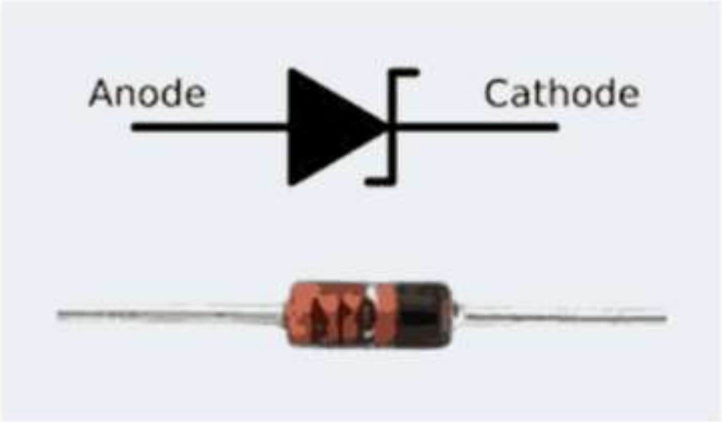
# Special Semiconductor Devices

- Zener
- LED
- Tunnel
- Photodiode
- Shockley

❖ SCR

# Zener Diode

- ✓ The diodes designed to work in breakdown region.
- ✓ By varying the doping level, it is possible to produce Zener diode with breakdown voltages from about 2 V to 200 V.
- ✓ As discussed previously, the large current at breakdown is brought about by two factors…
  - Zener effect



- Avalanche effect

# Contd.

## Zener effect

- ✓ When the diode is heavily doped, the depletion layer is very narrow.
- ✓ When the voltage across the diode is increased (in reverse bias), the electric field across the depletion layer becomes very intense.
- ✓ When this field is about $3 \times 10^{7}$ V/m, electrons are pulled from the covalent bonds.
- ✓ A large number of electron-hole pairs are thus produced and the reverse current sharply increases.

✓ This is known as the Zener effect.

# Contd.

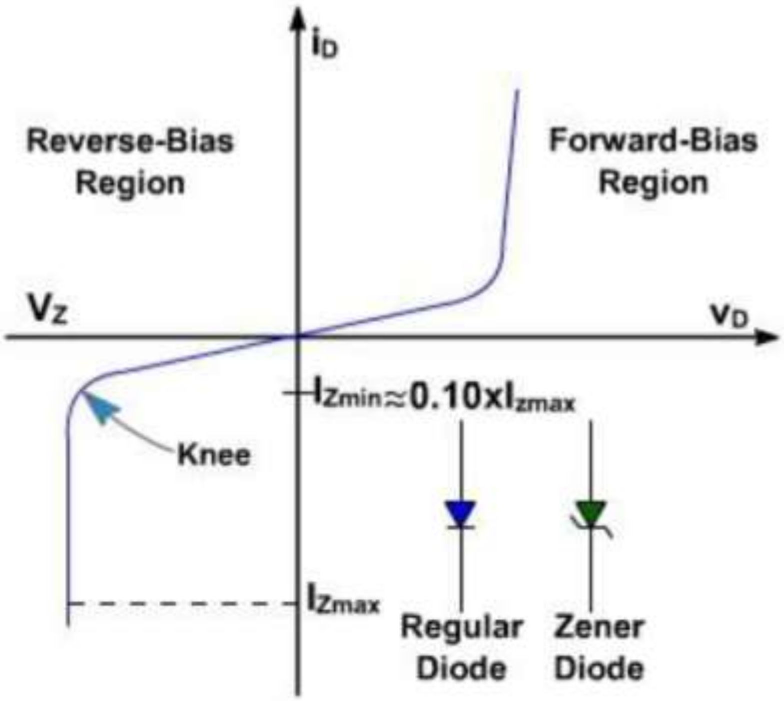
## Avalanche effect

- ✓ Avalanche effect occurs because of a cumulative action.
- ✓ The external applied voltage accelerates the minority carriers in the depletion region.
- ✓ They attain sufficient kinetic energy to ionise atoms by collision.
- ✓ This creates new electrons which are again accelerated to high-enough velocities to ionise more atoms.
- ✓ This way, an avalanche of free electrons is obtained.

✓ The reverse current sharply increases.

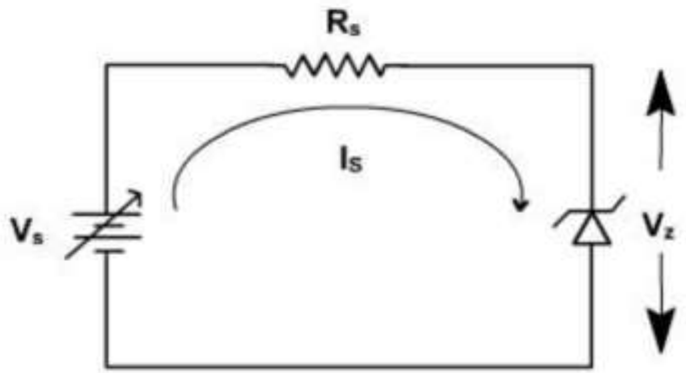
# Contd.

✓ If the reverse voltage exceeds the breakdown voltage, the Zener diode will normally not be destroyed as long as the current does not exceed maximum value.



# Contd.

- When Zener diode is forward biased it works as a diode and drop across it is 0.7 V.
- When it works in breakdown region the voltage across it is constant (VZ) and the current through diode is decided by the external resistance.
- Thus, Zener diode can be used as a voltage regulator in the configuration shown in fig. for regulating the dc voltage.
- It maintains the output voltage constant even through the current through it changes.



# Zener diode Voltage Regulator

- ✓ The simplest regulator circuit consists of a resistor Rs connected in series with the input voltage, and a Zener diode connected in parallel with the load.
- ✓ The voltage from an unregulated power supply is used as the input voltage $V_I$ to the regulator circuit.
- ✓ As long as the voltage across $R_L$ is less than the Zener breakdown voltage $V_Z$, the Zener diode does not conduct.

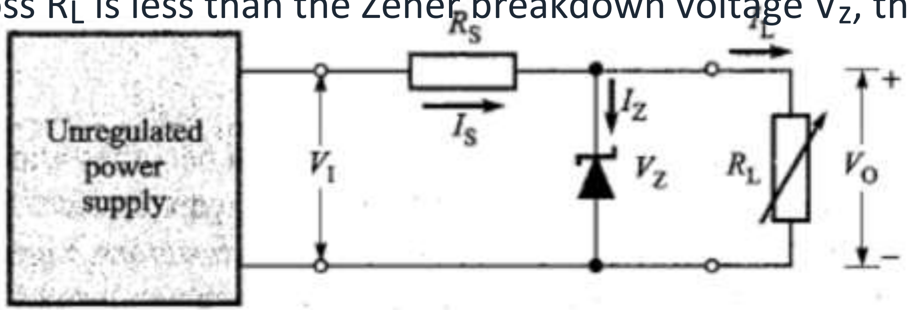



**Fig. 4.29** *The zener-diode voltage regulator*

# Contd.

✓ If the Zener diode does not conduct, the resistors $R_S$ and $R_L$ make a potential divider across $V_I$

✓ At an increased $V_I$, the voltage across $R_L$ becomes greater than the Zener breakdown voltage.

✓ It then operates in its breakdown region. The resistor Rs limits the zener current from exceeding its rate maximum $Iz_{max}$.

✓ The current from the unregulated power supply splits at the junction of the Zener diode and the load resistor.

✓ = +

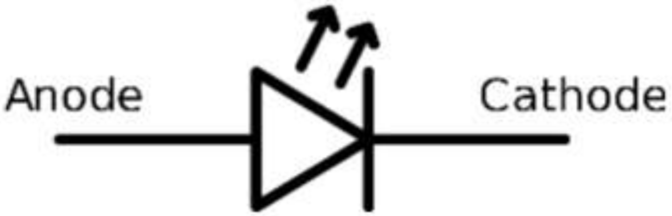
✓ When the Zener diode operates in breakdown region, the voltage Vz across it remains fairly constant even though the current Iz flowing through it may vary considerably.

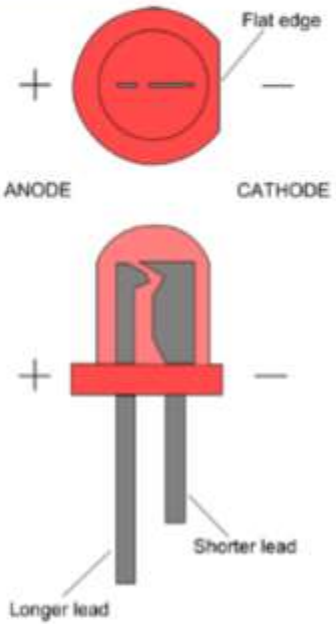
# Contd.

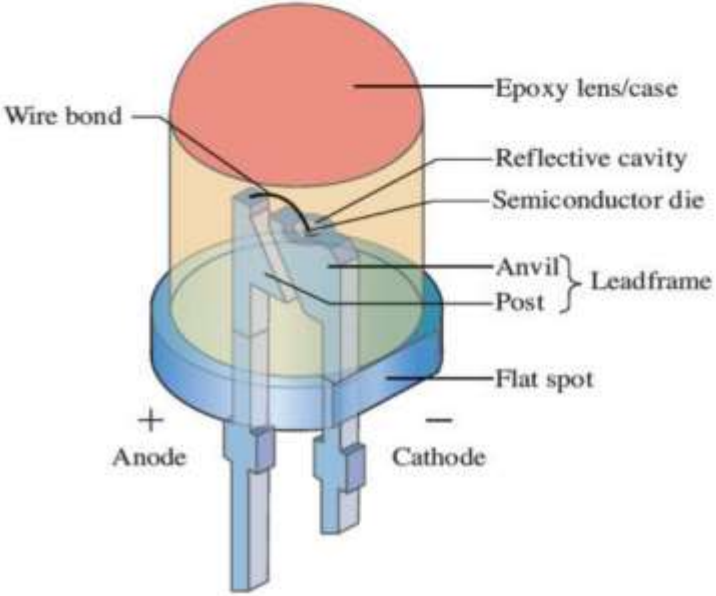
- ✓ If the load current $I_L$ should increase (because of the reduction in load resistance), the current $I_Z$ through the Zener diode falls by the same percentage in order to maintain constant current $I_S$.
- ✓ This keeps the voltage group across $R_s$ constant. Hence, the output voltage $V_O$ remains constant.
- ✓ If, on the other hand, the load current should decrease, the Zener diode passes an extra current Iz such that the current Is is kept constant.
- ✓ The output voltage of the circuit is thus stabilised.

# Light Emitting Diode (LED)

- ✓ In a forward biased LED, free electrons cross the junction and fall into holes.
- ✓ As these electrons fall from a higher to lower energy level, they radiate energy.
- ✓ In an ordinary diode, the radiated energy is in the form of heat.
- ✓ In the light-emitting diode (LED), the radiated energy is in the form of **light** (or photons).




✓ A light-emitting diode (LED) is a semiconductor light source that emits light when current flows through it.

