Unit 22

Solid State Electronics

Teaching Periods 15 *Weightage %* 10

The cat whisker device, an early solid-state electronic component, was discovered by German physicist Ferdinand Braun in 1874. Braun found that by touching a thin wire (the "whisker") to a crystal of galena (lead sulfide), he could detect radio waves, creating a primitive radio detector. This discovery led to the development of crystal detectors, used in early radios, and paved the way for modern semiconductor devices, such as diodes and transistors, which revolutionized electronics.

In this unit student should be able to:

- Intrinsic (pure) and doped semiconductors.
- How the *N*-type and *P*-type semiconductors are produced.
- Explain the concept of holes and electrons in semiconductors.
- Explain how electrons and holes flow across a junction.
- Describe a *P-N* junction(diode).
- Discuss its forward and reverse biasing.
- Describe the I-V characteristic curves of *P-N* junction.
- Define rectification and describe the use of diodes for half and full wave rectifications.
- Describe the function and use of LED, Photodiode and Photo voltaic cell.
- Distinguish between *P-N-P*&*N-P-N* transistors.
- Describe the operations of transistors.
- Deduce current equation and apply it to solve problems on transistors.
- Apply operation principles of the transistor including I-V characteristics and biasing methods.
- Explain the use of transistors as a switch and an amplifier (common-emitter).
- Explain common-base and common collector configurations.
- Describe the properties of an ideal operational amplifier.
- Express operational amplifier as a comparator.
- Understand the effects of negative feedback on the gain of an operational amplifier.
- Draw the circuit diagrams for both the inverting and the non-inverting amplifier for single signal input.
- Understand the virtual earth approximation and derive an
- Express for the gain of inverting amplifiers.
- Recall and use expressions for the voltage gain of inverting and of non-inverting amplifiers.

Introduction:

Solid-state electronics is a branch of electronics that deals with the flow of electric current through solid materials, such as semiconductors, insulators, and conductors. It involves the design, development, and application of electronic devices and circuits that use these materials to control and manipulate electrical energy. Solid-state electronics has revolutionized the field of electronics, enabling the creation of smaller, faster, and more efficient devices, such as transistors, diodes, integrated circuits, and microprocessors, which are essential components in modern computers, smart phones, and other electronic devices. The field is constantly evolving, with advancements in materials science, nanotechnology, and quantum mechanics.

22.1.1 Intrinsic (Pure) and Extrinsic (Doped) Semiconductors:

Intrinsic (Pure) Semiconductors:

Intrinsic semiconductors are materials that are chemically pure, meaning they do not contain any significant amount of impurity atoms. The two most commonly used intrinsic semiconductors are silicon (Si) and germanium (Ge). These materials have a crystalline structure, and their electrical properties are determined by the arrangement and behavior of their atoms.

Extrinsic (doped) Semiconductors:

Doped semiconductors are created by introducing impurity atoms into the intrinsic semiconductor material. This process is known as doping, and it significantly alters the electrical properties of the semiconductor. Doping can be done with two types of impurities, resulting in two types of doped semiconductors: n-type and p-type.
In summary, intrinsic semiconductors are pure materials with moderate conductivity, whereas doped semiconductors are intentionally infused with impurities to enhance their electrical properties, making them essential for modern electronic devices.

22.1.2 Production of P-Type and N -Type Semiconductors:

The intentional addition of impurities alters the conductivity and electrical properties of the semiconductor, allowing for the controlled operation of charge carriers.

N-type Semiconductors:

It is characterized by an excess of positively charged carriers, known as "holes," or majority Positive charge carriers.

In *P*-type semiconductors, the holes effectively behave as positive charge carriers in the material. These holes are essentially vacancies in the crystal lattice structure, where an electron is missing from a **covalent bond**.

Semiconductor material, silicon (Si) or germanium (Ge) is the base semiconductor material.

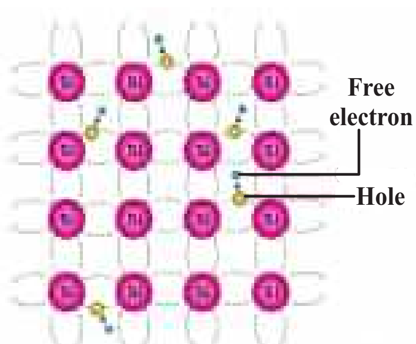


Figure 22.1
free electrons and hole in semiconductor

Doping with Donor Impurities:

A small amount of a group-V element (penta-valent) is doped into the semiconductor's crystal lattice, as illustrated in figure 22.2. Common donor impurities include phosphorus (P) or arsenic (As).

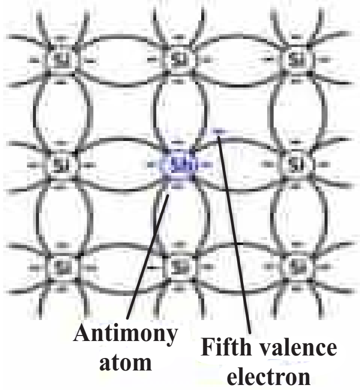


Figure 22.2 N-type

DO YOU KNOW?

Acceptor Ionization: At normal operating temperatures, thermal energy is sufficient to ionize the acceptor atoms, creating mobile holes in the valence band. These holes contribute to the overall conductivity of the material.

These impurity atoms have one more valence electron than the semiconductor material, creating extra electrons that are free to move and conduct electricity.

P-type Semiconductors:

It is characterized by an excess of negatively charged carriers, namely electrons, or majority negative charge carriers.

In *N*-type semiconductors, electrons are the primary charge carriers responsible for the material's electrical conductivity.

Doping with Acceptor Impurities:

If element of group-III (tri-valent) is added into the crystal lattice of the semiconductor as shown in figure 22.3. Common acceptor impurities include boron (B) or gallium (Ga). These impurity atoms have one fewer valence electron than the semiconductor material, creating "holes" in the crystal lattice where electrons can move.

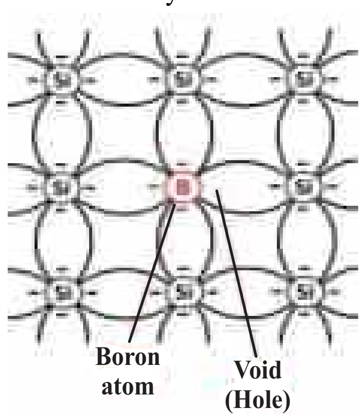


Figure 22.3 P-type

22.1.3 Electron and Hole in Semiconductor:

When an electric field is applied then electric current flow is performed in two ways.

When the temperature is increased then some ***valence electrons* enter into the conduction band** and become free electrons. Whenever an electron enters into the conduction band, then a vacant space or a hole is produced in the valence band as shown in figure 22.4. Due to the influence

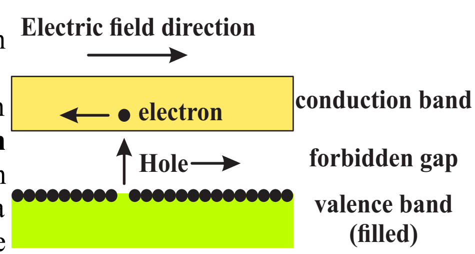


Figure 22.4 electrons and Holes

of potential difference or electric field, flow of electrons and holes are produced.

At room temperature, some electrons from the valence band can cross this small energy gap and are accumulated in the conduction band. As a result, an equal number of holes and electrons are produced. This phenomenon is called electron-hole pair Production.

At the temperature above absolute zero, if the electric field is applied then conduction electrons move towards anode and holes move towards the cathode. So, it can be said that the current flow in the semiconductor is the flow of electrons and holes in the valence and conduction bands in opposite directions.

DO YOU KNOW?

Most familiar intrinsic semiconductors are germanium and silicon. The energy gap between their valence band and conduction band are 0.72 eV and 1.1 eV respectively.

22.2 P-N Junction:

The ***P-N*** junction is formed when the *p*-type and *n*-type semiconductors are joined, is called as *P-N* junction as shown in figure 22.5. *P-N* junction is formed within a single crystal of material rather than just simply joining or fusing together two separate pieces. This junction is a crucial component in electronics and forms the basis for many semiconductor devices like diodes and transistors.

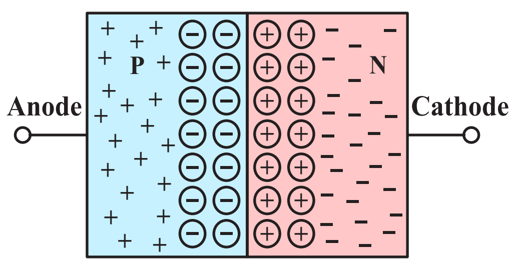


Figure 22.5PN JUNCTION

22.2.1 Flow of Electrons and Holes across Junction:

Initially, a large density rise exists across the junction who leads to a migration of electrons and holes. When electrons move from the N-type to the P-type, negative ions are left behind. Simultaneously, holes from P-type migrate toward the N-type, creating positive ions. This process which is called diffusion, continues until an equilibrium is reached, resulting in a potential barrier zone around the junction, as shown in figure 22.6.

