Sheikh Hasina University, Netrokona

Department of Computer Science and Engineering

CSE-2205: Introduction to Mechatronics

Lec-17: Electrical Actuation System

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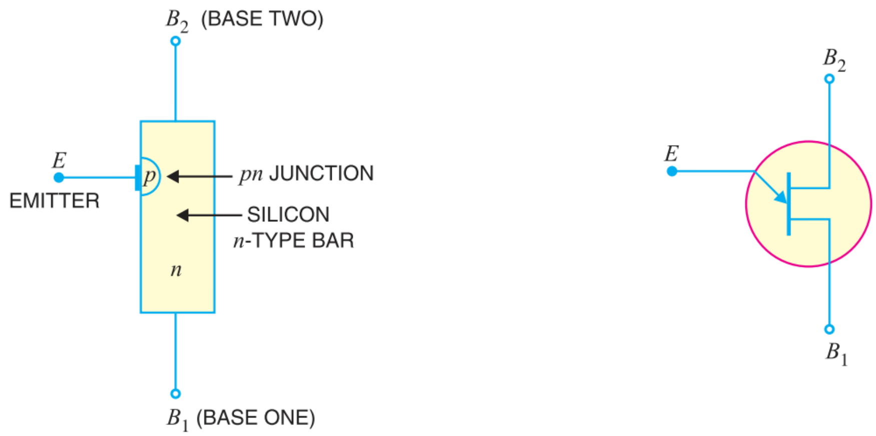
Contents

Unijunction Transistor (UJT)

A Unijunction Transistor (UJT) is a three-terminal semiconductor switching device known for its unique characteristics, especially the regenerative increase in emitter current when triggered. This makes it suitable for various applications such as switching, pulse generation, and saw-tooth generation.

Construction of UJT



(i) (ii)

1. **Basic Structure:** Fig. (i) illustrates the basic structure of a Unijunction Transistor. It consists of an n-type silicon bar with electrical connections on each end.

2. **Terminals:**
   - The leads connected to these connections are called base leads: base-one (B1) and base-two (B2).
   - A pn junction is formed partway along the bar between B1 and B2, closer to B2.
   - The lead to this junction is called the emitter lead (E).

3. **Symbol:** Fig. (ii) shows the symbol of a Unijunction Transistor, where the emitter is depicted closer to B2 than B1.

4. **Common Names:**
   - Since the device has one pn junction and three leads, it is commonly called a Unijunction Transistor (uni means single).
   - Due to having only one pn-junction, the device is essentially a form of a diode, earning it the name double-based diode.

Key Points:

1. **Diode-Like Nature:** With only one pn-junction, the UJT is essentially a form of a diode. The two base terminals are taken from one section of the diode.

2. **Emitter Characteristics:** The emitter is heavily doped with many holes, while the n-region is lightly doped. This results in very high resistance (typically 5 to 10 kΩ) between the base terminals when the emitter lead is open.

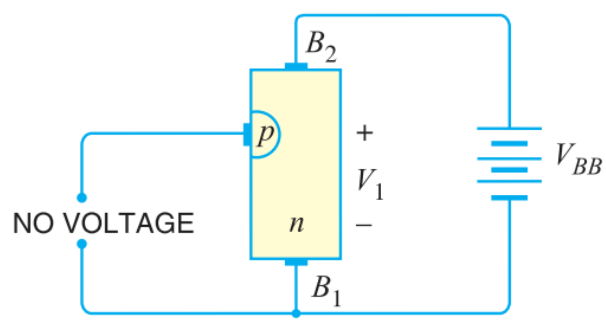
3. **Unique Regenerative Characteristic:** When triggered, the UJT exhibits regenerative behavior, causing the emitter current to increase until it is limited by the emitter power supply.

4. **Applications:** UJTs find applications in switching circuits, pulse generators, saw-tooth generators, and other applications where their unique characteristics are advantageous.

Basic Circuit Operation:

1. **Voltage Gradient Establishment:**

    - Fig. (i) shows the basic circuit operation of a UJT. The device normally has B2 positive with respect to B1.