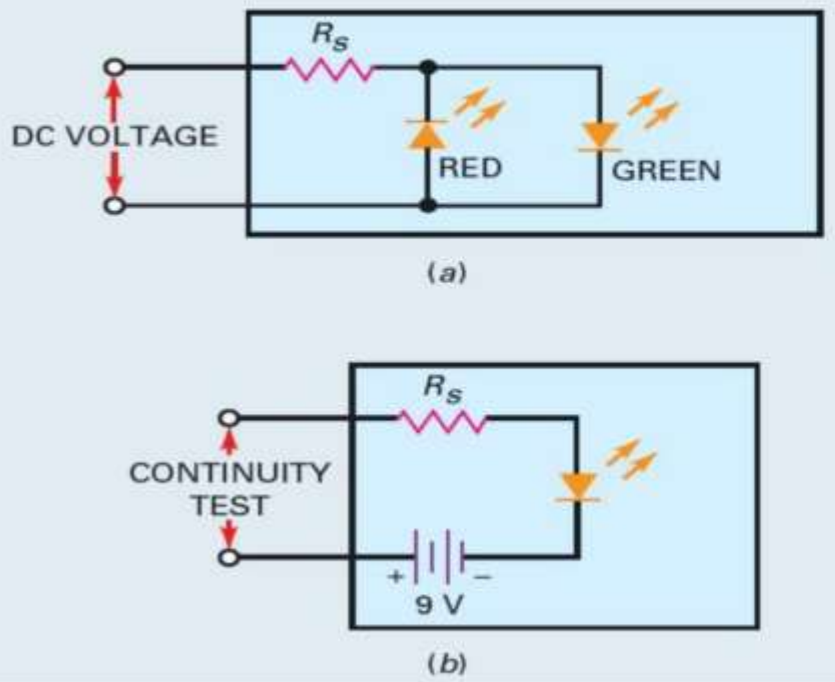
✓ The length of the anode terminal is deliberately made longer than the cathode terminal for identification.

# Contd.

- ✓ Germanium and silicon diodes have less probabilities of radiating light.
- ✓ By using materials such as gallium arsenide phosphide (GaAsP) and gallium phosphide (GaP), a manufacturer can produce LEDs that radiate red, green or orange lights.
- ✓ **Applications**: Instrument displays, panel indicators, digital watches, calculators, multi-meters, intercoms, telephone switch boards, etc.
- ✓ **Advantages:** They work on low voltages (1 or 2 V) and currents (5 to I0 mA) and thus consume less power. They require no heating, no warm-up time, and hence are very fast in action. They are small in size and light in weight. They are not affected by mechanical vibrations and have long life (more than 20 years).

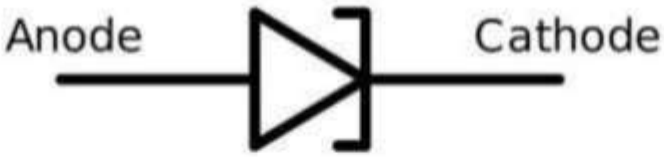
# LED Applications

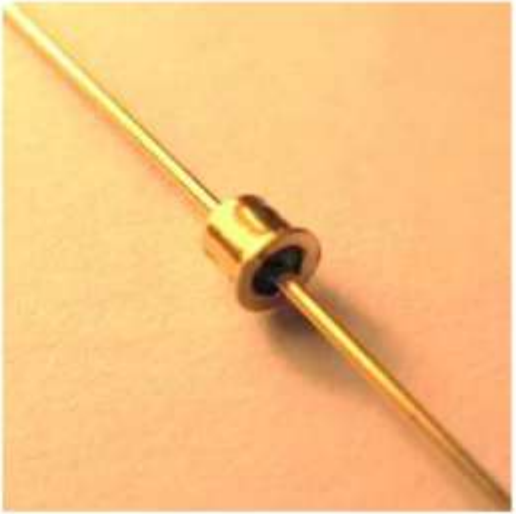
(a) Polarity indicator; (b) continuity tester.



# Tunnel Diode

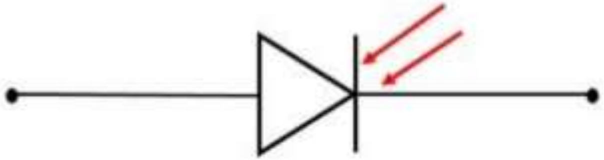
- ✓ A tunnel diode (also known as a Esaki diode) is a type of semiconductor diode that has effectively "negative resistance" due to the quantum mechanical effect called tunneling.
- ✓ Tunnel diodes have a heavily doped PN junction that is about 10 nm wide.
- ✓ The heavy doping results in a broken band gap, where conduction band electron states on the N-side are more or less aligned with valence band hole states on the P-side.



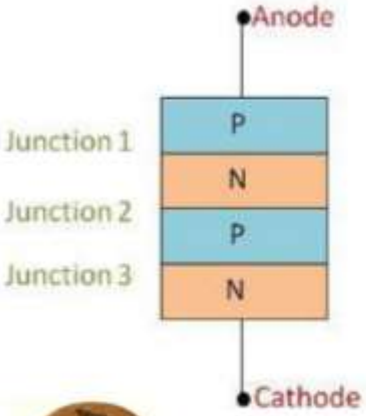
# Photo Diode

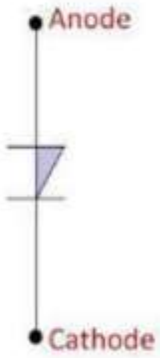
- ✓ A photodiode is a semiconductor device that converts light into an electrical current.
- ✓ The current is generated when photons are absorbed in the photodiode.
- ✓ Photodiodes may contain optical filters, built-in lenses, and may have large or small surface areas.



# Shockley Diode

- ✓ It is a four-layer semiconductor diode.
- ✓ It is a PNPN diode, with alternating layers of P-type and N-type material.
- ✓ It is equivalent to a thyristor with a disconnected gate.
- ✓ It is used mainly for switching applications.
- ✓ The two main important applications of shockley diode as relaxation oscillator and trigger switch are discussed below.




✓ The Shockley diode has a negative resistance characteristic.

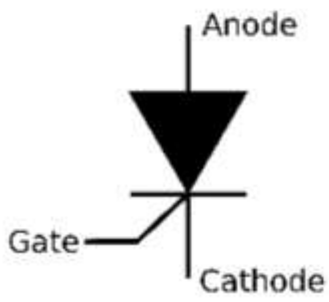
# SCR

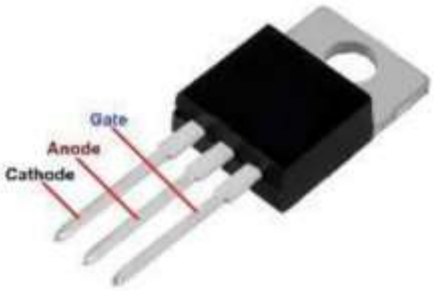
✓ A silicon controlled rectifier

✓ It is a four-layer solid-state current-controlling device.

✓ SCRs are unidirectional devices (i.e. can conduct current only in one direction) as opposed to TRIACs, which are bidirectional (i.e. charge carriers can flow through them in either direction).

✓ SCRs can be triggered normally only by a positive current going into the gate as opposed to TRIACs,



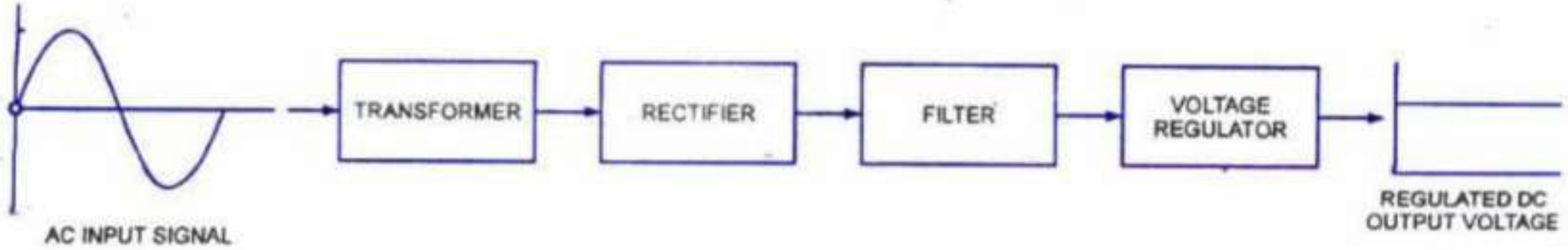



which can be triggered normally by either a positive or a negative current applied to its gate electrode.

# Rectifier

**TYPES OF RECTIFIER….**

- Half wave Rectifier
- Full wave Rectifier
- Bridge Rectifier




*Block Diagram of a DC Power Supply*

# Rectifiers

- ✓ Electric energy is available in homes and industries in India, in the form of alternating voltage.
- ✓ The supply has a voltage of 220 V (rms) at a frequency of 50 Hz.
- ✓ For the operation of most of the devices in electronic equipment's, a dc voltage is needed.
- ✓ A rectifier is an electrical device that converts alternating current (AC), which periodically reverses direction, to direct current (DC), which flows in only one direction.
- ✓ The reverse operation is performed by the inverter.

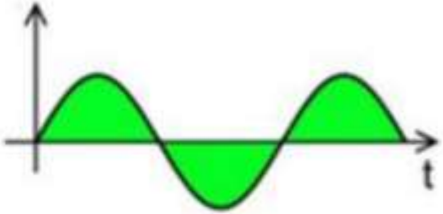
# Half Wave Rectifier

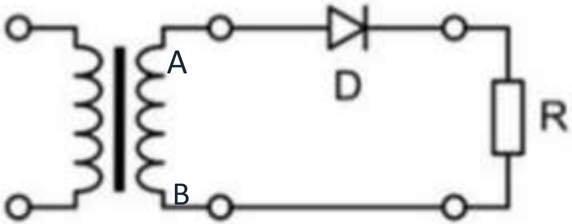
Most electronic equipment’s have a transformer at the input. It serves two purposes…. Firstly, it allows us to step the voltage down and secondly the transformer will provide isolation from the power line.

The primary of the transformer is connected to the power mains.

An AC voltage is induced across the secondary of the transformer.

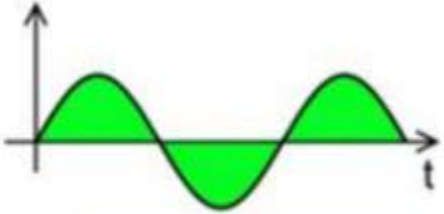
This voltage may be less than the primary voltage depending upon the turn’s ratio of the transformer. The voltage across the secondary … = $V = V_m sin\omega t$

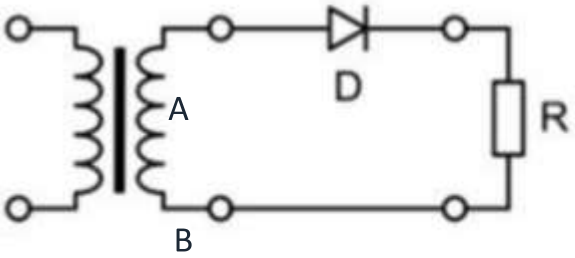


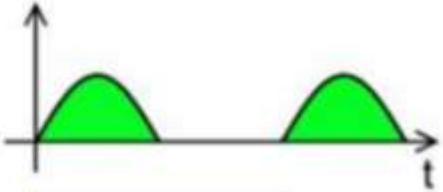



# Contd.

- ✓ In half-wave rectification of a single-phase supply, either the positive or negative half of the AC wave is passed, while the other half is blocked.
- ✓ Half-wave rectification requires a single diode.
- ✓ Rectifiers produce a unidirectional but pulsating direct current; half-wave rectifiers produce far more ripple than full-wave rectifiers, and much more filtering is needed to eliminate harmonics of the AC frequency from the output.