The potential barrier, formed due to repulsion between donor and acceptor atoms, creates a depletion layer. This layer is devoid of free charge carriers, preventing further movement across the junction.

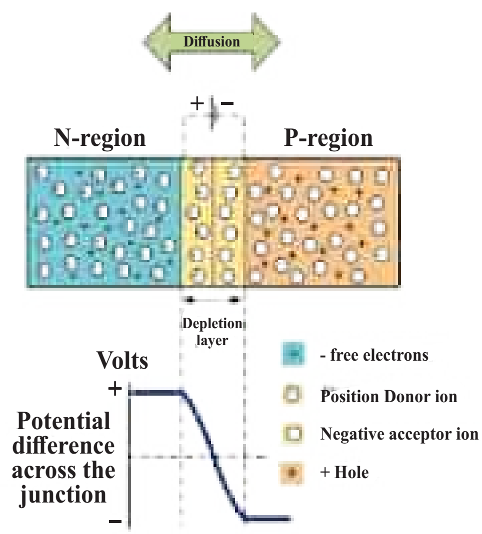


Figure 22.6 Charges flow in PN Junction

22.2.2 P-N Junction as Diode:

A diode is a semiconductor device that is formed through P-N junction and used in allowing the flow of electric current in one direction and blocking in the opposite. The symbol of the *P-N* junction diode is shown in figure 22.7

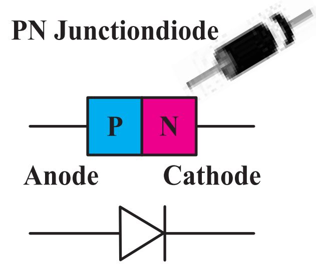


Figure 22.7 Diode

Properties of Diode:

Below are some of the common properties of a diode:

1. Diode has the ability to rectify electric current.
2. It can create a potential barrier and make use of its capacitance properties.
3. Diode creates various nonlinear current-voltage characteristics.

22.2.3 Diode Biasing:

Forward Bias:

When the P-type is connected to the positive terminal of the battery and the N-type is connected to the negative terminal is called Forward bias as shown in figure 22.8.

In this condition, the applied electric field and the built-in electric field at the *P-N* junction are in opposing directions. Adding both the electric fields gives a resultant electric field, which is found to be smaller than the built-in electric field. So the depletion region becomes thinner and less resistant.

When the applied voltage is high, the resistance of the depletion region becomes insignificant. At 0.3V to 0.6 V, the resistance of the depletion region in silicon becomes absolutely insignificant, allowing current to flow freely through it.

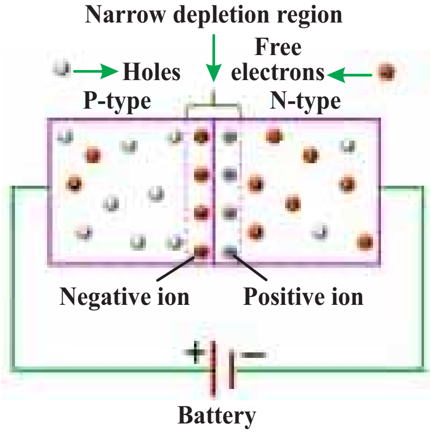


Figure 22.8 Forward Bias

Reverse Bias:

When the P-type is connected to the negative terminal of the battery and the N-type is connected to the positive side is called Reverse Bias as shown in figure 22.9

In this condition, the applied electric field and the built-in electric field are both in the same direction. The resultant electric field and the built-in electric field are also in the same direction, resulting in a more resistive, thicker depletion region. If applied voltage increased, it results thicker and more resistant depletion region.

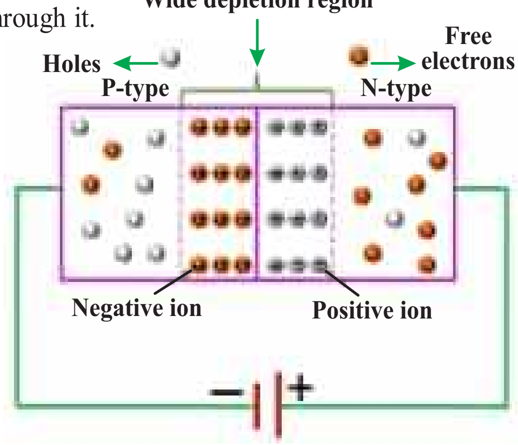


Figure 22.9 Reverse Bias

Self-Assessment Questions:

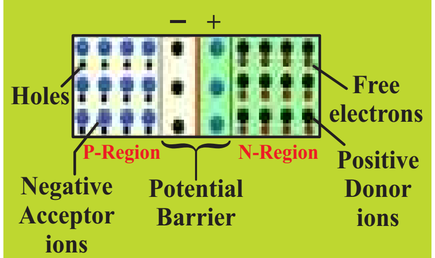
1. What causes the formation of the depletion region in a PN junction at equilibrium?
2. How does forward biasing affect the depletion region and current flow in a PN junction?
3. Why is the current very small in a PN junction under reverse bias?

DO YOU KNOW?

The depletion layer or region acts as a barrier that controls the flow of current. When a voltage is applied, the depletion layer widens or narrows, allowing more or fewer charge carriers to pass through. This mechanism enables the transistor to amplify or switch electronic signals.

The depletion layer is characterized by:

1. Reduced carrier concentration
2. Increased resistance
3. Decreased conductivity



22.2.4 I-V Characteristics of *p-n* Junction:

The relationship between the voltage across the junction and current through the circuit is known as the (V-I) characteristics of a *P-N* junction or semiconductor diode.

The V-I characteristics of the *P-N* junction can be explained in three cases:

- Zero bias or unbiased
- Forward bias
- Reverse bias

At zero bias, no electric current flows through the diode because there's no external voltage applied to enable the movement of electrons or holes. In forward bias as shown in figure 22.10 (a) when the diode voltage (V_d) reaches 0.7 V for silicon and 0.3 V for germanium, current starts flowing. The current increases gradually at first, creating a non-linear curve until the diode surpasses the potential barrier, after which it operates normally and the curve steepens linearly with increasing external voltage.

In reverse bias, only a small leakage current flows, represented to the left of the origin in the graph as shown in figure 22.10(c). This current remains low until the diode breaks down, at which point it can be destroyed unless a high series resistance limits the current.

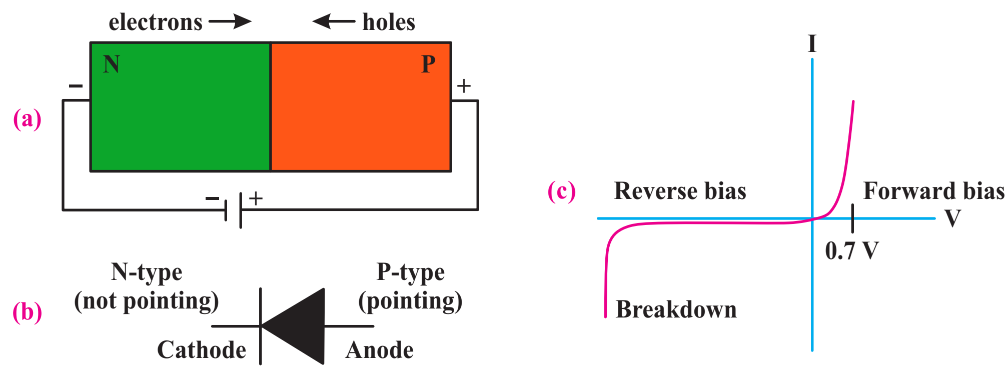


Figure 22.10 I-V Characteristics of *p-n* Junction (a,b,c)

Self-Assessment Questions:

1. Why does reverse saturation current occur in a PN junction?
2. How do the IV characteristics of a PN junction change in forward bias?

22.2.5 Rectification:

Rectification is the process of converting an alternating current (AC) waveform into a direct current (DC) waveform, i.e., creating a new waveform that has only a single polarity as shown in 22.11.

A diode allows electric current to flow in forward bias condition and blocks the current in reverse bias condition. Rectification is classified into two types according to the output characteristics which are:

(i) half-wave rectification and

(ii) full-wave rectification.

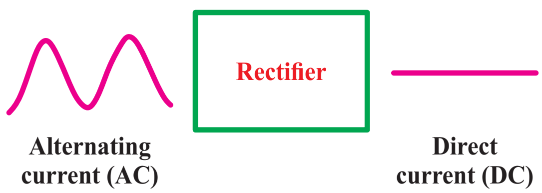


Figure 22.11 Rectification

Half Wave Rectification:

Since a diode allows *AC* current to flow only in one direction, it can serve as a rectifier. As shown in figure 22.12(a). The *AC* source applies a voltage across the diode alternately positive and negative. When the positive cycle of AC voltage passes through the diode, the diode is forward biased and act as a closed circuit there is current through the resistor R.