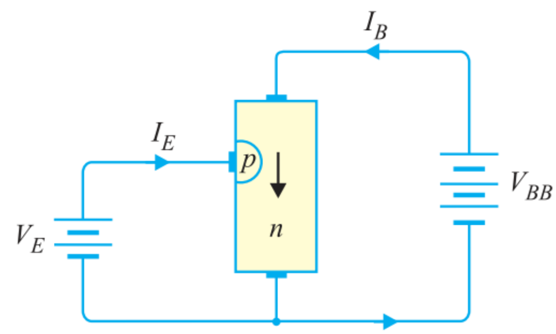


(i)

    - When a voltage VBB is applied between B_2 and B_1 with the emitter open, a voltage gradient is established along the n-type bar.
    - The emitter is located nearer to B_2, so more than half of VBB appears between the emitter and B_1.
    - The voltage V_1 between the emitter and B_1 establishes a reverse bias on the pn junction, cutting off the emitter current. A small leakage current flows from B_2 to the emitter due to minority carriers.

2. **Forward Biasing the pn Junction:**

    - Fig. (ii) considers the case when a positive voltage is applied at the emitter.



(ii)

- If the input voltage to the emitter exceeds V_1, the pn junction becomes forward-biased.
- Holes are injected from the p-type material into the n-type bar. These holes are repelled by the positive B_2 terminal and attracted towards the B_1 terminal.
- This accumulation of holes in the emitter to B_1 region decreases the resistance in this section of the bar.
- The decreased internal voltage drop from emitter to B_1 results in an increase in the emitter current (I_E).
- As more holes are injected, a condition of saturation is eventually reached, and the emitter current is limited by the emitter power supply. The UJT is now in the ON state.

3. **Negative Pulse and OFF State:**
   - Considers the scenario where a negative pulse is applied to the emitter.
   - In this case, the pn junction is reverse-biased, and the emitter current is cut off.
   - The device is then said to be in the OFF state.

Components in the Equivalent Circuit

1. **Interbase Resistance (R_{BB}):**
   - The resistance of the silicon bar is denoted as the interbase resistance (R_{BB}).
   - R_{BB} is represented by two resistors in series:
     - R_{B2}: Resistance of the silicon bar between B_2 and the point where the emitter junction lies.
     - R_{B1}: Resistance of the bar between B_1 and the emitter junction. This resistance is variable, depending on the bias voltage across the pn junction.
   - The total interbase resistance (R_{BB}) is given by $R_{BB} = R_{B1} + R_{B2}$.
   - The typical value of R_{BB} ranges between 4 kΩ and 10 kΩ.
2. **Emitter Diode (D):**
   - The pn junction in the emitter is represented by a diode (D).

- This diode symbolizes the behavior of the emitter junction in response to biasing.

Circuit Action:

1. **No Voltage Applied ($V_{BB} = 0$):**
   - With no voltage applied to the UJT, the interbase resistance is given by

$$R_{BB} = R_{B1} + R_{B2}$$

   - This represents the condition when there is no external bias applied to the UJT.

2. **Voltage Applied ($V_{BB} \neq 0$):**
   - If a voltage VBB is applied between the bases with the emitter open, the voltage will divide across R_{B1} and R_{B2}.
   - The voltage across R_{B1}, denoted as V_1, is given by the voltage division formula:

$$V_1 = \frac{R_{B1}}{R_{B1} + R_{B2}} V_{BB}$$

$$V_1/V_{BB} = \frac{R_{B1}}{R_{B1} + R_{B2}}$$

   The ratio V_1/V_{BB} is called intrinsic stand-off ratio and is represented by Greek letter η.

$$\eta = \frac{R_{B1}}{R_{B1} + R_{B2}}$$

$$\text{Voltage across } R_{B1} = \eta V_{BB}$$

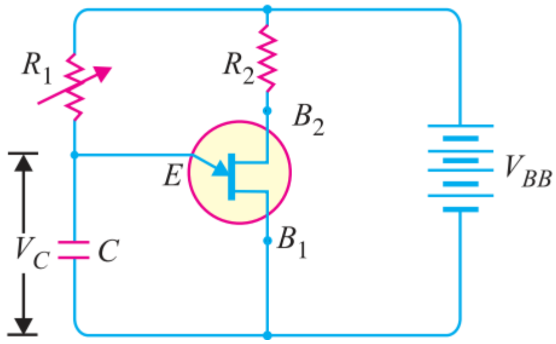
- As a progressively rising positive voltage is applied to the emitter, the diode becomes forward-biased when the input voltage exceeds ηV_{BB} by the forward voltage drop across the silicon diode (V_D).
- The equation representing this condition is

$$V_P = \eta V_{BB} + V_D$$

Applications of UJT

UJT relaxation oscillator

The UJT relaxation oscillator shown in Fig. is a simple electronic circuit that generates a saw-tooth waveform. Here's an explanation of how the oscillator works:



Components of the UJT Relaxation Oscillator:

1. **UJT (Unijunction Transistor):**
    - The UJT is a key component in this circuit. It acts as a switch that controls the charging and discharging of the capacitor.
2. **Resistor R1:**
    - R1 is a resistor connected in series with the charging path of the capacitor. It determines the time constant of the charging circuit and, consequently, the frequency of the output waveform.
3. **Capacitor C:**
    - C is a capacitor that charges and discharges in response to the switching action of the UJT. The charging and discharging of the capacitor produce a saw-tooth waveform at the output.
4. **Battery V_{BB}:**
    - VBB is a voltage source that powers the circuit. When turned on, it initiates the charging and discharging cycles of the capacitor.

Operation of the UJT Relaxation Oscillator:

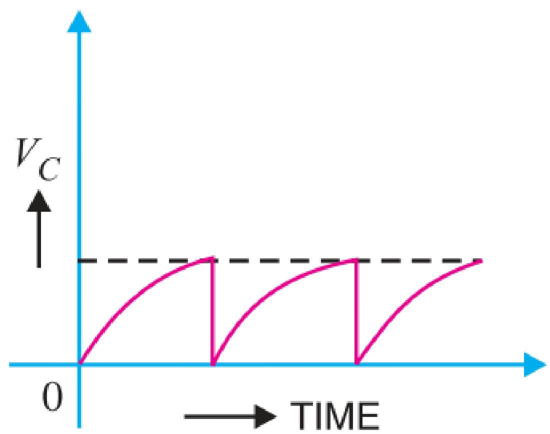
1. **Charging Phase:**
    - When the battery V_{BB} is turned on, the capacitor C starts to charge through resistor R_1.
    - During the charging period, the voltage across the capacitor rises in an exponential manner as it follows the charging curve.
2. **Switching to Discharging:**
    - When the capacitor voltage reaches the peak-point voltage (V_P) determined by the UJT, the UJT switches to its low-resistance conducting mode.
    - The UJT now provides a low-resistance path for the discharge of the capacitor.
3. **Discharging Phase:**

- The capacitor discharges rapidly through the UJT between the emitter (E) and B1.
- As the capacitor voltage rapidly decreases back to zero, the emitter ceases to conduct, and the UJT switches off.

4. **Next Cycle:**
    - The circuit then enters the next cycle, allowing the capacitor to charge again.
    - The process repeats, generating a continuous saw-tooth waveform at the output.

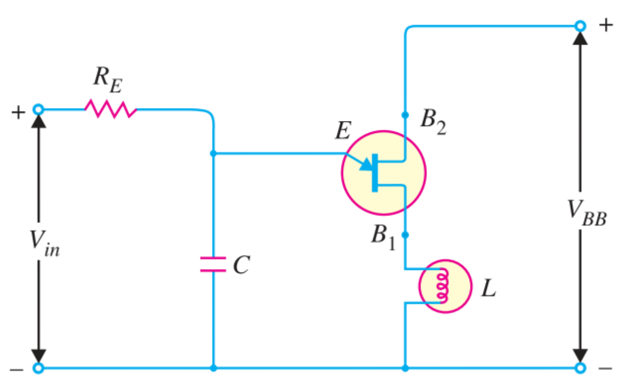
Frequency Control:

- The frequency of the output saw-tooth wave can be adjusted by changing the value of resistor R1.
- R1 influences the time constant (R_1C) of the capacitor charging circuit, and changing its value alters the rate at which the capacitor charges, thereby affecting the oscillator frequency.



Overvoltage detector

The circuit shown in Fig. is an overvoltage detector using a Unijunction Transistor (UJT). Here's an explanation of how the circuit operates:



Components of the Overvoltage Detector:

1. **UJT (Unijunction Transistor):**

- The UJT acts as a switch in the circuit. Its switching action is based on the input voltage exceeding the peak-point voltage (V_P).