=

=

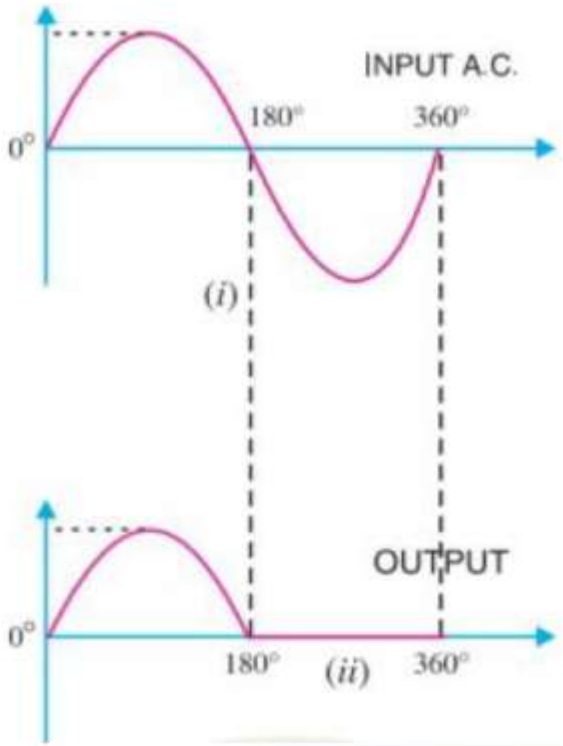
Where= Average output voltage

# Operation

- ✓ AC voltage across secondary terminals AB changes its polarity after each half cycle.
- ✓ During negative half cycle terminal A is negative so diode is reversed biased and conducts no current.
- ✓ So, current flows through diode during positive half cycle only.
- ✓ In this way current flows through load RL in one direction only.

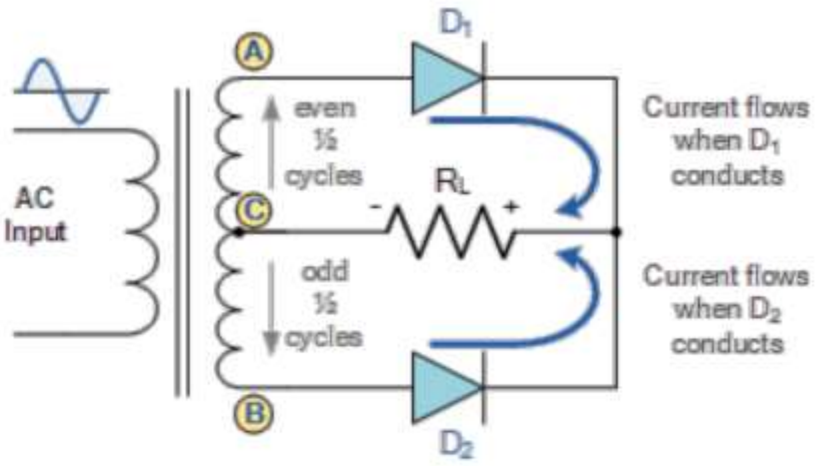
# Frequency of Half wave Rectifier

- ✓ Output frequency of Half wave rectifier is equal to input frequency.
- ✓ This means when input AC completes one cycle, rectified wave also completes once cycle.
- ✓ =



# Full Wave Rectifier

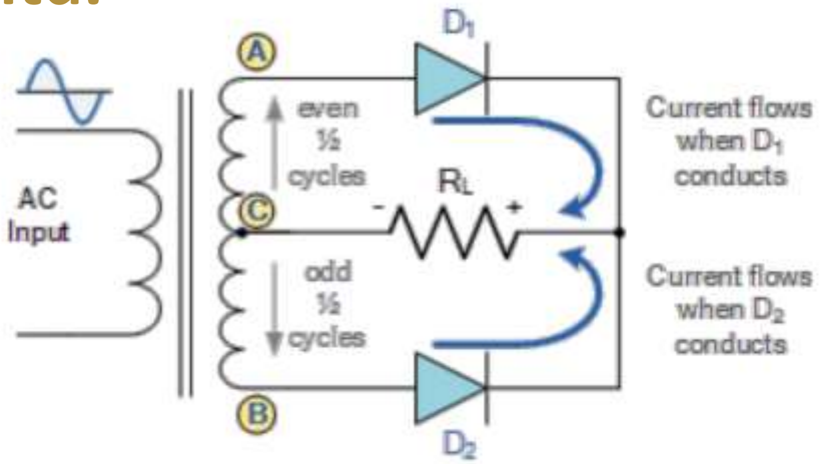
- ✓ In a half wave rectifier, we utilize only one half cycle of the input wave.
- ✓ In a full wave rectifier we utilize both the half cycles.
- ✓ Alternate half cycles are inverted to give a unidirectional load current.
- ✓ For single-phase AC, if the transformer is center-tapped, then two diodes back-to-back (i.e. anodes-to-anode or cathode-to-cathode) can form a full-wave rectifier.

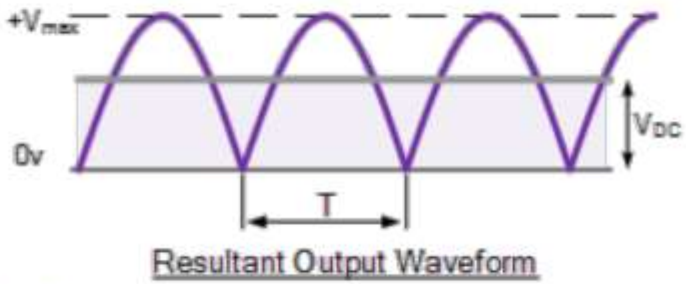


# Contd.

- ✓ When point A of the transformer is positive with respect to point C, diode $D_1$ conducts in the forward direction as indicated by the arrows.
- ✓ When point B is positive (in the negative half of the cycle) with respect to point C, diode $D_2$ conducts in the forward direction and the current flowing through resistor R is in the same direction for both half-cycles.

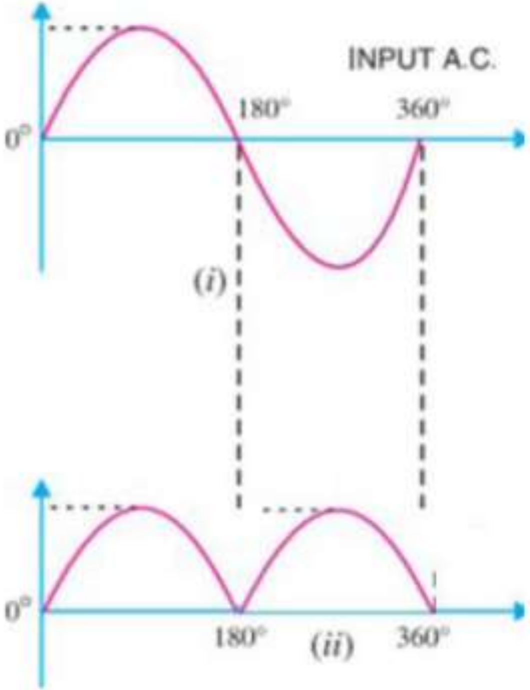
$= 2 \times$



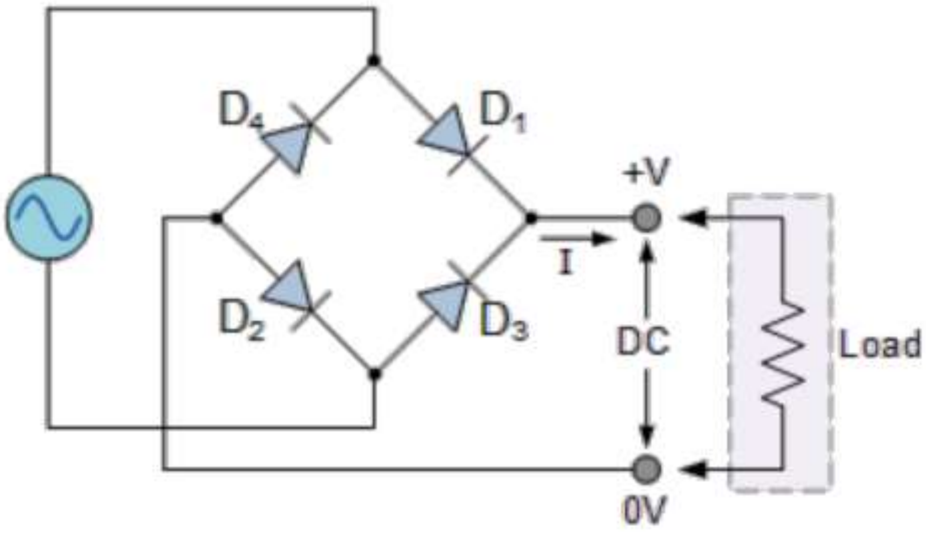
# Frequency of Full wave Rectifier

- ✓ Output frequency of Full wave rectifier is equal to double of input frequency.
- ✓ This means when input AC completes one cycle, rectified wave completes two cycle.
- ✓ = 2

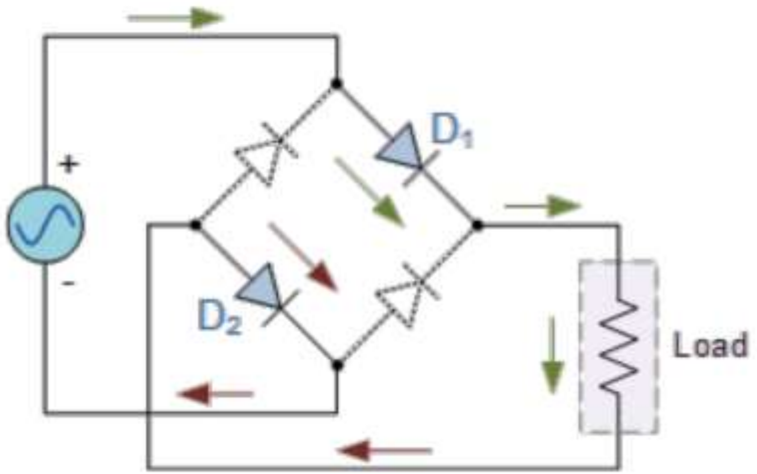


# Bridge Rectifier

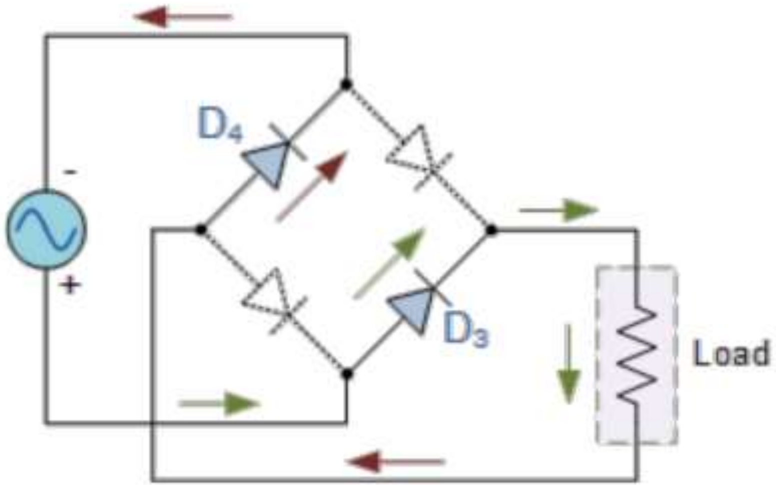
- ✓ The main advantage of this bridge circuit is that it does not require a special centre tapped transformer, thereby reducing its size and cost.
- ✓ The four diodes labelled $D_1$ to $D_4$ are arranged in “series pairs” with only two diodes conducting current during each half cycle.
- ✓ During the positive half cycle of the supply, diodes $D_1$ and $D_2$ conduct in series while diodes $D_3$ and $D_4$ are reverse biased.