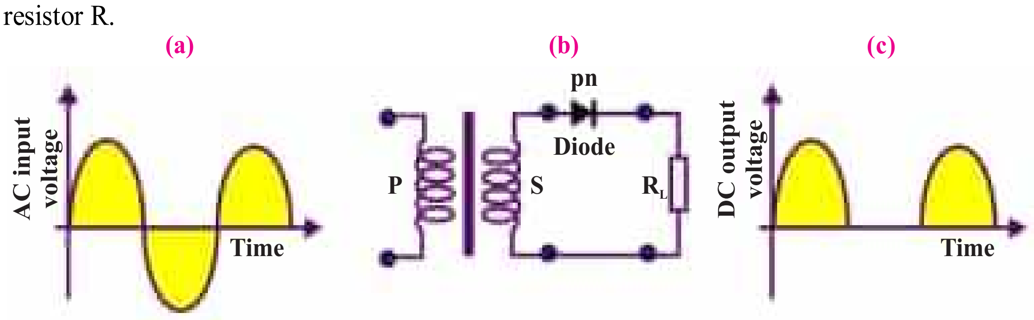


Figure 22.12 (a,b,c) Half Wave Rectifications

During the negative half cycle, the diode is connected with the negative supply which reverses biases the diode, the diode behaves like an open circuit and does not produce the output across the load.

Hence a graph of the voltage V_{ab} across R as a function of time looks likes the output voltage shown in figure 22.12(b). This is called half wave rectification which seems unidirectional from its output signal.

Applications of a Half-wave Rectifier:

- Low power simple battery charger circuit.
- Fire Alarm circuits.
- Soldering Iron circuit.
- Amplitude Modulation (AM) Radio circuits as a Detector.

Full-Wave Rectification:

Full-wave rectification uses two diodes (as shown in figure 22.13(a,b,c).During the positive half cycle of input AC signal, this makes the diode D_1 forward biased (acts as closed switch) and diode D_2 reverse biased (acts as open switch). Therefore, current flows through the load resistor R.

During the negative half cycle of input AC signal, this makes the diode D_2 forward biased and the diode D_1 reverse biased. Therefore, the current will flow through diode D_2 through, load resistor R and lower half of the secondary winding.

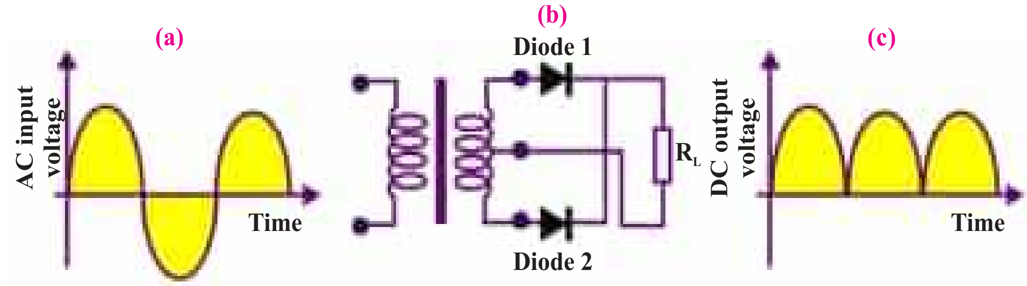


Figure 22.13 (a,b,c) Full-Wave Rectifications

Note that the current through the load is in the same direction for both half cycles of input AC supply. Hence DC output is obtained across the load.

Applications of a Full-wave Rectification:

- Mobile phones, laptops, charger circuits.
- Uninterruptible Power Supply (UPS) circuits to convert AC to DC.
- Our home inverters convert AC to DC.
- LCD, LED TVs.

22.2.6 Function and uses of light emitting diode (LED), Photodiode, Photo voltaic cell:

1. Light Emitting Diode (LED):

A light-emitting diode (LED) is a special type of junction in which current flows, when it is activated in a forward direction as shown in figure 22.14.

In this process, electrons move from the negative side to the positive side, combining with holes emits a photon with energy similar to the material's band gap.

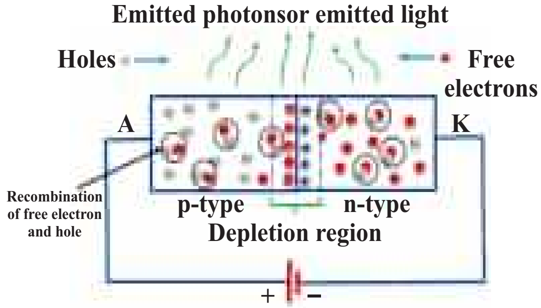


Figure 22.14 Light emitting diode

Silicon diodes don't work well for this, but compounds like gallium and arsenic create efficient LEDs. Gallium arsenide (GaAs), with a crystal structure similar to silicon, is often used..

LED bulbs replace traditional lighting in various applications such as flashlights, streetlights, traffic signals, car brake lights, billboards, and LCD screens. LEDs, also known as solid-state lighting, last longer (50000 hours vs 2000 hours for regular bulbs), are more efficient, and durable.

DO YOU KNOW?

Doping GaAs with group VI atoms like Se and group II atoms as acceptors enhances its properties. GaAs has a 1.42 eV energy gap, producing near-infrared photons (870 nm wavelength), making it suitable for infrared LEDs in remote controls for devices like TVs, DVD players, and car door locks

2. Photodiode:

A photodiode is a type of light detector that converts light into current or voltage. It includes optical filters, built-in lenses, and surface areas.

Photodiodes are often used in reverse bias, where a voltage encourages the flow of photocurrent, maximizing sensitivity**.** These detectors are usually made of semiconductor materials like silicon, which can absorb photons of light.

When light particles (photons) hit the semiconductor material, they transfer energy to electrons, creating electron-hole pairs. This process generates an electric current proportional to the incident light's intensity.

In simple terms, brighter light results in a higher current from the photodiode.

Photodiodes find widespread use in various applications, including:

- **Optical Communication:** Photodiodes are employed in optical communication systems, such as fiber optics, to detect and convert transmitted light signals into electrical signals.
- **Light Sensors:** They are used in electronic devices like cameras, light meters, and automatic lighting systems to sense ambient light levels.
- **Barcode Readers:** Photodiodes are often used in barcode scanners to detect the reflected light from the barcode.
- **Medical Devices:** In some medical instruments, photodiodes are used for tasks like measuring oxygen levels in blood.

3. Photo Voltaic Cells:

Solar cell or photovoltaic cell is heavily doped P-N junction diodes used to convert sunlight into electric energy.

If the energy of incident photon is greater than the band gap energy, it creates electron-hole pairs, as shown in figure 22.15. That absorbed photon excites an electron from the valence band and produce a current, when connected to an external circuit, work as source of emf and power. The basic element of a photovoltaic cell is a

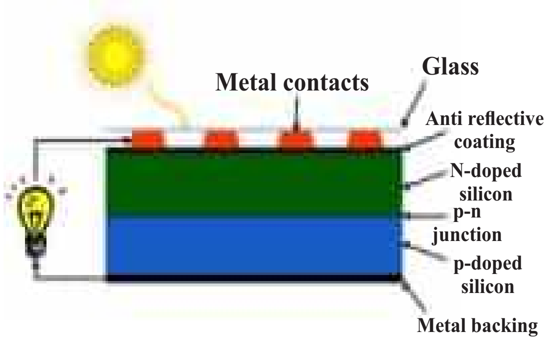


Figure 22.15 Photo Voltaic Cells

semiconductor material, usually made of silicon. Silicon is chosen for its widespread availability. Other semiconductor materials, such as cadmium telluride or copper indium gallium selenide, are also used in different types of solar cells.

A typical silicon *P-N* junction may produce about 0.6 V. Many are connected in series to produce higher voltage. Such series strings are connected in parallel within a photovoltaic panel i.e., solar panel. A good photovoltaic panel can have an output of perhaps 50 W/m^2, averaged over day and night, sunny and cloudy.

Uses of Photodiodes:

- **Camera:** Light meters, Automatic Shutter Control, Photographic Flash Control
- **Medical:** CAT Scanners, X-Ray Detection, Pulse Oximeters, Blood Particle Analysis
- **Automotive:** Headlight Dimmer, Twilight Detectors
- **Communication:** Fiber Optic Link, Optical Remote Control
- **Industry:** Bar Code Scanners, Light Pen, Encoders, Surveying Instruments, Copiers-Density of Toner.

22.3 Transistors and their characteristics:

A transistor is a semiconductor device that amplifies or switches electronic signals by controlling the flow of current between its three layers: base, collector, and emitter. It acts as a gatekeeper, allowing or blocking the flow of current between the collector and emitter, based on the voltage applied to the base.

Both *N-P-N* and *P-N-P* transistors can be made, and they are shown schematically in figure 22.16.