2. **Capacitor C:**
   - C is a capacitor connected to the emitter and B_1 of the UJT. It is responsible for discharging when the UJT switches on.
3. **Pilot Lamp L:**
   - The pilot lamp is connected between the emitter and B_1 circuit. It serves as an indicator of overvoltage conditions.

Operation of the Overvoltage Detector:

1. **Normal Operating State:**
   - When the input voltage is less than the peak-point voltage (V_P) of the UJT, the UJT remains switched off.
   - The capacitor C charges through a resistor (not explicitly mentioned in the description but likely present in the circuit).
   - In this state, the pilot lamp L is not lit.
2. **Overvoltage Condition:**
   - When the input voltage exceeds the peak-point voltage (V_P) of the UJT, the UJT switches on.
   - The capacitor C discharges rapidly through the low-resistance path between terminals E and B_1 created by the switched-on UJT.
3. **Indicator Activation:**
   - As the capacitor discharges, a current flow through the pilot lamp L.
   - The current through the lamp causes it to light up, serving as a visual indicator of the overvoltage condition in the circuit.

Functionality:

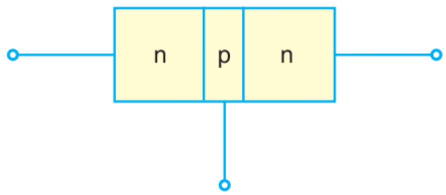
- The UJT serves as a threshold detector. When the input voltage surpasses a certain level (V_P), the UJT switches on, allowing the capacitor to discharge through the UJT.
- The pilot lamp is only lit when the UJT is switched on due to overvoltage. In normal operating conditions, the lamp remains off.

Note:

- The resistor used for charging the capacitor is not explicitly mentioned, but it is assumed to be part of the circuit for the charging process.

- The peak-point voltage (V_P) is a characteristic voltage for the UJT, and when this voltage is exceeded, the UJT switches from its high-resistance to low-resistance state.

Transistors



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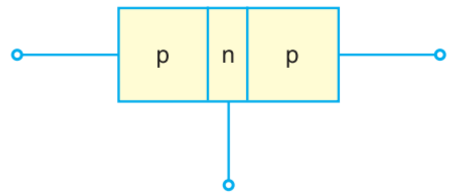


(ii)

NPN Transistor:

1. **Structure:** Composed of two n-type semiconductors with a thin section of p-type in between.
2. **Symbol:** Shown as an arrow pointing outwards from the base, representing the direction of conventional current flow.
3. **Operation:** When a small current flows into the base (the middle p-type layer), it allows a larger current to flow from the collector (the outer n-type layer) to the emitter (the other n-type layer).

PNP Transistor:

1. **Structure:** Formed by two p-type semiconductors with a thin section of n-type in between.
2. **Symbol:** Shown as an arrow pointing into the base, indicating the direction of conventional current flow.
3. **Operation:** Similar to NPN, but the direction of current flow is reversed. When a small current flows out of the base, it allows a larger current to flow from the emitter to the collector.

Key Points:

1. **PN Junctions:** Transistors have two pn junctions, making them essentially two diodes connected back-to-back.
2. **Three Terminals:** Transistors have three terminals: emitter, base, and collector. Each terminal connects to a different semiconductor type.
3. **Thin Middle Section:** The thinness of the middle section is crucial. It allows for the controlled flow of current from the input terminal (base) to the output terminals (collector or emitter), making the transistor an amplifying device.

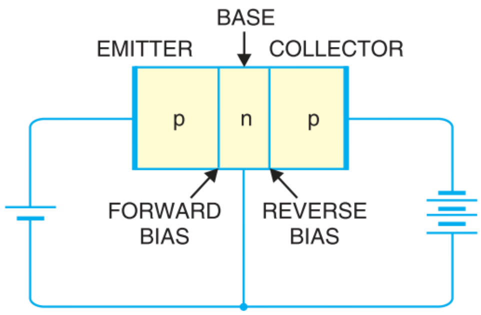
Functionality:

- Transistors act as amplifiers and switches in electronic circuits. They amplify weak signals and are fundamental components in digital and analog circuits.
- The thin middle layer, often called the base, is where the input signal controls the flow of current between the other two layers (collector and emitter).