## Positive Half cycle




## Negative Half cycle

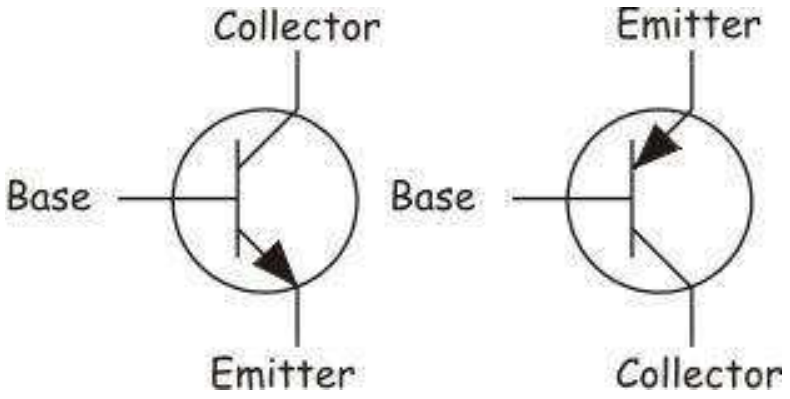


# Advantage and Disadvantage of Bridge Rectifier

- ✓ Bridge rectifier has many advantages over a centre tap rectifier. It does not require centre tapped secondary winding. Bridge rectifier is useful when higher dc voltages are required.

- ✓ The main disadvantage of a bridge rectifier is that it requires four diodes, two of which conduct on alternate half cycles. This creates a problem when low dc voltages are required because two diode voltage drops (1.4 V in case of Si diodes). For this reason, in low voltage applications we prefer the centre tap rectifier which has only one diode drop (= 0.7 V).

# Transistor




**NPN Transistor**

**PNP Transistor**

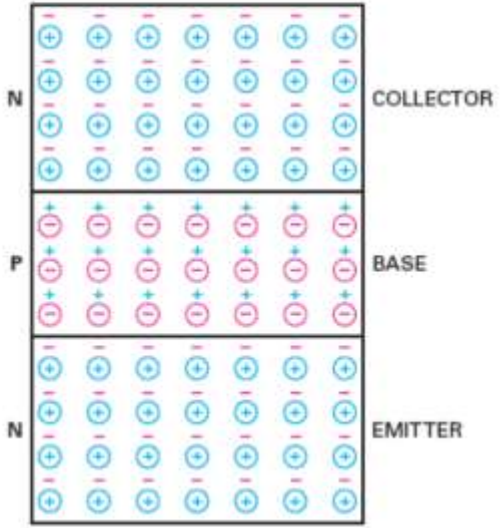
# Transistor Introduction

- ✓ In 1951, William Shockley invented the first junction transistor
- ✓ A semiconductor device that can **amplify (enlarge) electronic signals** such as radio and television signals.
- ✓ The transistor has led to many other semiconductor inventions, including the **Integrated Circuit (IC)**, a small device that contains thousands of miniaturized transistors.
- ✓ Because of the IC, modern computers and other electronic miracles are possible.

# Bipolar Junction Transistor

- ✓ It has three doped region: **Emitter, Base and Collector**
- ✓ In an actual transistor, the base region is much thinner as compared to the collector and emitter regions
- ✓ An NPN device: There is a P region between two N regions
- ✓ The **emitter is heavily doped**
- ✓ The **base is lightly doped**
- ✓ The doping level of the collector is intermediate, between the heavy doping of the emitter and the light doping of the base.

**Figure 6-1** Structure of a transistor.

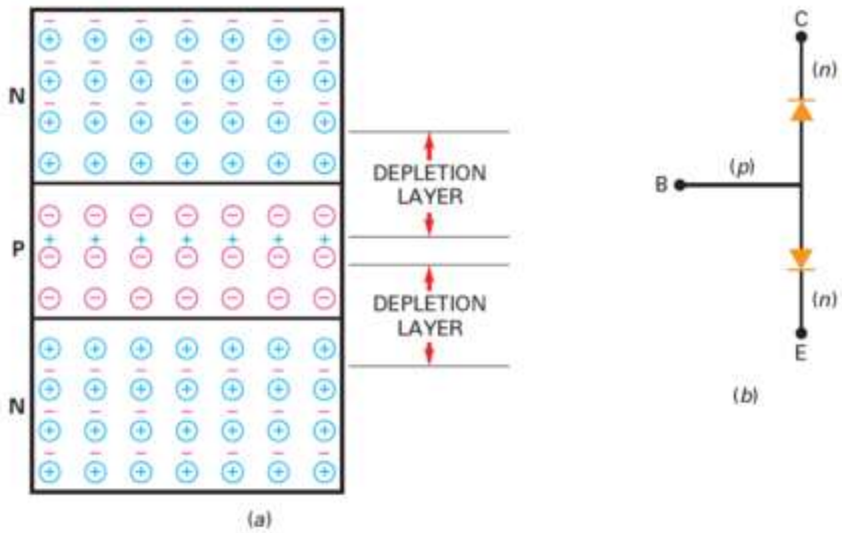


✓ The collector is physically the **largest** of the three regions.

# Unbiased Transistor

- ✓ The transistor of Fig. 6-1 has **two junctions**: one between the emitter and the base, and another between the collector and the base.
- ✓ Because of this, a transistor is like two back-to-back diodes.
- ✓ The lower diode is called the emitter-base diode, or simply the **emitter diode.**
- ✓ The upper diode is called the collector-base diode, or the **collector diode.**

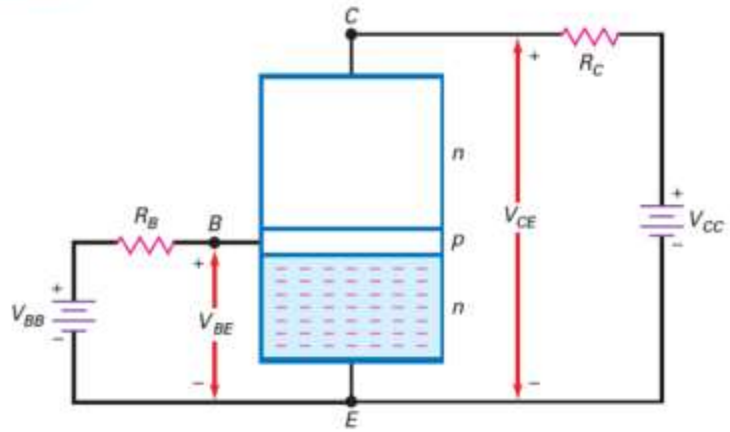
**Figure 6-2** Unbiased transistor. (a) Depletion layers; (b) diode equivalent.



# Biased Transistor

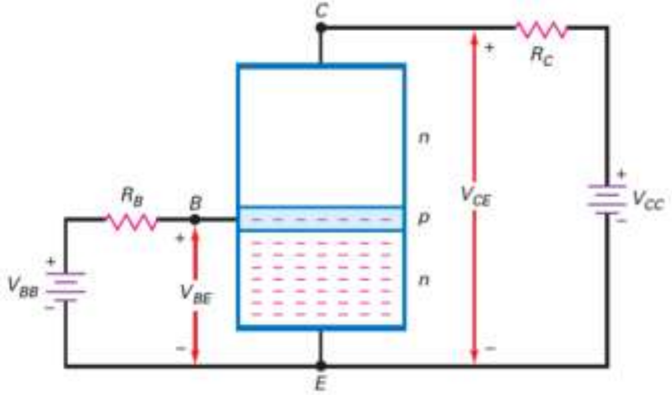
- ✓ Figure 6-3 is the usual way to bias a transistor.
- ✓ The left source $V_{BB}$ forward-biases the emitter diode, and the right source $V_{CC}$ reverse-biases the collector diode.
- ✓ Although other biasing methods are possible, but this produce the most useful results.
- ✓ If $V_{BB}$ is greater than the emitter-base barrier potential in Fig. 6-3, emitter electrons will enter the base region, as shown in Fig. 6-4.
- ✓ The base is lightly doped and very thin.

**Figure 6-3** Biased transistor.



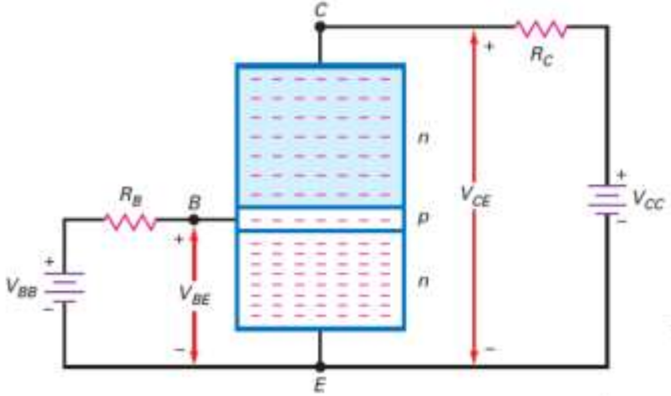
✓ So only a few free electrons will recombine with holes in the lightly doped base.

Figure 6-4 Emitter injects free electrons into base.




- Almost all the free electrons go into the collector, as shown in Fig. 6-5.
- Once they are in the collector, they feel the attraction of the $V_{CC}$ source voltage.
- Because of this, the free electrons flow through the collector and through $R_C$ until they reach the positive terminal of the collector supply voltage.

Figure 6-5 Free electrons from base flow into collector.

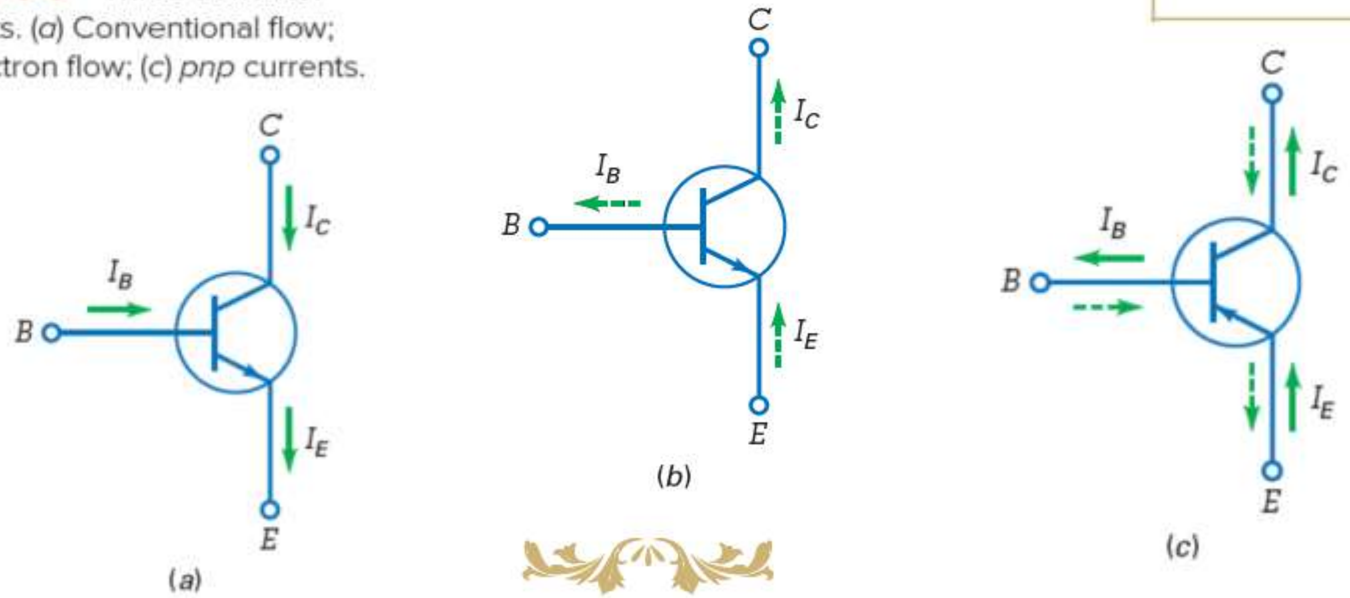


# Transistor Currents

= +

≈

**Figure 6-6** Three transistor currents. (*a*) Conventional flow; (*b*) electron flow; (*c*) *pnp* currents.



## Alpha

- ✓ The dc alpha (symbolized ) is defined as the dc collector current divided by the dc emitter current:
- ✓ — =
- ✓ Since the collector current almost equals the emitter current, the dc alpha is slightly less than 1.