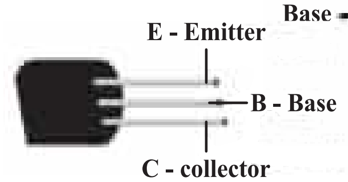


Figure 22.16 (a) Transistor

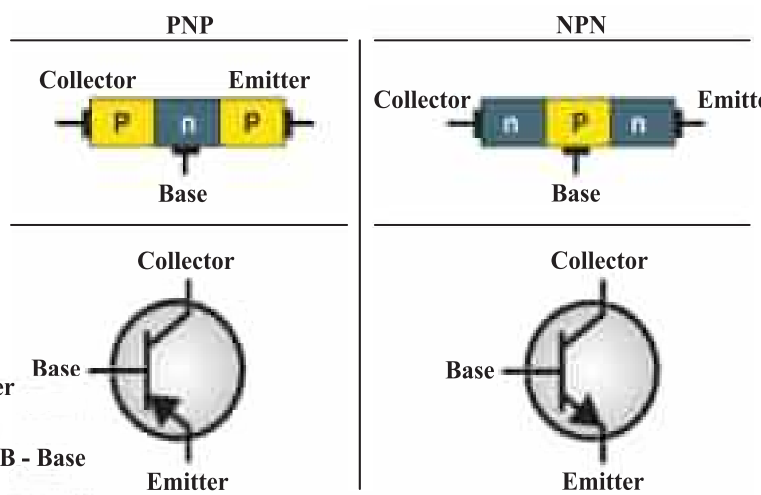


Figure 22.16 (b) PNP and (c) NPN JUNCTION

The arrow is always placed on the emitter; it indicates the direction of current flow in normal operation.

There are three main characteristics listed below:

1. Input Characteristics
2. Output Characteristics
3. Constant-Current Characteristics.

22.3.1 Distinguish between *N-P-N* and *P-N-P*:

N-P-N	*P-N-P*
It contains two N-type semiconductors.	It contains two P-type semiconductors.
Its current is directed outwardly.	Its current is directed inwardly.
In this transistor combination, electrons are majority current carriers.	In this transistor combination, holes are majority current carriers.
Its current direction is emitter to base.	Its current direction is base to emitter.
It has holes as minority current carriers.	It has electrons as minority carriers.
It's switched on when electrons enter the base.	It's switched on when holes enter the base.
As current reduces at base, transistor does not function across the collector terminal and switches off.	When current is available at base, then transistor switches off.

22.3.2 Operation of transistors:

Transistors are categorized as PNP and NPN. For simplicity the NPN transistor is taken as shown in figure 22.17 (a). Its action has two requirements:

1. The base-emitter junction is forward biased so that a current I_B is generated. Once this junction is conducting, $V_{BE} \cong 0.6$ V
2. The base-collector junction is reverse biased.

Transistor action then translates into relationship

$$I_C = \beta I_B \ldots\ldots\ldots\ldots 22.1$$

Where β is the current gain, which is typically 100. For completeness, the emitter current is then given by

$$I_E = I_B + I_C = (1+\beta)I_B \ldots\ldots\ldots\ldots 22.2$$

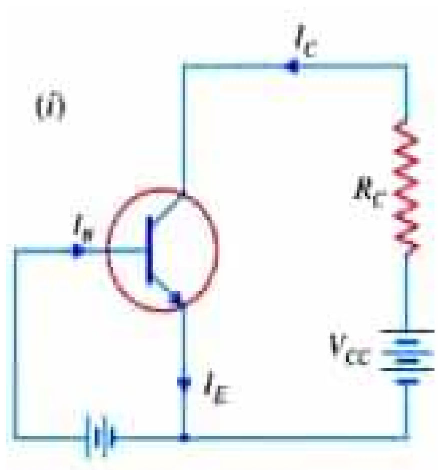


Figure 22.17 (a) NPN transistor

Figure 22.17 graphs a set of characteristics curves of the transistor. Those graphs show the collector current Ic as function of the collector-emitter voltage V_{CE}, for different values of the base current I_B. When the transistor-action conditions are not met, the transistor is off and Ic =0. This situation is called ***cutoff.***

Now assume that V_{BE} is forward biased and I_B is above some minimum value. As the collector-base junction becomes reverse biased, which we represent here by increasing V_{CE}, transistor action begins to unfold:

In a transistor's char acteristic curve, I_c (collector current) initially rises sharply until it reaches a certain point. Beyond this point, I_c continues to increase, but at a much slower rate. This might seem counterintuitive, but the rapid rise is called "saturation," indicating full current flow. The flat region that follows is when the transistor operates normally, where further increases in base current do not significantly increase I_c

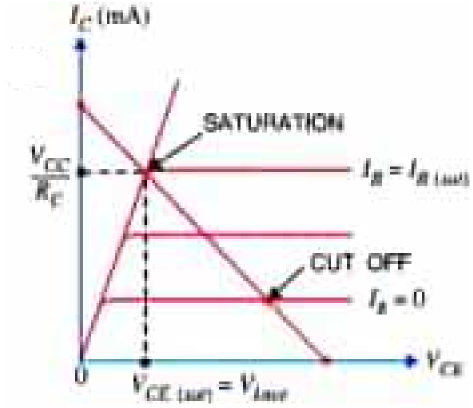


Figure 22.17 (b) transistor characteristics curves

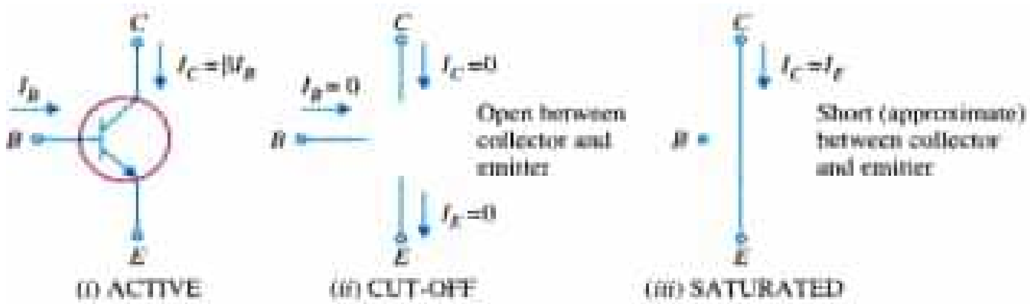


Figure 22.18 Transistors active-cut off and saturated

22.3.3 Transistors current equation:

It is a three-terminal device, with three possible ways to connect it within an electronic circuit with one terminal being common to both the input and output signals.

Bipolar Junction Transistor Configurations:

Each method of connection responding differently to its input signal within a circuit as the static characteristics of the transistor varies with each circuit arrangement.

The Common Emitter Amplifier Circuit

In this circuit shown in Figure 22.19, the current leaving the transistor must be equal the currents entering it because the emitter current (I_E) is the sum of the collector current (I_C) and the base current (I_B).

The common emitter transistor configuration has a substantial current gain because

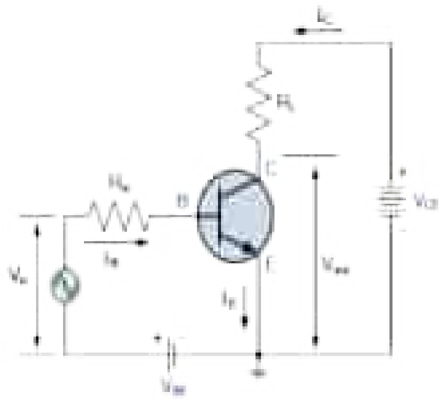


Figure 22.19 Common Emitter Amplifier

the load resistance (R_L) is connected in series with the collector. The current gain is represented by Beta (β),which is the ratio of I_C to I_B. For the common emitter setup,

$$I_E = I_C + I_B, \ldots\ldots\ldots\ldots 22.3$$

where the ratio of I_C to I_E is known as Alpha (α).It's important to note that Alpha is always less than one.

Due to the physical construction of the transistor, any small change in the base current (I_B) leads to a much larger change in the collector current (I_C). This means that slight variations in the current flowing through the base can effectively control the current in the emitter-collector circuit.

Typically, Beta values range between 20 and 200 for most transistors. For instance, if a transistor has a Beta value of 100, one electron flows from the base terminal for every 100 electrons flowing between the emitter-collector terminals.

The mathematical relationship between Alpha (α) and Beta (β) expresses the current gain of the transistor. $\alpha = \frac{I_C}{I_E}$ and $\beta = \frac{I_C}{I_B}$ $\therefore I_C = \alpha I_E = \beta I_B$

$$As \quad \alpha = \frac{\beta}{\beta + 1} \quad and \quad \beta = \frac{\alpha}{1 - \alpha}$$

$$I_E = I_C + I_B \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 22.4$$

Where: "I_C" is the current flowing into the collector terminal, "I_B" is the current flowing into the base terminal and "I_E" is the current flowing out of the emitter terminal.

This type of bipolar transistor configuration has greater input impedance, current and power gain than that of the common base configuration but its voltage gain is much lower. The common emitter configuration is an inverting amplifier circuit. This means that the resulting output signal has a 180° phase-shift with regards to the input voltage signal.

Worked Example 22.1

Find Alpha (α) rating of the transistor shown in diagram. Hence determine the value of I_C using both α and β=49rating of the transistor.

Solution:

Step 1: Write down the known quantities and quantities to be found.

I_B=240μA, I_E=12mA and β=49

I_C=?