Applications:

- Amplification of signals in audio and radio frequency circuits.
- Switching in digital circuits.
- Power amplification in electronic devices.

Transistor Structure



(*i*) (*ii*)

Emitter:

- **Function:** Supplies majority charge carriers (electrons or holes) to the base.
- **Biasing:** Always forward biased with respect to the base.
- **Example (PNP):** In a PNP transistor, the emitter (p-type) is forward biased and supplies hole charges to the base.

Collector:

- **Function:** Collects charge carriers injected by the emitter.
- **Biasing:** Always reverse biased.
- **Example (PNP):** In a PNP transistor, the collector (p-type) is reverse biased and receives hole charges that flow in the output circuit.

Base:

- **Function:** Forms two pn-junctions between the emitter and collector.
- **Base-Emitter Junction:** Forward biased, allowing low resistance for the emitter circuit.
- **Base-Collector Junction:** Reverse biased, providing high resistance in the collector circuit.

Additional Facts:

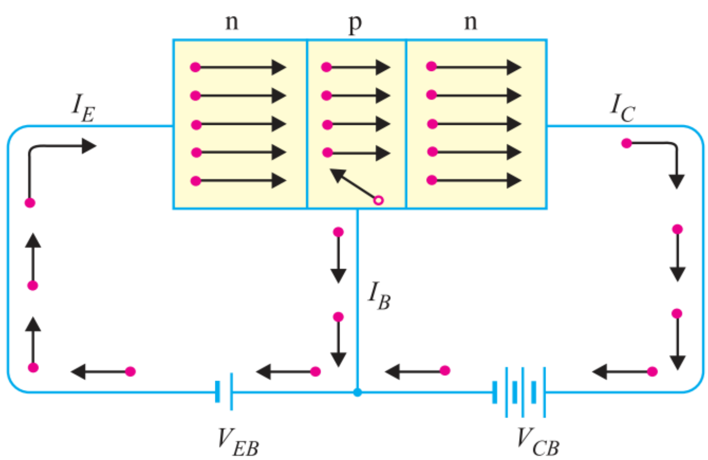
1. **Relative Sizes:** The base is much thinner than the emitter, while the collector is wider than both. However, for simplicity, diagrams often show the emitter and collector to be of equal size.
2. **Doping Levels:**
    - **Emitter:** Heavily doped to inject a large number of charge carriers.

- **Base:** Lightly doped and very thin to allow most of the injected carriers to reach the collector.
- **Collector:** Moderately doped.

Important Points:

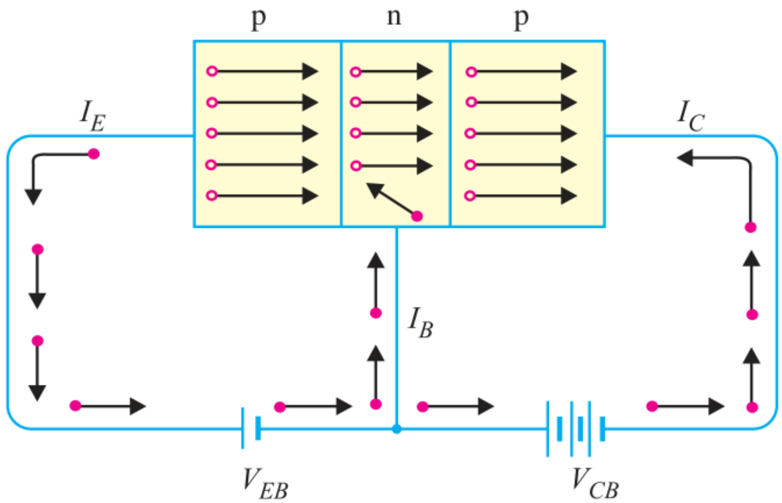
- Transistors, whether PNP or NPN, have three regions: emitter, base, and collector.
- The emitter is always forward biased, the collector is always reverse biased.
- The base facilitates the control of current flow between the emitter and collector.