## Beta

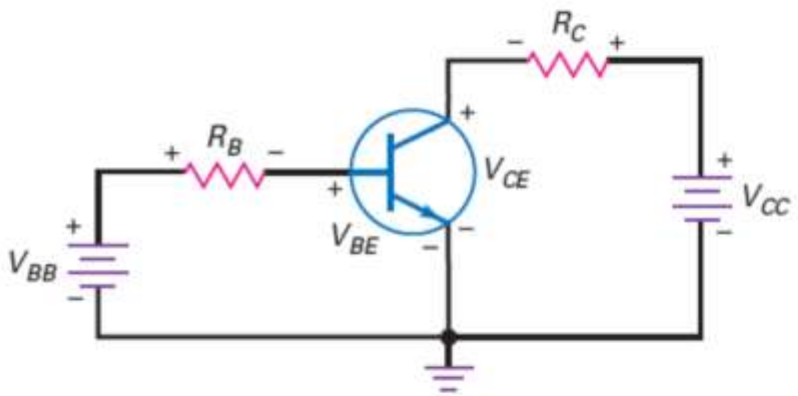
- ✓ The dc beta (symbolized ) of a transistor is defined as the ratio of the dc collector current to the dc base current:
- ✓ — =
- ✓ The dc beta is also known as the current gain be cause a small base current controls a much larger collector current.

# Transistor Configurations

- ✓ A transistor can be operated in Common Base (CB), Common Emitter (CE) or Common Collector (CC) configurations.
- ✓ A transistor can be used as an amplifier in any one of the three configurations. Any of its three electrodes can be made common to input and output. In all the configurations, the emitter-base junction is always forward-biased and the collector-base junction is always reverse-biased.
- ✓ When the load resistance is small compared to the collector resistance, the voltage gain of a CE stage becomes small and the amplifier may become overloaded. One way to prevent overloading is to use a common-collector (CC) amplifier or emitter follower. This type of amplifier has a large input impedance and can drive small load resistances.

# The Common Emitter (CE) Configuration

- ✓ The common side of each voltage source is connected to the emitter. Because of this, the circuit is called a common emitter (CE) connection.
- ✓ The circuit has two loops.
- ✓ The left loop is the **base loop**, and the right loop is the **collector loop.**



# Contd.

- ✓ In the base loop, the $V_{BB}$ source forward-biases the emitter diode with $R_B$ as a current-limiting resistance.
- ✓ By changing $V_{BB}$ or $R_B$, we can change the base current.
- ✓ Changing the base current will change the collector current.
- ✓ In other words, the base current controls the collector current.
- ✓ This is important. It means that a small current (base) controls a large current (collector).

✓ In the collector loop, a source voltage $V_{CC}$ reverse-biases the collector diode through $R_C$.

# Transistor Characteristics

## The Base curve:

✓ It looks like the graph of an ordinary diode.

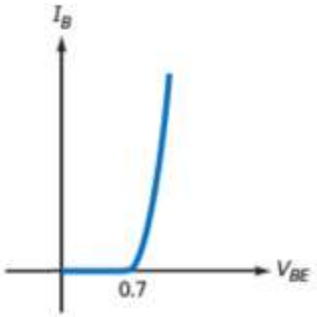
✓ Applying Ohm's law to the base resistor…

✓=⁻

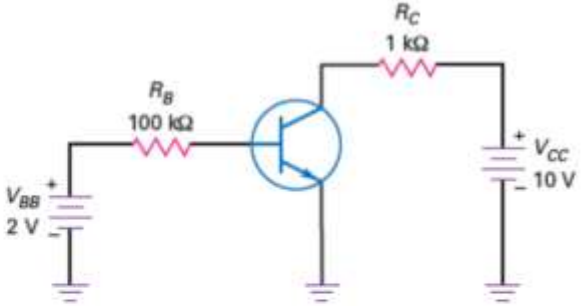
✓ If you use an ideal diode, = 0

✓ With the second approximation

= 0.7



(a)



(b)

# Example

Use the second approximation to calculate the base current in Fig. 6-8*b*. What is the voltage across the base resistor? The collector current if $\beta_{dc} = 200$?

**SOLUTION** The base source voltage of 2 V forward-biases the emitter diode through a current-limiting resistance of 100 kΩ. Since the emitter diode has 0.7 V across it, the voltage across the base resistor is:

$$V_{BB} - V_{BE} = 2\text{ V} - 0.7\text{ V} = 1.3\text{ V}$$

The current through the base resistor is:

$$I_B = \frac{V_{BB} - V_{BE}}{R_B} = \frac{1.3\text{V}}{100\text{ k}\Omega} = 13\ \mu\text{A}$$

With a current gain of 200, the collector current is:

$$I_C = \beta_{dc} I_B = (200)(13\ \mu\text{A}) = 2.6\text{ mA}$$

# Transistor Characteristics – Contd.

✓ **The Collector curve:**

✓ We can vary $V_{BB}$ and $V_{CC}$ in Fig. 6-9a to produce different transistor voltages and currents.

✓ By measuring $I_C$ and $V_{CE}$, we can get data for a graph of $I_C$ versus $V_{CE}$.

✓ For instance, suppose we change $V_{BB}$ as needed to get $I_B$ =10 A.

✓ With this fixed value of base current, we can now vary $V_{CC}$ and measure $I_C$ and $V_{CE}$.

✓ Plotting the data gives the graph shown in Fig. 6-9b.

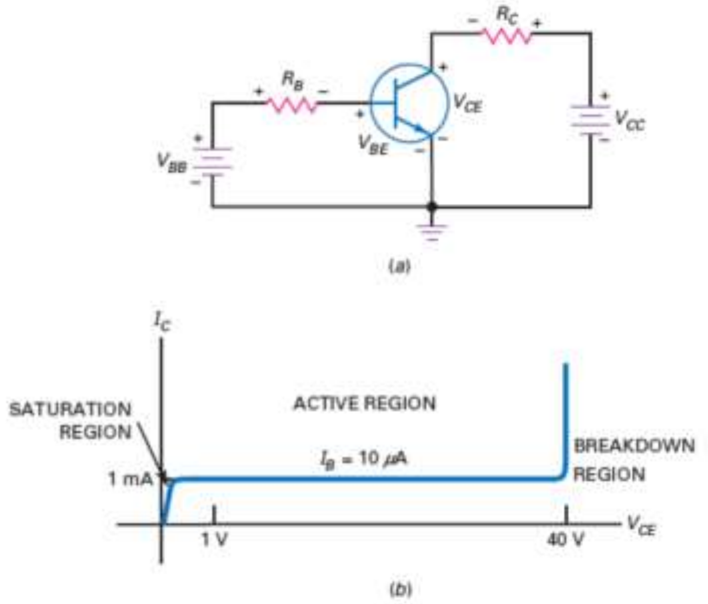
✓ When $V_{CE}$ is zero, the collector diode is not reverse biased.

✓ This is why the graph shows a collector current of zero when $V_{CE}$ is zero.

# Contd.

- When $V_{CE}$ increases from zero, the collector current rises sharply in Fig. (b).
- When $V_{CE}$ is a few tenths of a volt, the collector current becomes almost constant and equal to 1 mA.
- If $V_{CE}$ is greater than 40 V, the collector diode breaks down and normal transistor action is lost.

**Figure 6-9** (a) Basic transistor circuit; (b) collector curve.



# Regions of Operation

- ✓ The curve of Fig. 6-9b has different regions where the action of a transistor changes.
- ✓ **First,** there is the region in the middle where $V_{CE}$ is between 1 and 40 V.
- ✓ This represents the normal operation of a transistor.
- ✓ In this region, the emitter diode is forward biased, and the collector diode is reverse biased.
- ✓ Furthermore, the collector is gathering almost all the electrons that the emitter has sent into the base.
- ✓ This is why changes in collector voltage have no effect on the collector current.
- ✓ This region is called the **Active region**.

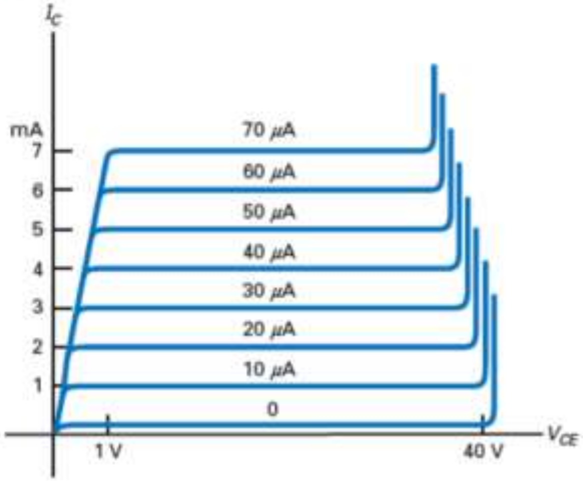
- ✓ Graphically, the active region is the horizontal part of the curve.
- ✓ In other words, the collector current is constant in this region.

# Contd.

- ✓ **Second** region of operation is the **Breakdown region**.
- ✓ The transistor should never operate in this region because it will be destroyed.
- ✓ Unlike the Zener diode, which is optimized for breakdown operation, a transistor is not intended for operation in the breakdown region.
- ✓ **Third,** there is the early rising part of the curve, where $V_{CE}$ is between 0 V and a few tenths of a volt.
- ✓ This sloping part of the curve is called the **Saturation region**.

✓ In this region, the collector diode has insufficient positive voltage to collect all the free electrons injected into the base.

Figure 6-10 Set of collector curves.




- ✓ Figure 6-10 has an unexpected curve, the one on the bottom.
- ✓ This represents a **fourth** possible region of operation.
- ✓ Notice that the base current is zero, but there still is a small collector current. On a curve tracer, this current is usually so small that you cannot see it.
- ✓ We have exaggerated the bottom curve by drawing it larger than usual.
- ✓ This bottom curve is called the **Cut-off region** of the transistor, and the small

collector current is called the collector cut-off current.

# Different Biasing Methods

**Table 5.1** *Four ways of biasing a junction transistor*

| *Condition* | | *Emitter junction* | *Collector junction* | *Region of operation* |
|---|---|---|---|---|
| I. | FR | Forward biased | Reverse biased | Active |
| II. | FF | Forward biased | Forward biased | Saturation |
| III. | RR | Reverse biased | Reverse biased | Cutoff |
| IV. | RF | Reverse biased | Forward biased | Inverted |

- ✓ Transistors operate in the **active region** when they are used to **amplify** weak signals.
- ✓ The **saturation and cut-off regions** are useful in digital and computer circuits, referred to as **switching circuits**.