Step 2: Write down the formula and rearrange if necessary.

$$\alpha = \frac{\beta}{\beta + 1} = \frac{49}{49+1} = \quad 0.98$$

The value of I_C can be found by using either α or β as under

$I_C = \alpha \times I_E$

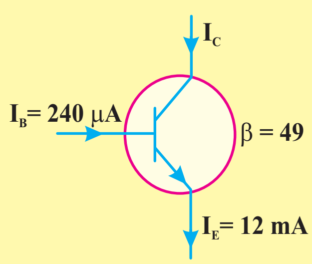
$I_C = 0.98 \times 12$ mA

I_C= 11.76 mA

$I_C = \beta \times I_B$

$I_C = 49 \times 240$μA

I_C= 11.76 mA



22.3.4 Operation Principles and I-V Characteristics and Methods of Transistor Biasing:

Bipolar Junction Transistor (BJT):

Operation Principles:

1. **Emitter, Base, and Collector:**
   - The three layers of a BJT are called the emitter (E), base (B), and collector (C).
   - The flow of current in an N-P-N transistor is from the emitter to the collector, and in a P-N-P transistor, it's from the collector to the emitter.
2. **Transistor Action:**
   The operation of a BJT involves the injection of minority carriers (electrons in N-P-N or holes in P-N-P) from the emitter into the base region. This controls the majority carrier flow from the collector to the emitter.

I-V Characteristics:

Transistors use current-voltage characteristics to show how input voltage relates to output current. This helps understand how transistors amplify or switch signals.

Active Region:

Here, the transistor amplifies signals. A small current at the base-emitter junction (I_B) causes a larger current from collector to emitter (I_C). The graph shows a straight line, illustrating signal amplification.

Saturation and Cutoff:

Beyond the active region, these regions appear. In saturation, the transistor is ON, allowing maximum collector current. In cutoff, it's OFF, with minimal collector current.

Proper biasing keeps transistors in the active region for linear amplification. Understanding these characteristics is crucial for designing circuits for signal processing, amplification, and switching. Understanding these I-V characteristics is essential for designing circuits that utilize transistors for signal processing, amplification, and switching applications.

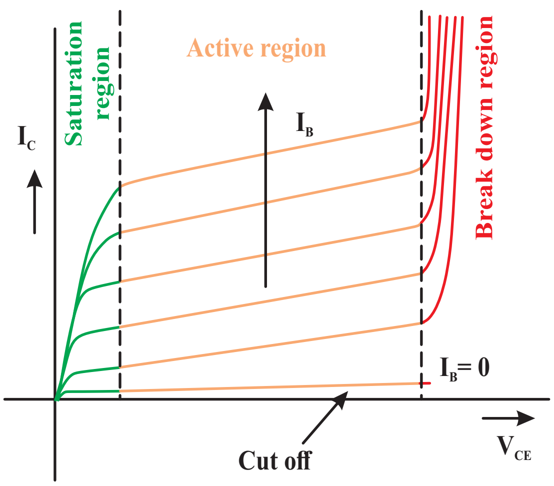


Figure 22.20. Active Region: Saturation and Cutoff

Biasing Methods:

Biasing is the process of applying external voltages to a transistor to establish a desired operating point for proper amplification or switching. There are several biasing methods for transistors. Here are some common biasing methods:

Bipolar Junction Transistor (BJT) Biasing Methods:

1. **Fixed Bias (Base Bias):**
   - Connects a resistor between the base and the power supply to establish a fixed voltage at the base.
   - Simple but not very stable.
2. **Emitter Bias (Emitter Stabilized Bias):**
   - Connects a resistor from the emitter to the power supply, stabilizing the operating point.
   - More stable than fixed bias.
3. **Collector Feedback Bias:**
   - Combines features of fixed bias and emitter bias for improved stability.
   - Uses a resistor network to provide feedback.
4. **Voltage Divider Bias:**
   - Utilizes a resistor divider network to bias the base and provide stability.
   - More stable than fixed bias but less stable than emitter bias.

22.3.5 The transistors as a switch:

A transistor can be used as a switch in electronic circuits, where it functions to either allow or block the flow of current. There are two main configurations for using a transistor as a switch: the NPN (negative-positive-negative) and PNP (positive-negative-positive) configurations.

NPN Transistor as a Switch:

The transistor Q_1 in figure 22.22 shows how to control output current with input.

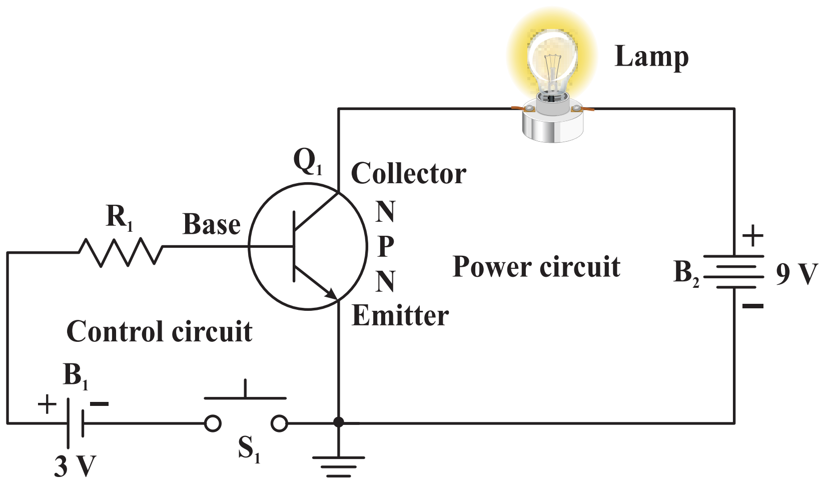


Figure 22.22 transistors as a switch

Here are key points to note:

1. **Off State:**

Normally, Q_1 allows no output current unless we apply forward voltage to its base-emitter circuit.

2. Forward Voltage:

The amount of output current is controlled by the forward voltage that controls base current. In figure 22.22:

- The input control circuit determines base current.
- The output current is collector current for the power circuit.
- Q_1 is an NPN transistor, needing a positive VBE for forward voltage.
- The emitter is common to both input control and power circuits.
- Common-emitter (CE) circuit is the most common transistor arrangement.

The base-emitter junction of Q_1 in figure 22.22 can be forward biased by battery B_1. Switch S_1 must be closed to apply forward voltage. Battery B_2 provides reverse voltage to the collector of Q_1. Reverse polarity means the collector is more positive than the base.

When switch S_1 is open:

- No current flows in the base-emitter or control circuit because no forward voltage is applied.
- Resistance from emitter to collector of the transistor is very high.
- No current flows in the power circuit, and the lamp doesn't light up.

When switch S_1 is closed:

- A small current flows in the control circuit.
- R_1 limits current in the base circuit.
- Resistance from emitter to collector of Q_1 decreases.
- A large current flows in the power circuit, lighting up the lamp.

Opening switch S_1 in the control circuit turns off the lamp in the power circuit because resistance from emitter to collector of Q_1 increases again, almost to infinity.

Transistor as an Amplifier:

Consider the circuit shown in figure 22.23. The dc operating voltages are shown in figure 22.23(a), without any input signal. The dc biasing levels are set by the feedback resistor R_2. The NPN transistor is biased so that the collector-to-emitter voltage Vc is half of the supply voltage. For the supply voltage of 10 v, therefore, the collector voltage is set at one-half the total, or +5 V. The 0.7 V at the base is partially turning on the transistor. The transistor acts as an amplifier when in this partially turned-on condition. It is the amount of dc forward bias that determines the operating level of the transistor.

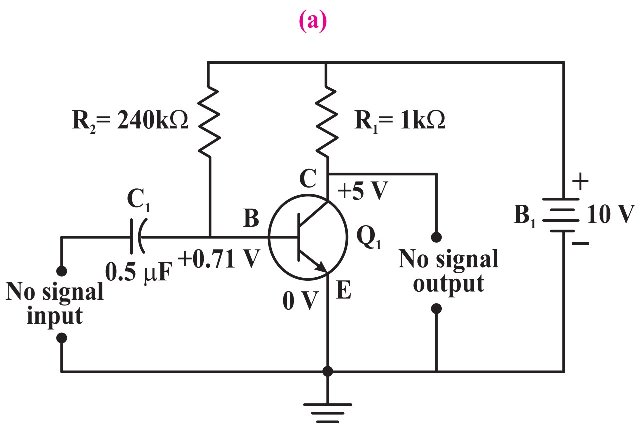


Figure 22.23 (a)
Transistors as an Amplifier

An input signal has been added to the amplifier in figure 22.23 (b), Input is coupled to the base by C_1. Amplified output is taken from the collector. The input signal is 0.02 V_{pp} as measured on an oscilloscope. The measured output signal voltage is 3 V_{pp}. The ac gain of the amplifier, therefore is calculated as

Av = Vout/ V= 3 /0.02 = 150

The output signal (3 V_{pp}) is 150 times greater than the input signal of 0.02 V_{pp}. This amplifier stage is said to have a voltage gain of 150.