NPN Transistor Action



1. **Configuration:**
    - Forward bias on the emitter-base junction (n-type emitter, p-type base).
    - Reverse bias on the collector-base junction (n-type collector, p-type base).
2. **Operation:**
    - Electrons in the n-type emitter flow towards the base, constituting the emitter current (IE).
    - Only a small percentage (less than 5%) of these electrons combine with holes in the p-type base, forming the base current (IB).
    - The majority of electrons (more than 95%) cross into the n-type collector, forming the collector current (IC).
    - Almost the entire emitter current flows into the collector circuit.
3. **Relationship:**
    - The emitter current (IE) is the sum of the base current (IB) and collector current (IC): IE = IB + IC.

PNP Transistor Action



1. **Configuration:**
   - Forward bias on the emitter-base junction (p-type emitter, n-type base).
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2. **Operation:**
   - Holes in the p-type emitter flow towards the base, constituting the emitter current (IE).
   - Only a small percentage (less than 5%) of these holes combine with electrons in the n-type base, forming the base current (IB).
   - The majority of holes (more than 95%) cross into the p-type collector, forming the collector current (IC).
   - Almost the entire emitter current flows into the collector circuit.
3. **Note:**
   - While current conduction within the pnp transistor is by holes, in the external connecting wires, the current is still carried by electrons.

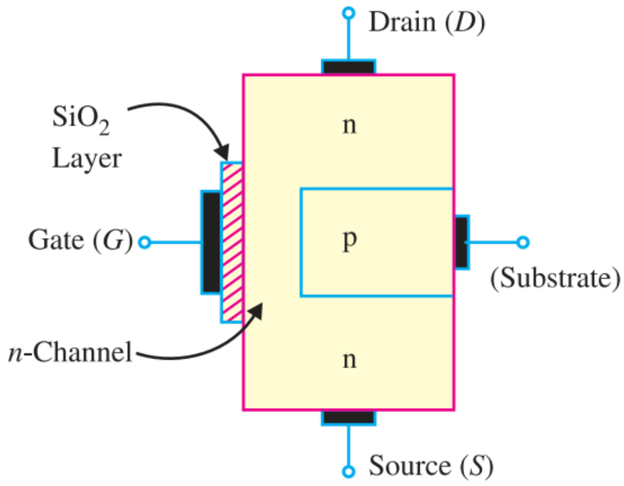
Metal Oxide Semiconductor FET (MOSFET)

Drawbacks of JFET and Introduction to MOSFET:

The JFET (Junction Field Effect Transistor) has a limitation in that its gate must be reverse biased for proper operation, restricting it to negative gate operation for n-channel and positive gate operation for p-channel. This limitation results in depletion-mode operation only. However, the Metal Oxide Semiconductor FET (MOSFET) addresses this issue by allowing both depletion-mode and enhancement-mode operations.

Types of MOSFETs:

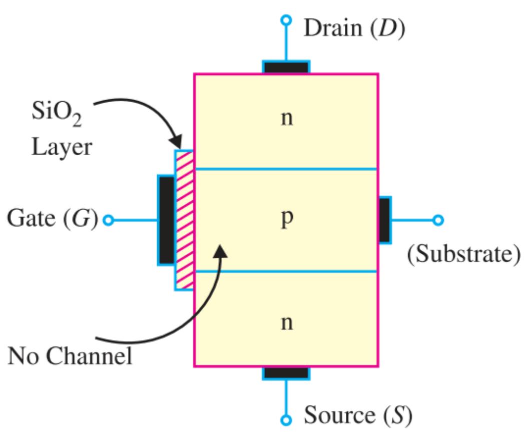
1. **Depletion-type MOSFET (D-MOSFET):**



n-Channel D-MOSFET

- **Operation Modes:** Depletion-mode and enhancement-mode.
- **Construction:** The n-channel D-MOSFET consists of a piece of n-type material with a p-type region (substrate) on the right and an insulated gate on the left. Electrons flow from source to drain through the narrow channel between the gate and the p-type substrate.
- **Gate Construction:** The gate features a thin layer of insulating material, usually silicon dioxide (SiO2), forming a capacitor. The metallic gate is deposited over the oxide layer, and the arrangement creates a capacitor with the gate and the channel separated by SiO2.
- **Terminal Connection:** The substrate is commonly connected to the source internally.
- **Operation:** The D-MOSFET can be operated in both depletion-mode and enhancement-mode due to the insulated gate.