# Transistor Amplifying Action

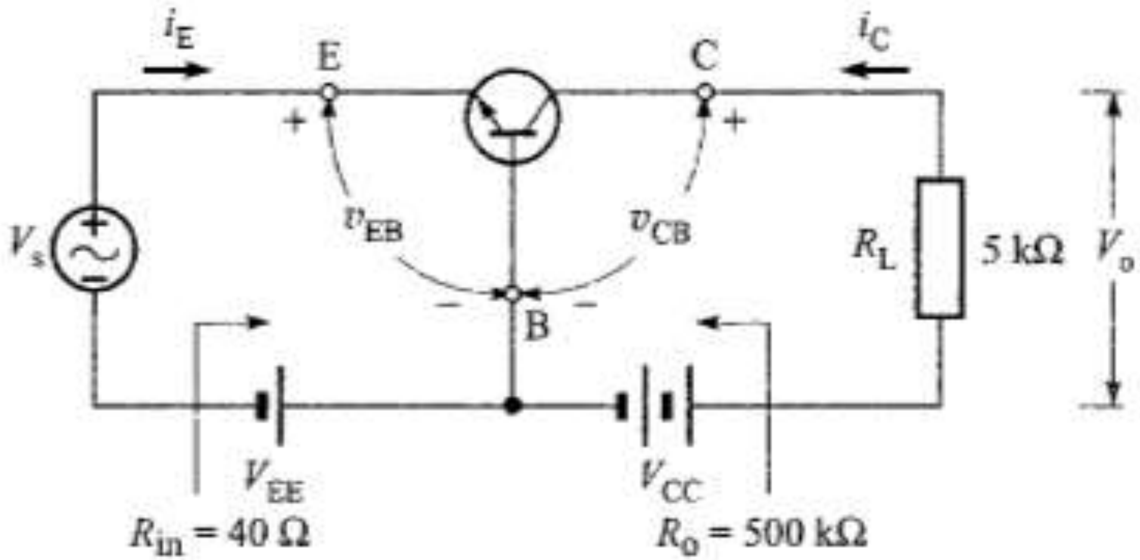



**Fig. 5.8** *A basic transistor amplifier in common-base configuration*

# Contd.

- ✓ Emitter-base junction is forward biased, it offers very low impedance to the signal source Vs.
- ✓ In the CB configuration, the input resistance typically varies from 20 to 100
  .
- ✓ The output junction (collector-base junction) being reverse-biased, offers high resistance.
- ✓ Typically, the output resistance may vary from 100 k to 1 M .
- ✓ Assume that the input signal voltage is 20 mV.
- ✓ Using an average value of 40 for the input resistance, we get the effective

value of the emitter current variation as … ✓ $= 20 \times 10_{-3} = 0.5$

40

✓ And $\approx$ $= 0.5$ mA

# Contd.

- Now, the output resistance of the transistor is very hight (say, 500 k ) and the load resistance is comparatively low (5 k )
- The output voltage is…

✓ $=$ $= (0.5 \times 10{-}3)\ 5 \times 103\ = 2.5$ ( )

- The ratio of the output voltage to the input voltage is known as the Voltage Gain ( )

✓ $=$ $=$ $2.5\ \ {-3} = 125$ $20 \times 10$

- The transistor's amplifying action is basically due to its capability of transferring its signal current from a low resistance circuit to high resistance circuit.

✓ Transfer + Resistor --> Transistor

# Field Effects Transistor (FET)

# Field Effect Transistor (FET)

✓ The primary difference between the two types of transistors is the fact that the **BJT transistor is a current-controlled device** while the **JFET transistor is a voltage-controlled device**

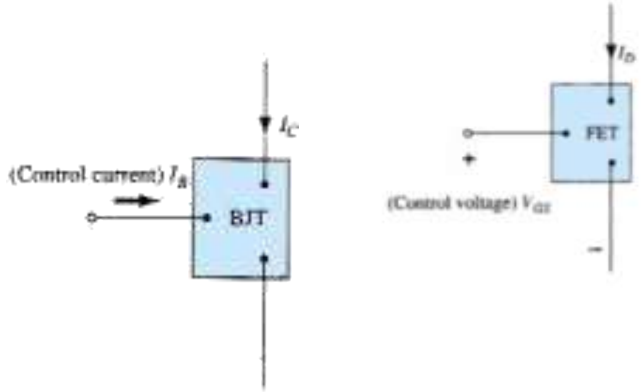




Figure 5.3 Water analogy for

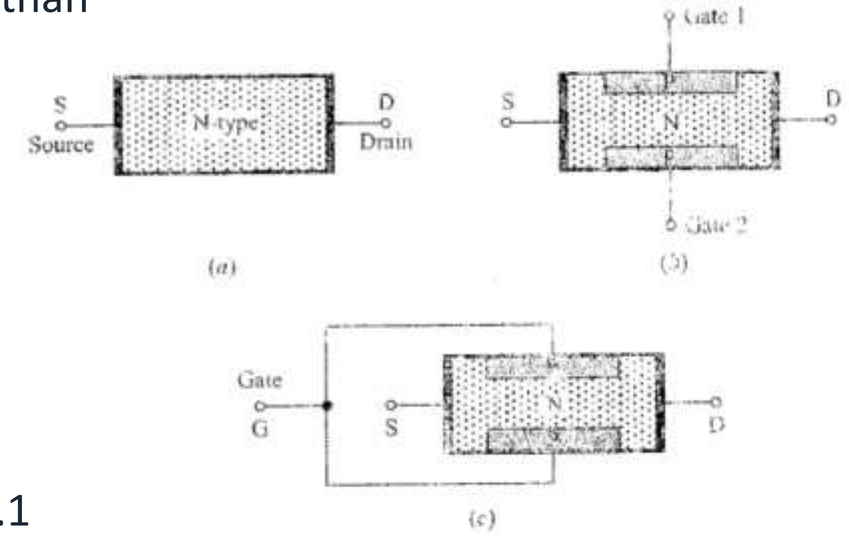
✓ The source of water pressure can be likened to the applied voltage from drain to source that will establish a flow of water (electrons) from the spigot (source).

✓ The "gate," through an applied signal (potential), controls the flow of water (charge) to the "drain."

the JFET control mechanism.

# N- Channel JFET

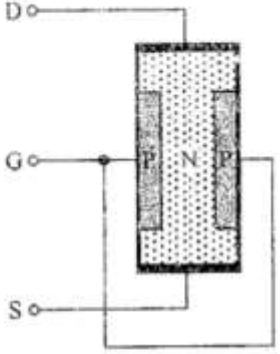
- ✓ In its simplest form, the structure of an N-channel JFET starts with nothing more than a bar of N-type silicon.
- ✓ This bar behaves like a resistor between its two terminals, called source and drain (Fig. 6.1 a).
- ✓ We introduce heavily doped P-type regions on either side of the bar.
- ✓ These P regions are called gates (Fig. 6.1 b).



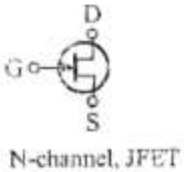
✓ Usually, the two gates are connected together (Fig. 6.1 c).

# Contd.

- ✓ The gate terminal is analogous to the base of a BJT.
- ✓ This is used to control the current flow from source to drain.
- ✓ Thus, source and drain terminals are analogous to emitter and collector terminals respectively, of a BJT.
- ✓ In Fig. 6.1 d, the bar of the JFET has been placed vertically.
- ✓ The circuit symbol of N-channel JFET is shown in Fig. 6. 1 e.



(d)

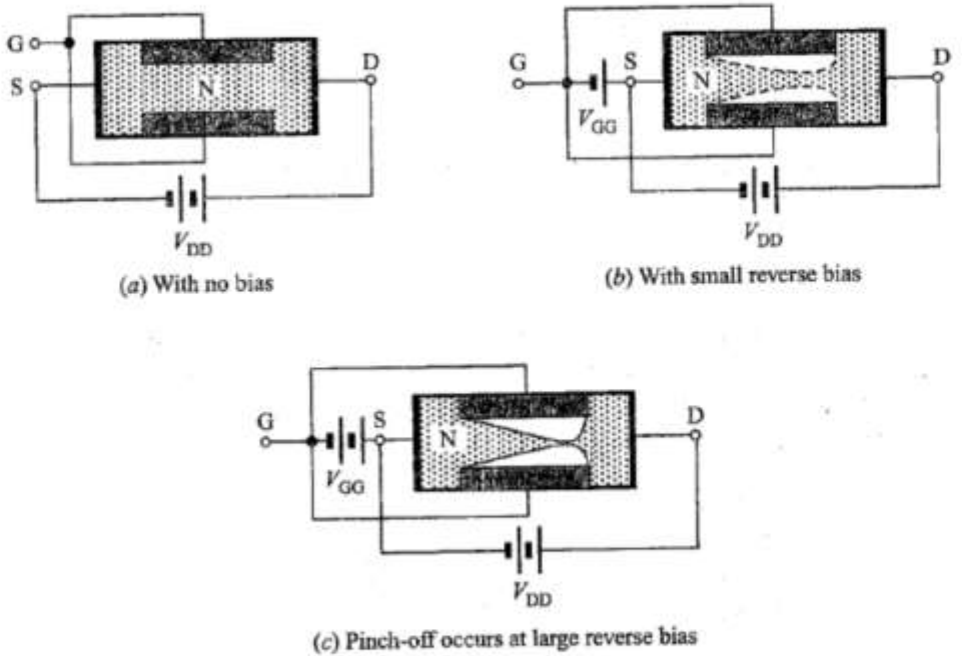


(e)

- ✓ Note that the arrow is put in the gate terminal.

# Effect of Gate-Source Voltage on the channel

- ✓ Normally, we operate an N-channel JFET by applying positive voltage to the drain with respect to the source (Fig. 6.2a).
- ✓ Due to this voltage, the majority carriers in the bar (electrons in this case) start flowing from the source to the drain.
- ✓ This flow of electrons makes the drain current $I_D$.



# Contd.

✓ The electrons in the bar have to pass through the space between the two P regions. As we shall see, the width of this space between the P regions can be controlled by varying the gate voltage. That is why this space is called a channel.

✓ To see how the width of the channel changes by varying the gate voltage, let us consider Fig. 6.2b. Here we have applied a small reverse bias to the gate. Because of the reverse bias, the width of the depletion increases.

✓ Since the N-type bar is lightly doped compared to the P regions, the depletion region extends more into the N-type bar. This reduces the width of the channel.

# Contd.

- ✓ The electrons have to pass through the channel of reduced width. Reduction in the width of the channel (the conductive portion of the bar) increases its resistance. This reduces the drain current $I_D$
- ✓ The width of the depletion region is more at the drain end than at the source end. As a result, the channel becomes narrower at the drain end.
- ✓ Let us see what happens if the reverse gate-bias is increased further.
- ✓ The channel becomes narrower at the drain end and the drain current further reduces. If the reverse bias is made sufficiently large, the depletion regions tends to extend into the channel and meet. This pinches off the current flow (Fig. 6.2c). The gate-source voltage at which pinch-off occurs is called pinch-off voltage Vp.