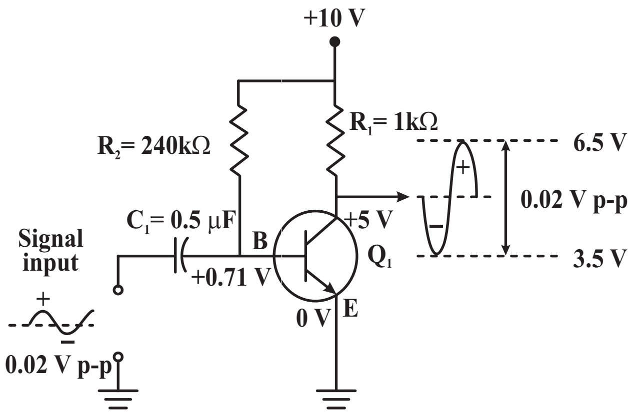


Figure 22.23 (a,b)
Transistors as an Amplifier

Worked Example 22.2

In a common base connection, I_C = 0.95 mA and I_B = 0.05 mA. Find the value of α.

Solution:

Step 1: Write down the known quantities and quantities to be found.

I=0.95mA I_B = 0.05mA R = 470 Ohm α.= ?

Step 2: Write down the formula and rearrange if necessary.

We know $I_E = I_B + I_C = 0.05+0.95 = 1mA$

Current amplification factor = $\propto = \frac{I_C}{I_E} = \frac{0.95}{1} = 0.95$

Result: 0.95

22.3.6 Common Collector (CC) Circuit:

In CC configuration, the input signal is applied to the base, and the output signal is taken from the emitter, with the collector terminal serving as the common connection.

Figure 22.24 depicts this setup. Here, when the base-emitter junction is forward biased, a small base current I_B causes a much larger collector current I_C to flow. The emitter current I_E is approximately equal to I_C since $I_E = I_B + I_C$ and I_B is significantly smaller than I_C.

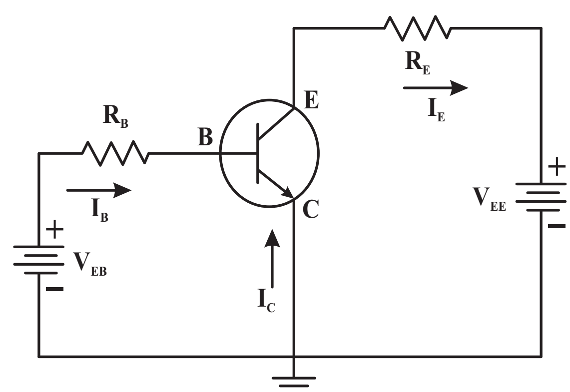


Figure 22.24 common collector circuits

Advantages:

CC amplifiers offer high current gain and low input impedance, making them suitable for applications where a high-resistance input needs to drive a low-resistance output load.

Applications:

Commonly used in impedance matching and signal buffering circuits due to their favorable characteristics.

Common Base (CB) Circuit:

In CB configuration, the input and output signals share the base terminal of the transistor.

Figure 22.25 demonstrates this configuration. Here, the input signal is applied to the emitter, and the output signal is taken from the collector. The base-emitter junction is forward biased to allow transistor operation.

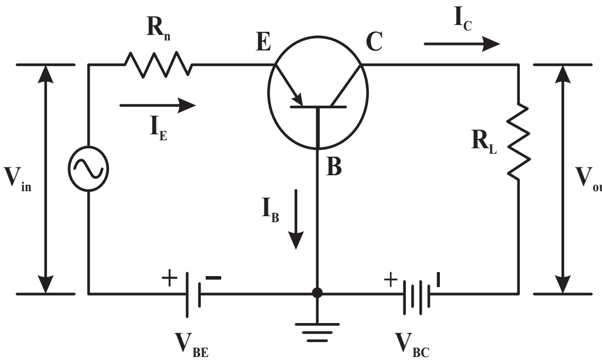


Figure 22.5 Common Base (CB) Circuit

Characteristics:

CB amplifiers provide low input impedance and approximately unity voltage gain. The current gain in CB configuration is expressed as $\frac{I_{out}}{I_{in}}$ or the formula $\frac{I_C}{I_E}$

However, as the base current is extremely small compared to the collector current, the emitter current is therefore approximately equal to the collector current. Thus $I_E \approx I_C$

Applications:

Less commonly used compared to CC and Common Emitter (CE) configurations, CB amplifiers are employed in specific applications where low input impedance and unity voltage gain are advantageous.

22.4 Operational Amplifier:

An operational-amplifier is a **direct coupled high gain amplifier**. It can be operated on both with AC and DC signals. Operational Amplifier, also called as an Op-Amp, is an integrated circuit, which can be used to perform various linear, non-linear, and mathematical operations as shown in figure 22.26.

Op-amps are ideal for DC amplification and are used often in signal conditioning, filtering or other mathematical operations (add, subtract, integration and differentiation).

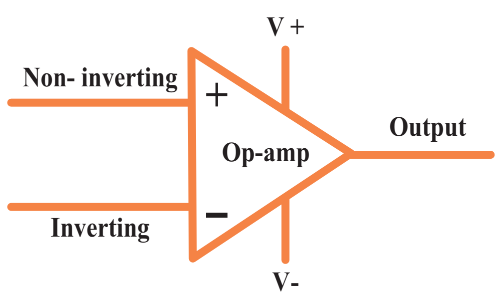


Figure 22.26 Operational Amplifier

22.4.1 Properties of an Ideal Operational Amplifier (Op-Amp):

The ideal op-amp has the following properties:

Characteristics	Ideal Op-Amp
Infinite open-loop voltage gain	An ideal op amp is a device often used as an amplifier. When you input voltage into it, the op amp outputs a amplified voltage. In an ideal scenario, the op amp would provide extremely high gain, essentially infinite, amplifying the signal countless times for maximum gain as needed.
Infinite input resistance (Impedance)	An ideal op amp has super high input impedance, which means it won't load the circuit. If input impedance is low, the op amp draws more current; if it's high, less current is drawn. We aim for high input impedance to avoid disturbing the original circuit by minimizing current pulled from it, ideally with infinite input impedance.
Zero output resistance (Impedance)	In an ideal op amp, the output impedance is zero. This means when the op amp generates a signal, we want it to have zero resistance, ensuring that the maximum voltage goes to the output load. In a circuit, voltage gets divided based on the impedance. Higher impedance means more voltage drop. For the voltage to drop across the output load, the load's impedance should be greater than the op amp's output. That's why, ideally, we aim for zero output impedance in the op amp.
Gain independent of frequency	In an ideal op amp, the produced gain remains constant regardless of the input signal's frequency. This means the amplification stays reliable and consistent across all frequencies.
Infinite bandwidth	The bandwidth of an op-amp is the range of frequencies it amplifies equally. An ideal op-amp amplifies all frequencies, so it should ideally have an infinite bandwidth.
Infinite slew rate	An ideal op-amp should change the output instantaneously as the input is changed. The slew rate of the op-amp is the factor that affects this time delay. An infinite slew rate means there is no time delay.
Zero noise contribution	Any signal includes a small amount of noise. The ideal op-amp does not produce any noise itself, although it will amplify any noise that is present in its input.

22.4.2 Op-Amp as comparator:

The op-amp shown in figure 22.27 is connected to two power supplies. One battery of 9V is connected between the zero-volt line and the +9V positive supply terminal of the op-amp and the other between the zero-volt line and the negative power supply terminal. These batteries are not shown.

The output voltage is given by

$V_{out} = G_o \times (V^+ - V^-)$, where G_o is the open-loop voltage gain. Notice that all of these voltages are measured with reference to the zero-volt line, which is often connected to earth.

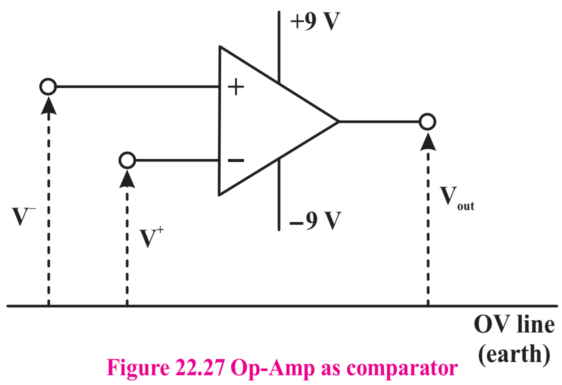


Figure 22.27 Op-Amp as comparator

Suppose that $G_o = 10^5$ and that $V^+ = 0.15$ V and $V^- = 0.10$ V. Then equation becomes

$V_{out} = 10^5 \times (0.15 - 0.10) = 5000$ V

Certainly, it's impossible. The op-amp is therefore saturated and V_{out} will be close to one of the power supply voltages, in this case 9 V because V^+ is bigger than V^-.

In fact:

- If V^+ is slightly greater in magnitude than V^-, then V_{out} will have magnitude equal to the positive power supply voltage.
- If V^+ is slightly smaller in magnitude than V^-, then V_{out} will have magnitude equal to the negative power supply voltage.

