Lecture 10: Field Effect Transistors (FETs)

Introduction to Field Effect Transistors (FETs)

Field Effect Transistors (FETs) are a class of transistors that use an electric field to control the flow of current. Unlike Bipolar Junction Transistors (BJTs), which rely on current control, FETs operate by voltage control, making them more energy-efficient in many applications. FETs are widely used in digital circuits, analog amplification, and switching applications.

Basic Structure and Operation of FETs

A FET consists of three primary terminals:

- **Source (S):** The terminal through which charge carriers enter the transistor.
- **Drain (D):** The terminal through which charge carriers leave the transistor.
- **Gate (G):** The terminal used to control the flow of carriers between the source and the drain.

The main channel between the source and drain is made of either **n-type** or **p-type** semiconductor material. Depending on the channel type, FETs are classified as:

- **N-channel FETs:** The channel is made of n-type material, and electrons are the primary charge carriers.
- **P-channel FETs:** The channel is made of p-type material, and holes are the primary charge carriers.

Working Principle

FETs operate by applying a voltage to the gate terminal, which controls the width of the conducting channel between the source and drain. The relationship between the gate voltage (V_G) and the source-drain current (I_D) determines the FET's behavior:

- When the gate voltage is below a certain threshold (V_{th}), the channel is OFF, and no current flows.
- When the gate voltage exceeds V_{th}, the channel opens, allowing current to flow between the source and drain.

Types of FETs

The two most common types of FETs are:

1. **Junction Field Effect Transistors (JFETs):** The gate forms a PN junction with the channel.
2. **Metal-Oxide-Semiconductor Field Effect Transistors (MOSFETs):** The gate is insulated from the channel by a thin oxide layer, allowing for very high input impedance.

FETs as Voltage-Controlled Switches

FETs are ideal for use as switches because of their high input impedance and fast switching speed. In a typical circuit:

- An N-channel MOSFET conducts when the gate voltage (V_G) is positive relative to the source (V_S).
- A P-channel MOSFET conducts when V_G is negative relative to V_S.

Example: Simple Switching Circuit

Consider an N-channel MOSFET used to control a load (e.g., an LED):

- The source is connected to ground.
- The drain is connected to one side of the load, with the other side connected to a power supply.
- When V_G exceeds V_{th}, the MOSFET turns ON, completing the circuit and powering the load.

FETs in Analog Amplification

FETs are also used as amplifiers in analog circuits due to their linear behavior in certain operating regions:

- In the **saturation region**, the drain current (I_D) is relatively constant and depends on the gate-source voltage (V_{GS}).
- The gain of a FET amplifier is determined by the transconductance (g_m) and the load resistance (R_L):

$$A_v = g_m R_L, \quad \text{where} \quad g_m = \frac{\partial I_D}{\partial V_{GS}}.$$

Example: Common-Source Amplifier In a common-source configuration:

- The input signal is applied between the gate and source.

- The output is taken from the drain and source.
- The circuit provides voltage gain, making it suitable for audio and RF applications.

Comparing BJTs and FETs

While both BJTs and FETs are used in amplification and switching, they differ in several ways:

- **Control Mechanism:** BJTs are current-controlled devices, while FETs are voltage-controlled.
- **Input Impedance:** FETs have a much higher input impedance than BJTs, making them more energy-efficient.
- **Switching Speed:** FETs are generally faster than BJTs, especially in digital applications.
- **Linear Amplification:** BJTs offer higher gain in linear regions, making them more suitable for some analog applications.

Example Problems

1. **Problem 1: Threshold Voltage and Switching**
   - An N-channel MOSFET has a threshold voltage (V_{th}) of $2\,\mathrm{V}$. Calculate whether the MOSFET is ON or OFF for $V_G = 1.5\,\mathrm{V}$ and $V_G = 3\,\mathrm{V}$.
   - **Solution:**
     - For $V_G = 1.5\,\mathrm{V}$: Since $V_G < V_{th}$, the MOSFET is OFF.
     - For $V_G = 3\,\mathrm{V}$: Since $V_G > V_{th}$, the MOSFET is ON.
2. **Problem 2: Simple Amplifier**
   - Design a common-source FET amplifier with a transconductance (g_m) of $2\,\mathrm{mS}$ and a load resistance (R_L) of $1\,\mathrm{k\Omega}$. Calculate the voltage gain (A_v).
   - **Solution:** The voltage gain is:

$$A_v = g_m R_L = (2 \times 10^{-3}) \cdot (1 \times 10^{3}) = 2.$$

Summary

- FETs are voltage-controlled devices widely used in modern electronics.
- They can function as efficient switches or linear amplifiers.

- Compared to BJTs, FETs offer higher input impedance and faster switching, making them suitable for digital applications.
- Understanding the operation regions (cutoff, linear, saturation) is key to designing circuits with FETs.