2. **Enhancement-type MOSFET (E-MOSFET):**



n-Channel E-MOSFET

- **Operation Mode:** Enhancement-mode.
- **Construction:** The E-MOSFET is designed for enhancement-mode operation only.

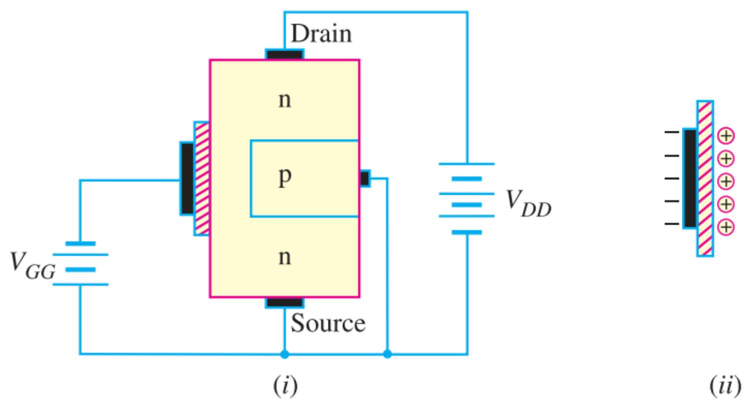
- **Operation:** The E-MOSFET can be operated solely in enhancement-mode, allowing increased channel width and conductivity.

Advantages of MOSFET over JFET:

- **High Input Impedance:** MOSFETs offer high input impedance.
- **Cost of Production:** MOSFET production is cost-effective compared to JFET.

D-MOSFET

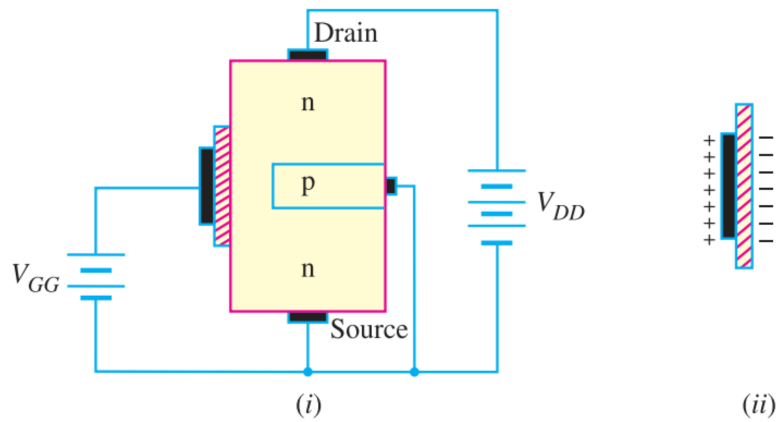
Circuit Diagram:



Depletion Mode Operation:

1. **Circuit Operation (Depletion Mode):**
    - The gate forms a small capacitor, with one plate being the gate and the other plate being the channel, separated by a metal oxide layer.
    - When the gate voltage is negative, electrons accumulate on the gate (Fig. 19.47 ii).
    - These electrons repel the free electrons in the n-channel, leading to a layer of positive ions in part of the channel (Fig. 19.47 ii).
    - This depletion (emptying) of the n-channel reduces the number of free electrons available for conduction, effectively increasing the channel's resistance.
    - The negative gate voltage results in a resistance change in the n-channel, affecting the current from source to drain.
    - The more negative the gate voltage, the lower the current.

Enhancement Mode Operation:



2. **Circuit Operation (Enhancement Mode):**

    - In enhancement-mode operation, the gate is positively biased.
    - The gate, acting as a capacitor, induces negative charges in the n-channel (Fig. 19.48 ii).
    - These negative charges are additional free electrons drawn into the channel.
    - The positive gate voltage enhances the conductivity of the channel by increasing the total number of free electrons.
    - The greater the positive voltage on the gate, the higher the conduction from source to drain.
    - Unlike JFET, D-MOSFET allows applying positive gate voltage and still maintaining essentially zero current.
    - The positive gate operation is termed enhancement mode, as it enhances the conductivity of the channel.

Summary:

- **Depletion Mode:** Negative gate voltage depletes the n-channel, increasing resistance and reducing current.
- **Enhancement Mode:** Positive gate voltage enhances the n-channel's conductivity, increasing current.