The op-amp is serving as a comparator, comparing V^+ and V^-. If these voltages are slightly different, then the output voltages tell us which one is larger.

22.4.3 Effects of negative feedback on the gain of an operational amplifier:

Negative Feedback:

Negative feedback occurs when a portion of the output signal, like voltage or current, is feedback into the input in a way that opposes or subtracts from the input signal.

Advantages:

1. Reduced Gain:
   Negative feedback decreases the overall gain of the system.
2. Decreased Distortion and Noise:
   It minimizes distortion and noise, leading to a cleaner output signal.
3. Improved Stability:
   The gain becomes more stable and less sensitive to external changes, such as temperature.
4. Increased Bandwidth:
   Enhances the system's bandwidth.
5. Better Impedance:
   Lowers the output impedance and raises the input impedance.

Operation in Electronic Systems:

Feedback is unidirectional, flowing from output to input, ensuring the loop gain (G) remains independent of load and source impedances. A summing point at the input subtracts the feedback signal from the input signal, creating an error signal that drives the system.

Example Circuit (Figure 2.28):

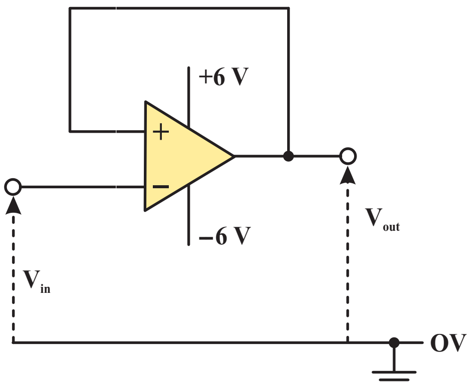


Figure 2.28 Operations in Electronic Systems

Setup:

Input V_{in} is connected to the non-inverting input (+) of an op-amp. The output V_{out} is fed back to the inverting input (-).

Operation:

With an infinite open-loop gain and no saturation, V^- equals V^+. As V_{in} changes, V_{out} adjusts to maintain , $V^- = V^+$. Equation: $V_{out} = G_o \times (V^+ - V^-)$

Simplified: Since $V_{out} = V^-$ and $V_{in} = V^+$ then we have

$V_{out} = G_o (V_{in} - V_{out})$

$V_{out} (1+G_o) = G_o V_{in}$

The closed-loop gain G is given by: $G = \frac{V_{out}}{V_{in}} = \frac{G_o}{1+G_o}$ ……………..22.5

As G_o is very high about 10^5, there is little difference between G_o and $(1+G_o)$, so the closed-loop gain is very nearly 1. This analysis is true as long as the output voltage is smaller than the supply voltage, in this case as long as V_{out} is between -6 v and +6 v.

Practical Example:

A Piezo-electric microphone with high internal resistance can be connected to an op-amp to increase current output while maintaining the same voltage.

Negative Feedback Benefits Summary:

- Less distortion.
- Increased bandwidth.
- The gain is more stable and not affected by changes in temperature, etc.

The output resistance (impedance) can be low and the input resistance high.

22.4.4 The circuit diagrams for both the inverting and the non-inverting amplifier for single signal input:

Inverting operational amplifier:

In inverting operational amplifiers, the op amp forces the negative terminal to equal the positive terminal, which is commonly ground. Therefore, the input current is determined by the V_{IN} / R_1 ratio as shown in Figure 22.29: Inverting Operational Amplifier.

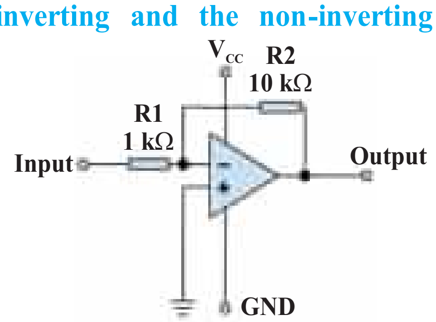


Figure 22.29
circuit diagrams for inverting Amp

In this configuration, the same current flows through R_2 to the output. Ideally, current does not flow into the operational amplifier's negative terminal due to its high Z_{IN}. The current flowing from the negative terminal through R_2 creates an inverted voltage polarity with respect to V_{IN}. This is why these op amps are labeled with an inverting configuration. Note that the op amp's output can only swing between its positive and negative supplies, so creating a negative output voltage requires an op amp with a negative supply rail. V_{OUT} can be calculated with Equation

$$V_{out} = -\frac{R_2}{R_1} \times V_{in} \ldots\ldots\ldots\ldots\ldots\ldots\ldots 22.6$$

Non-inverting operational amplifier:

In a non-inverting amplifier circuit, the input signal from the source is connected to the non-inverting (+) terminal as shown in figure 22.30. Non-Inverting Operational Amplifier

The operational amplifier forces the inverting (-) terminal voltage to equal the input voltage, which creates a current flow through the feedback resistors. The output voltage is always in phase with the input voltage, which is why this topology is known as non-inverting. Note that with a non-inverting amplifier, the voltage gain is always greater than 1, which is not always the case with the inverting configurations. V_{out} can be calculated with Equation:

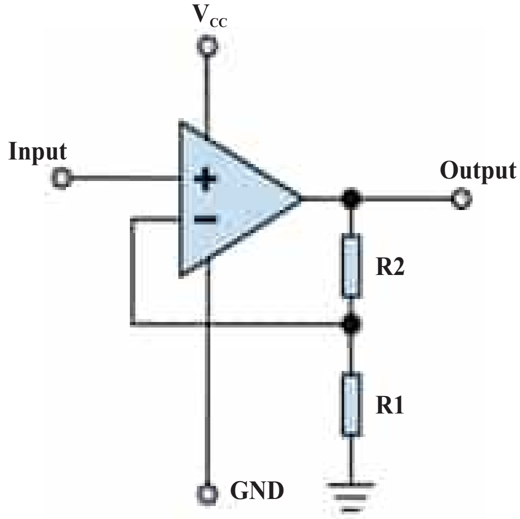


Figure 22.30 circuits for non-inverting amplifier

$$Vout = \frac{1 + R_2}{R_1} \times Vin \ldots\ldots\ldots\ldots\ldots\ldots 22.7$$

22.4.5 Virtual Earth Approximation:

To understand how the inverting amplifier works, you need to understand the concept of virtual earth approximation. In this approximation the potential at the inverting input (-) is very close to 0 V. There are two steps in the arguments:

The op-amps multiplies the difference in potential between the inverting and non-inverting inputs, V^- and V^+, to produce the output voltage V_{out}. Because the open-loop voltage gain is very high, the difference between V^- and V^+ must be almost zero.

The non-inverting input (+) is connected to the zero-volt line so $V^+ = 0$. Thus V^- must be close to zero and the inverting input (-) is almost at earth potential.

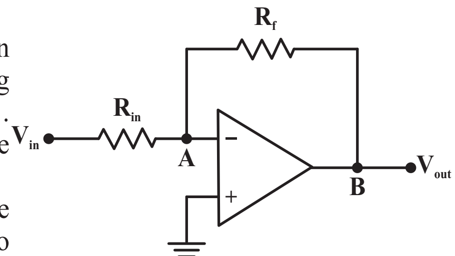


Figure 22.31 virtual earth approximation

The point A is known as a virtual earth as shown in figure 22.31. It cannot actually be 0V but it is very close to 0V. This approximation is true as long as the op-amp is not saturated, and for frequencies where the open-loop voltage gains is high.

Applications:

This approximation is often used in summing amplifier circuits and other applications where it simplifies analysis.

Summing Amplifier Example:

- In a summing amplifier, multiple input voltages can be summed using resistors connected to the inverting input.
- The virtual ground assumption makes it easier to analyze the currents and voltages in the circuit.

Gain of an Inverting Amplifier:

If the current in the input resistor R_{in} is I_{in} and the current in the feedback resistor R_f is I_f, then point P is at 0V:

$$I_{in} = \frac{V_{in}}{R_{in}} \quad and \;\; I_f = \frac{V_{out}}{R_f}$$

The input resistance of the op-amp is very high and so virtually no current enters or leaves the inverting input (-) of the op-amp. This means that I_{in} and I_f must be equal in size.
If V_{in} is apositive potential, then the current in two resistors flows from left to right. V_{out} will be negative because the current flows from P, which is at 0 V, to the output connection, which must have a lower voltage than 0 V. Thus

$$I_f = - I_{in} \;\text{ and } \frac{V_{out}}{Rf} = -\frac{V_{in}}{R_{in}}$$

The gain of the inverting amplifier is thus given by

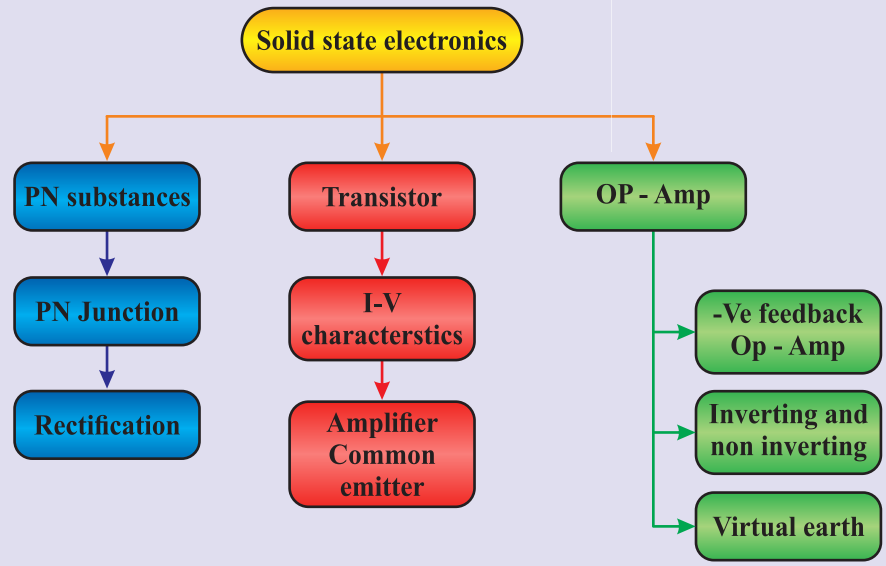
$$G = \frac{V_{out}}{V_{in}} = -\frac{R_f}{R_{in}} \ldots\ldots\ldots\ldots 22.8$$