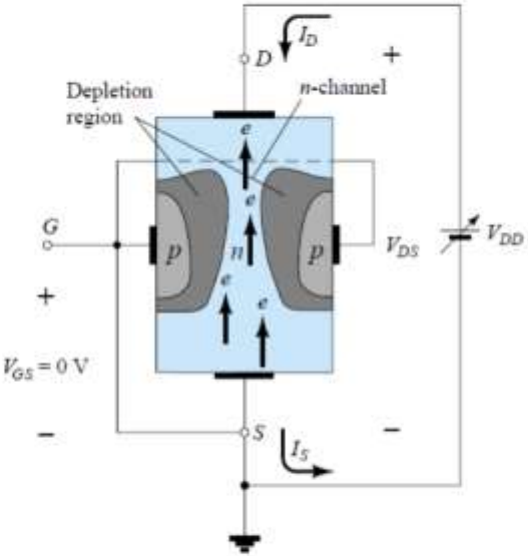



**Figure 5.4** JFET in the $V_{GS} = 0$ V and $V_{DS} > 0$ V.

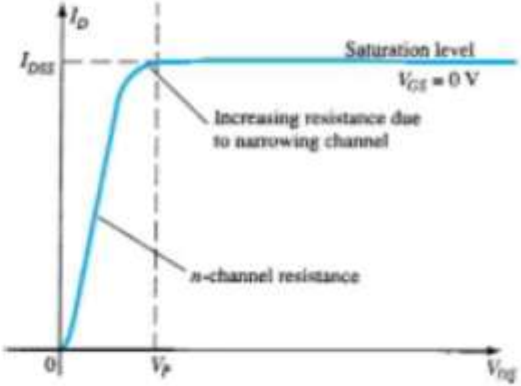



**Figure 5.6** $I_D$ versus $V_{DS}$ for $V_{GS} = 0$ V.

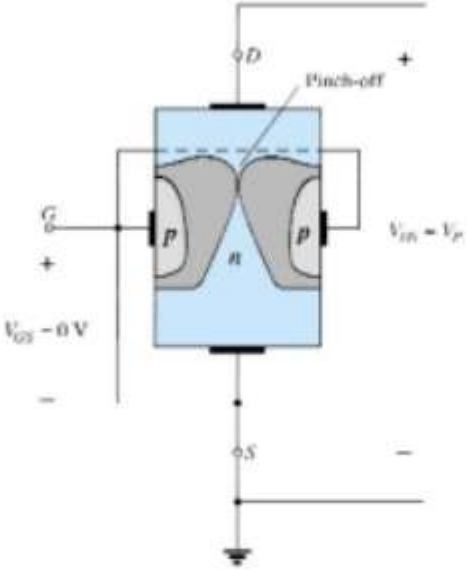



**Figure 5.7** Pinch-off ($V_{GS} = 0$ V, $V_{DS} = V_P$).

# N – Channel JFET characteristics

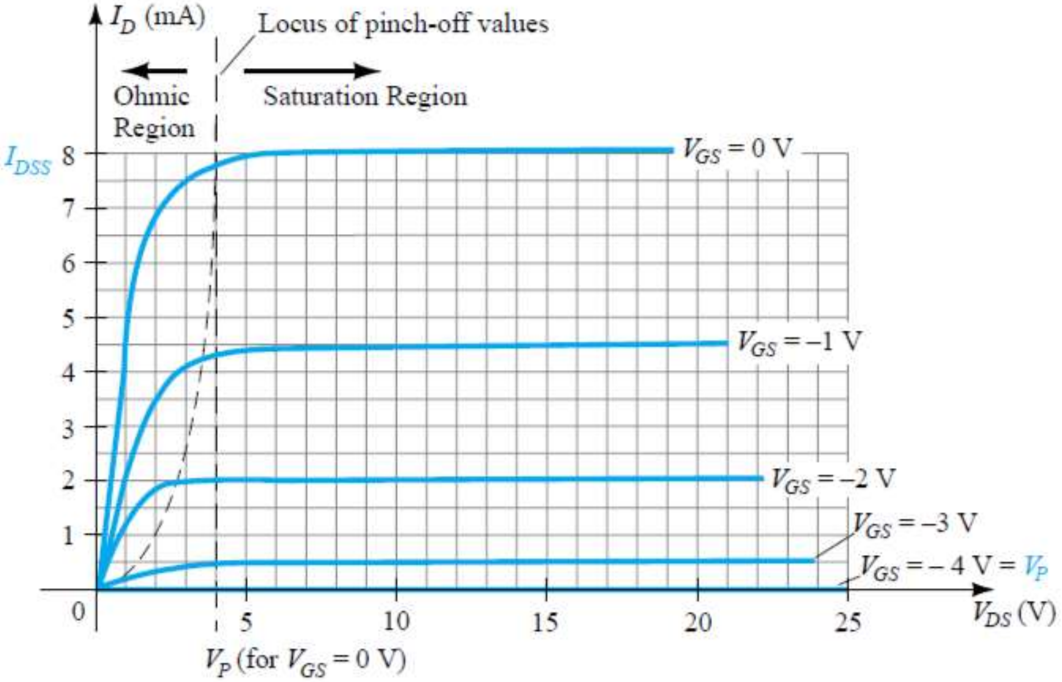



**Figure 5.10** *n*-Channel JFET characteristics with $I_{DSS} = 8$ mA and $V_P = -4$ V.

# Contd.

- ✓ Let us consider first, the curve for zero gate bias.
- ✓ For this curve, $V_{GS} = 0$. When $V_{DS}$ is zero, the channel is entirely open.
- ✓ But the drain current is zero, because the drain terminal does not have any attractive force for the majority carriers.
- ✓ For small applied voltage $V_{DS}$, the bar acts as a simple resistor.
- ✓ Current $I_D$ increases linearly with voltage $V_{DS}$

- ✓ This region (to the left of point $V_P$) of the curve is called ohmic region, because the bar acts as an ohmic resistor.

# Contd.

- ✓ Ohmic voltage drop is caused in the bar due to the flow of current $I_D$ .
- ✓ This voltage drop along the length of the channel reverse biases the gate junction.
- ✓ The reserve biasing of the gate junction is not uniform throughout.
- ✓ The reverse bias is more at the drain end than at the source end of the channel.
- ✓ So, as we start increasing $V_{DS}$, the channel starts constricting more at the drain end.

✓ The channel is eventually pinched off.

# Contd.

- ✓ The current $I_D$ no longer increases with the increase in $V_{DS}$
- ✓ It approaches a constant saturation value.
- ✓ The voltage $V_{DS}$ at which the channel is "pinched off" (that is, all the free charges from the channel are removed), is called **pinch-off voltage, Vp**.
- ✓ A special significance is attached to the drain current in the pinch-off region when $V_{GS} = 0$. It is given the symbol $I_{DSS}$
- ✓ It signifies the drain source current at pinch-off, when the gate is shorted to the source.

✓ Further increase in voltage $V_{DS}$ increases the reverse bias across the gate junction.

# Contd.

- ✓ Eventually, at high $V_{DS}$ breakdown of the gate junction occurs. The drain current $I_D$ shoots to a high value.
- ✓ Of course, when we use a JFET in a circuit, we avoid the gate junction breakdown.
- ✓ If the gate reverse bias is increased (say, $V_{GS}$ = - 1 V), the curve shifts downward.
- ✓ The pinch-off occurs for smaller value of $V_{DS}$

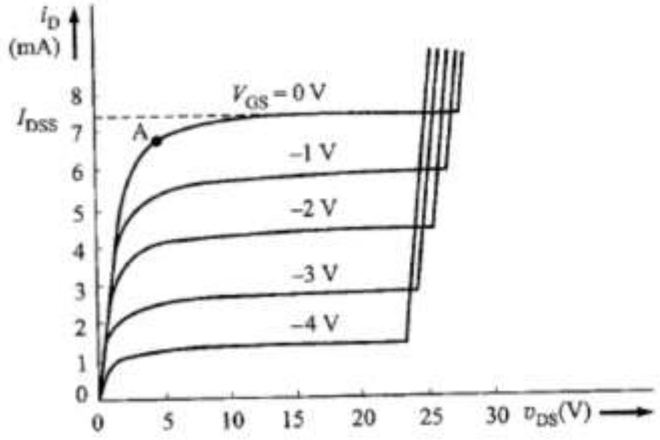



**Fig. 6.3** *Typical drain characteristics of an N-channel JFET*

✓ The maximum saturation drain current is also smaller, because the conducting channel now becomes narrower.

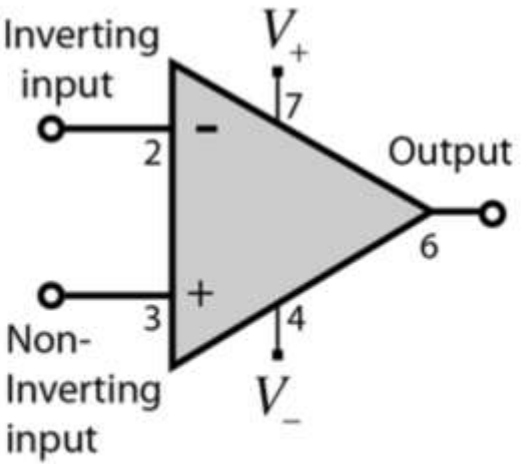
# Some important terminology regarding a JFET:

1. **Source:** The source is the terminal through which the majority carriers (electrons in case of N-channel JFET, and holes in case of P-channel JFET) enter the bar.
2. **Drain:** The drain is the terminal through which the majority carriers leave the bar.
3. **Gate:** On both sides of the N-type bar, heavily doped P regions are formed. These regions are called gates. Usually, the two gates are joined together to form a single gate.
4. **Channel:** The region between the source and drain, sandwiched between the two gates, is called channel. The majority carriers move from source to drain through this channel.

# Operational Amplifiers

# Introduction of Op – Amp

- ✓ Voltage amplifying device
- ✓ An Operational Amplifier is basically a three-terminal device which consists of two high impedance inputs.
- ✓ One of the inputs is called the **Inverting Input**, marked with a negative or "minus" sign, ( – ).
- ✓ The other input is called the **Non-inverting Input**, marked with a positive or "plus" sign ( + ).
- ✓ A third terminal represents the operational amplifiers **output.**



✓ The output voltage signal is the difference between the signals being applied to its two individual inputs.

# Equivalent circuit of an Op – Amp

- ✓ The output voltage is
  $= \quad = (2 - 1)$
- ✓ Where A = Large signal voltage gain
- ✓ $V_{id}$ = Difference input voltage
- ✓ $V_1$ = Voltage at the Inverting input terminal w.r.t. ground
- ✓ $V_2$= Voltage at the Non-inverting input terminal w.r.t. ground