D-MOSFET provides flexibility with both depletion-mode and enhancement-mode operations, offering a versatile semiconductor device for various applications.

Enhancement-Type MOSFET (E-MOSFET)

Structure of E-MOSFET:

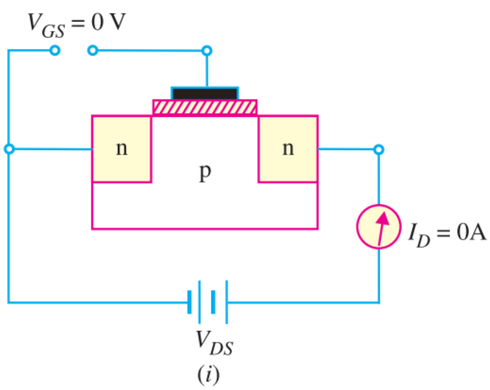
1. **Overview:**

    - The E-MOSFET (Enhancement-Type MOSFET) operates only in the enhancement mode, lacking a depletion mode.

- Unlike D-MOSFET, E-MOSFET has no physical channel connecting the source and drain when VGS = 0V.
- The substrate extends completely to the SiO2 layer [Fig. 19.55 (i)], and the device is normally OFF with zero VGS.

2. **Threshold Voltage (VGS (th)):**
    - E-MOSFET requires a gate-to-source voltage (VGS) of proper magnitude and polarity to start conducting.
    - The minimum value of VGS required to turn on the E-MOSFET is known as the threshold voltage [VGS (th)].
    - For n-channel E-MOSFET, it requires a positive VGS (greater than VGS (th)), while p-channel E-MOSFET requires a negative VGS (less than VGS (th)).

Operation of N-Channel E-MOSFET:



3. **Circuit Operation (N-Channel E-MOSFET):**
    - **OFF State (VGS = 0V):**
        - When VGS is zero [Fig. 19.55 (i)], there is no physical channel connecting the source and drain.
        - The p substrate has only a few thermally produced free electrons, resulting in essentially zero drain current (ID).
        - E-MOSFET is normally OFF at zero VGS, distinguishing it from JFET or D-MOSFET.
    - **ON State (Positive VGS):**
        - When VGS is positive [Fig. 19.55 (ii)], it attracts free electrons into the p region.
        - These free electrons combine with the holes near the SiO2 layer, creating a thin layer of n-type material (inducing an n-channel) adjacent to the SiO2 layer.
        - The E-MOSFET is turned ON, allowing drain current (ID) to flow from the source to the drain.

Applications of MOSFETs:

1. **Motor Control:**
    - MOSFETs are frequently used in motor control circuits. They act as switches to control the power supplied to motors, enabling precise speed and direction control in mechatronic systems.
2. **Inverter Circuits:**
    - MOSFETs are essential components in DC to AC inverter circuits, converting direct current (DC) to alternating current (AC). This is particularly important in mechatronic systems where AC power may be required.
3. **Switching Power Supplies:**
    - MOSFETs are commonly used in the power switching stages of switching power supplies. They provide efficient control of power flow and voltage regulation in mechatronic devices.
4. **Signal Amplification:**
    - MOSFETs can be used for signal amplification in low-power electronic systems, aiding in the processing of sensor signals and other low-level electronic inputs in mechatronic applications.
5. **Audio Amplifiers:**
    - In mechatronic systems that involve audio processing or communication, MOSFETs are used in audio amplifier circuits to boost and control audio signals.
6. **Analog Switching:**
    - MOSFETs can be employed in analog switching applications, facilitating the routing of analog signals between different components or subsystems in a mechatronic system.
7. **Switched-Mode Power Supplies (SMPS):**
    - MOSFETs are integral to the operation of SMPS, providing high-efficiency power conversion in mechatronic devices.
8. **Microcontroller Interface:**
    - MOSFETs are used to interface microcontrollers with high-power devices. They act as buffers, isolating the sensitive microcontroller circuitry from the higher power requirements of actuators and motors.
9. **Voltage Regulation:**
    - MOSFETs are utilized in voltage regulation circuits, ensuring a stable and regulated power supply for various components in mechatronic systems.