The negative sign shows that when the input voltage is positive the output voltage is negative and when the input is positive the output is negative. If the input voltage is alternating then there will be a phase difference of 180^o or π rad between the input and the output voltages.

SUMMARY

- ✓ A *p*-type substance is a semiconductor material which has an excess of positively charged particles called "holes" as its majority charge carriers.
- ✓ An *n*-type substance is a semiconductor material that has an excess of negatively charged electrons as its majority charge carriers.
- ✓ An intrinsic semiconductor is a pure semiconductor material with no intentional impurities added.
- ✓ Doping is the process of intentionally introducing impurities into a semiconductor crystal to modify its electrical properties.
- ✓ Doping with Donor Impurities: A small amount of a group V element is introduced into the crystal lattice of the semiconductor. Common donor impurities include phosphorus (P) or arsenic (As).
- ✓ Doping with Acceptor Impurities: A small amount of a group III element is introduced into the crystal lattice of the semiconductor. Common acceptor impurities include boron (B) or gallium (Ga).
- ✓ P-N Junction is formed when the *p*-type and *n*-type semiconductors are joined, is called as *p-n* junction.
- ✓ P-N Junction Diode is a semiconductor device that is formed through this method and used in allowing the flow of electric current in one direction and blocking in the opposite.
- ✓ Forward Bias: The *P-N* junction is forward-biased when the *P*-type is connected to the positive terminal of the battery and the *N*-type is connected to the negative terminal.
- ✓ Reverse Bias: The *P-N* junction is reverse biased when the*P*-type is connected to the negative terminal of the battery and the *N*-type is connected to the positive side.
- ✓ Rectification is the process of converting an alternating current (AC) waveform into a direct current (DC) waveform, i.e., creating a new waveform that has only a single polarity.
- ✓ A light -emitting diode (LED) is a *P-N* junction in which current flows as it becomes forward biased.
- ✓ A photodiode is one type of light detector which uses to convert the light into current or voltage based on the mode of operation of the device.
- ✓ Photo Voltaic Cells or Solar cells, also called photovoltaic cells, are rather heavily doped *p-n* junction diodes used to convert sunlight into electric energy.
- ✓ Transistor: The Bipolar Junction Transistor was invented in 1948 by J. Bardeen, W. Shockley and W. Brattain.
- ✓ It consists of a crystal of one type of doped semiconductor sandwiched between two of the opposite type.

CONCEPT MAP



EXERCISE

Section (A): Multiple Choice Questions (MCQs)
Choose the correct answer:

1. A semiconductor is an element with a valence electron ______.
   (a) Four (b) Eight (c) Two (d) One
2. A pure semiconductor is known as
   (a) Extrinsic (b) Intrinsic (c) Transistor (d) Diode
3. An acceptor atom is also called
   (a) Penta-valent atom (b) Trivalent atom
   (c) Minority carrier (d) Majority carrier
4. With which one of the following elements silicon should be doped so as to give p-type of semiconductor?
   (a) Germanium (b) Arsenic (c) Selenium (d) Boron
5. For a full-wave rectifier, the output frequency
   (a) Equals one-half the input frequency (b) Equals the line frequency
   (c) Equals two times the input (d) Is three times the line frequency

6. LED construction needs a semiconductor material is:
   (a) Silicon (b) Germanium (c) Gallium (d) Gallium arsenide
7. The frequency of a half-wave signal is
   (a) Twice the line frequency (b) Equal to the line frequency
   (c) One-half of the line frequency (d) One-fourth the line frequency
8. The voltage gain of an emitter follower circuit is
   (a) High (b) Low (c) Very high (d) Moderate
9. What is also called as the conventional amplifier?
   (a) Common-collector circuit (b) Emitter follower circuit
   (c) Common base circuit (d) Common emitter circuit
10. An op-amp with negative feedback provides _____ output parameter.
    (a) Gain (b) Bandwidth
    (c) Input-output impedance (d) Amplified

Section (B): CRQs (Short Answered Questions):

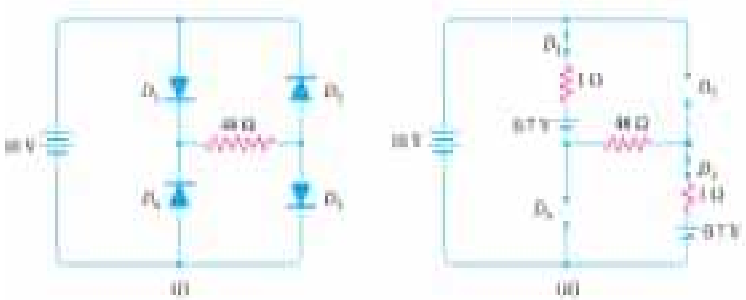
1. Describe a *p-n* junction (diode) and how holes and electrons are produced in semiconductor?
2. Define and distinguish between p-n-p & n-p-n transistors?
3. Explain common-base and common collector configurations?
4. Describe the operations of transistors.
5. Explain the use of transistors as a switch and an amplifier (common-emitter).
6. How would you understand the effects of negative feedback on the gain of an operational amplifier?
7. Draw and briefly describe the circuit diagrams for both the inverting and the non-inverting amplifier for single signal input?
8. Derive an expression for the gain of inverting amplifiers by using virtual earth approximation.
9. Describe the properties of an ideal operational amplifier.

Section (C): ERQs (Long Answered Questions):

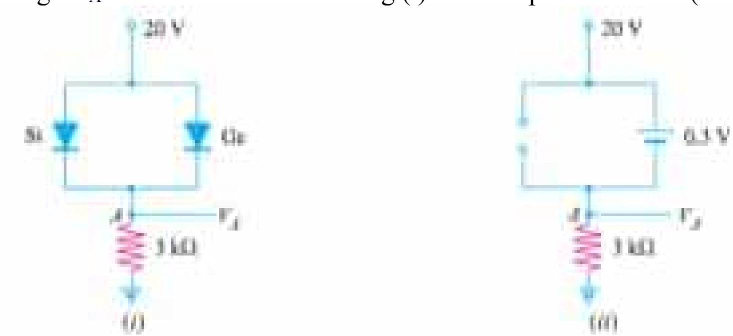
1. Define Intrinsic (pure) and doped semiconductors. And How the N-type and P-type semiconductors are produced
2. Describe a P-N junction (diode) discus its forward and reverse biasing.
3. Describe the I-V characteristic curves of P-N junction.
4. Define rectification and describe the use of diodes for half and full wave rectifications.
5. Describe the function and use of LED, Photodiode and Photo voltaic cell Describe the function and use of LED, Photodiode and Photo voltaic cell.
6. Explain the use of transistors as a switch and an amplifier (common-emitter).
7. Describe the properties of an ideal operational amplifier.

Section (D): Numerical:

1. A Ge diode has a voltage drop of 04 V when 12 mA flow through it. If the same 470 Ohm is used, what battery voltage is needed? **(6.04 V)**
2. A semiconductor diode laser has a peak emission wavelength of 1.55 µm. Find its band gap in eV. **(0.8 eV)**
3. Calculate the current through 48 Ω resistor in the circuit shown in Fig. (i). Assume the diodes to be of silicon and forward resistance of each diode is 1 Ω. **(8.6 V, 50 Ohm, 172 mA)**



4. Find the voltage V_A in the circuit shown in Fig.(i). Use simplified model. (19.7 V)



5. In a common base connection, I_E = 1mA, I_C = 0.95mA. Calculate the value of I_B. **(0.05 mA)**
6. Find the value of β if (i) α = 0.9 (ii) α = 0.98 (iii) α = 0.99. **(9, 49, 99)**
7. Calculate I_E in a transistor for which β = 50 and I_B = 20 µA. **(1.02 mA)**
8. Find the α rating of the transistor shown in Fig. Hence determine the value of I_C using both α and β rating of the transistor. **(0.98, 11.76)**