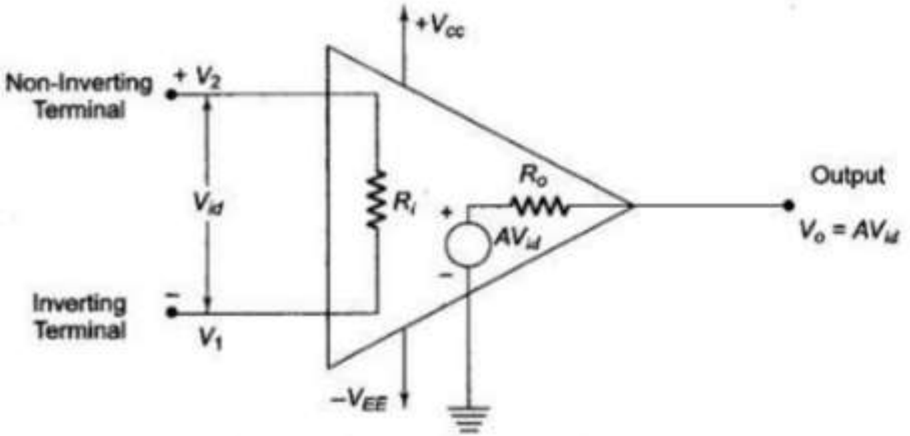
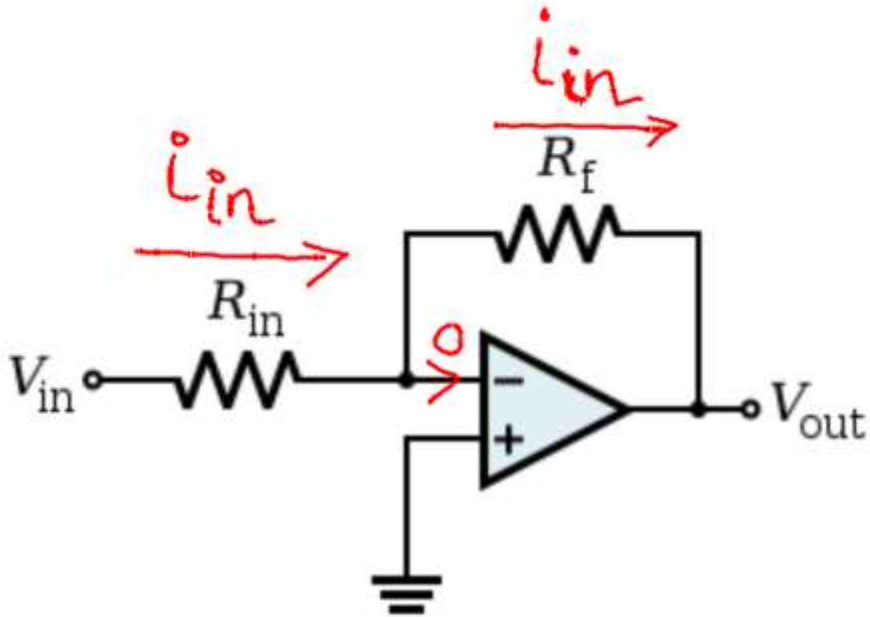



Fig. 14.6 Equivalent Circuit of OpAmp

# Inverting Configuration

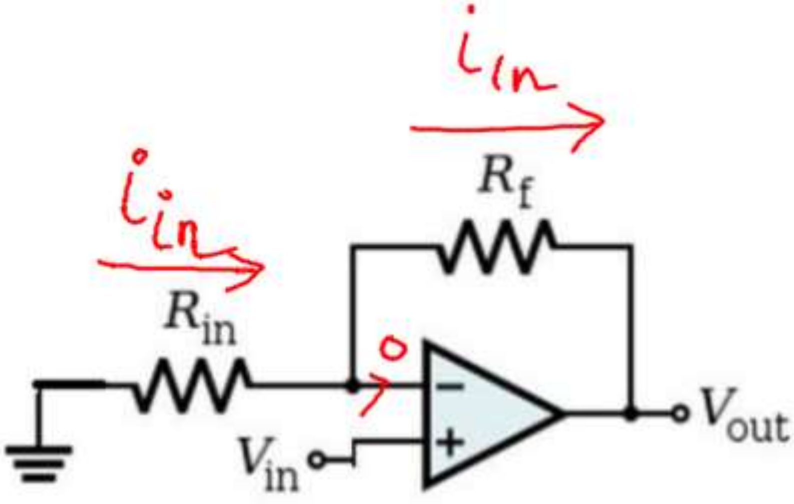



✓ = ✓ = –

✓ Divide by to get the voltage gain

✓ = = –

# Non - Inverting Configuration




✓

=

✓

= ( + )

✓ Divide by to get the voltage gain

✓ = = +

( = + )

# Offset voltage

- ✓ The input offset voltage is defined as the voltage that must be applied between the two input terminals of the op amp **to obtain zero volts at the output.**
- ✓ Ideally the output of the op amp should be at zero volts when the inputs are grounded.

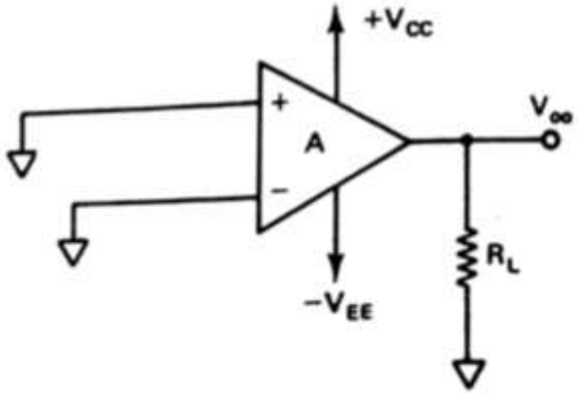
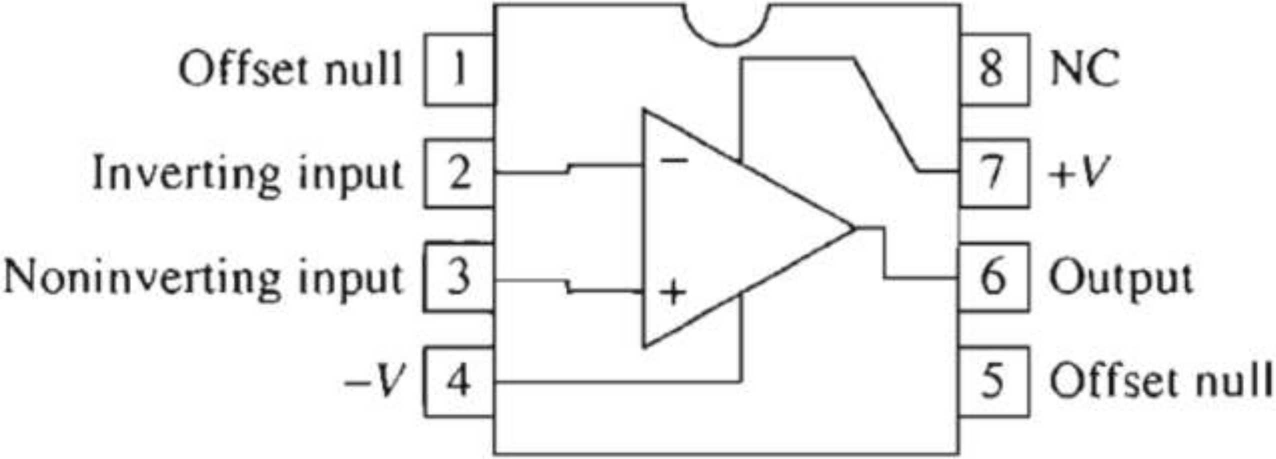


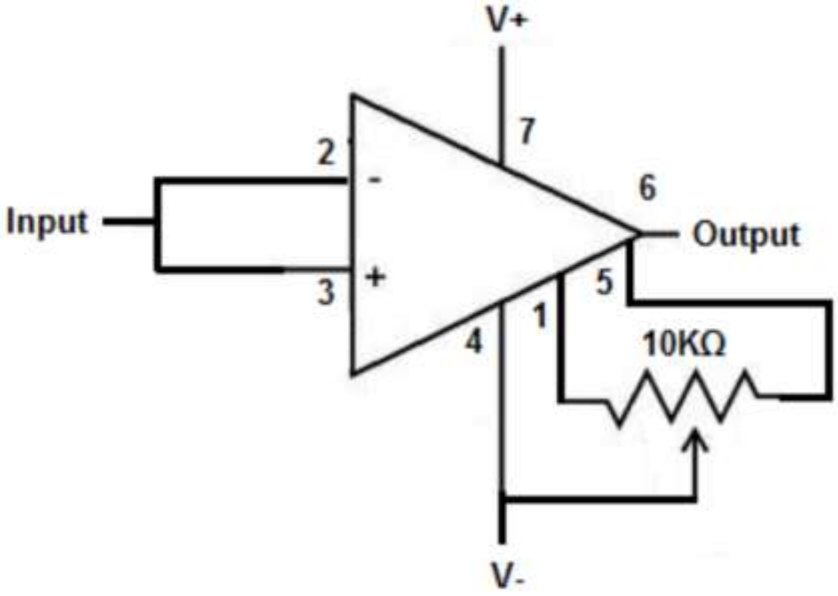

Figure 2 : Output offset voltage in op-amp

# IC 741 – Operational Amplifier



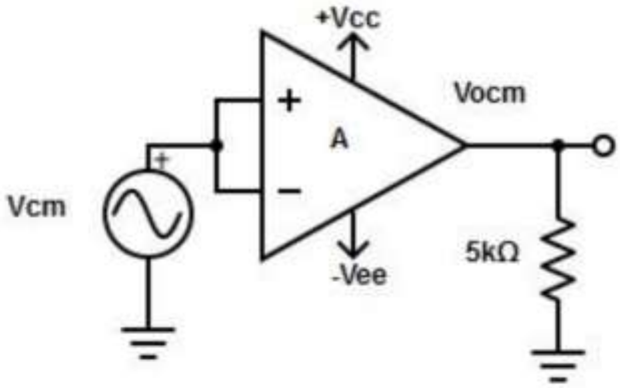
# How to Null Offset voltage?

- ✓ Two input terminals should be shorted and connected to GND (0 V).
- ✓ Using the offset null adjustment requires a potentiometer of 10 K with its wiper connected to the negative supply .
- ✓ On operational amplifiers with an offset null capability two pins are provided as shown in the pin diagram (pins 1 and 5).
- ✓ By varying wiper, we need to make output voltage 0 V.



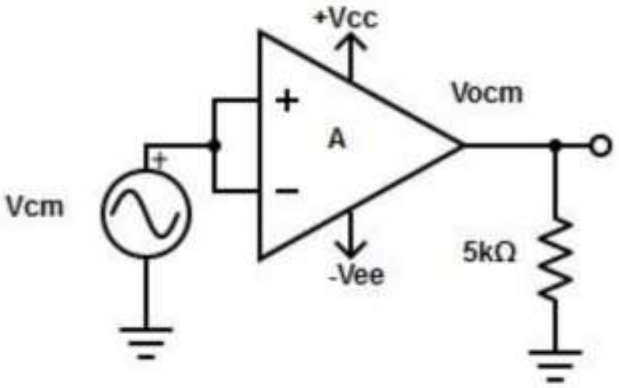
# Input Voltage Range

- ✓ When the same voltage is applied to both input terminals, the voltage is called a common-mode voltage, Vcm and the op-amp is said to be operating in the common-mode configuration.
- ✓ For the 741C the range of the input common-mode voltage is 13 V maximum.
- ✓ The common-mode configuration is used only for test purposes to determine the degree of matching between the inverting and noninverting input terminals.



# Common-Mode Rejection Ratio (CMRR)

- It can be defined as the ratio of the differential voltage gain Ad to the common mode voltage gain Acm.
- =
- The common-mode voltage gain can be determined using the equation
- =
- Generally the Acm is very small and Ad is very large, so CMRR is very large.
- The higher CMRR, the better is the matching between two input terminals.



# Slew Rate

✓ It is defined as the maximum rate of change of output voltage per unit of time and is expressed in volts per microseconds.

/

✓ =

# The Ideal Op – Amp

1. Infinite voltage gain A
2. Infinite input resistance Ri so that almost any signal source can drive it and there is no loading of the preceding stage.
3. Zero output resistance Ro so that the output can drive an infinite number of other devices.
4. Zero output voltage when input voltage is zero
5. Infinite bandwidth so that any frequency signal from 0 to Hz can be amplified without attenuation.
6. Infinite Common Mode Rejection Ratio (CMRR) so that the output common mode noise voltage is zero.
7. Infinite slew rate so that output voltage changes occur simultaneously with input voltage changes.

# Op amp Applications

- ✓ Summing amplifier
- ✓ Scaling amplifier
- ✓ Averaging amplifier
- ✓ Difference amplifier
- ✓ Integrator
- ✓ Differentiator

✓ Instrumentation amplifier

# Reference Books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