Lecture 4: Transistor Transfer Characteristics & Shockley's Equation

1. Introduction to Field-Effect Transistors (FETs)

Field-Effect Transistors (FETs) are voltage-controlled devices, where the output current is controlled by an input voltage. Unlike Bipolar Junction Transistors (BJTs), which are current-controlled, FETs offer high input impedance, making them ideal for various electronic applications.

1.1. Key Terminology

- **Drain (D)**: The terminal where charge carriers leave the channel.
- **Source (S)**: The terminal where charge carriers enter the channel.
- **Gate (G)**: The terminal that controls the flow of charge carriers through the channel.
- **V_{GS}**: Gate-to-Source voltage.
- **V_{DS}**: Drain-to-Source voltage.
- **I_D**: Drain current.

2. Shockley's Equation

For a Junction Field-Effect Transistor (JFET) and Depletion-type MOSFET (D-MOSFET), the relationship between the drain current (I_D) and the gate-to-source voltage (V_{GS}) in the saturation region is defined by **Shockley's Equation**:

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$$

Variables and Parameters:

- **I_{DSS}**: Maximum drain current (at $V_{GS} = 0V$).
- **V_P**: Pinch-off voltage (also known as $V_{GS(off)}$), where I_D becomes zero.
- **V_{GS}**: The controlling input voltage.

***Note**: Shockley's equation is a "square-law" relationship, meaning the transfer characteristic curve is parabolic rather than linear.*

3. JFET Transfer Characteristics

The **Transfer Characteristic Curve** is a plot of the drain current (I_D) as a function of the gate-source voltage (V_{GS}) for a constant drain-source voltage (V_{DS}).

JFET Transfer Curve

For an n-channel JFET, V_{GS} is typically negative. As V_{GS} becomes more negative, the depletion region widens, narrowing the channel and reducing I_D. When $V_{GS} = V_P$, the channel is completely pinched off, and $I_D = 0$.

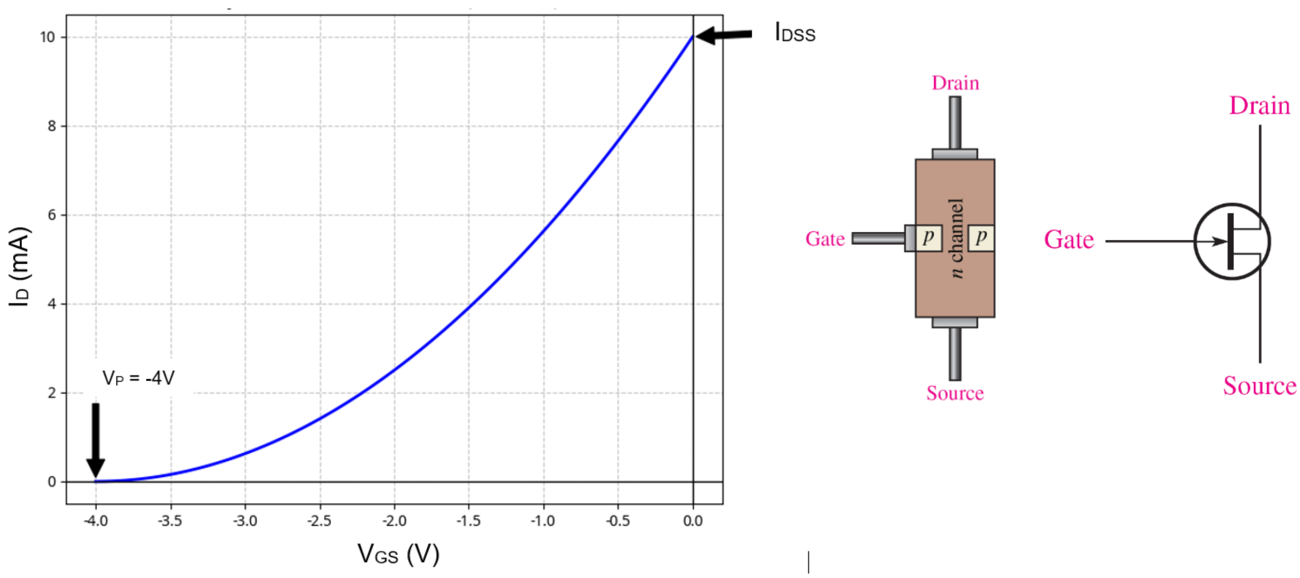

Figure 1 JFET Transfer Characteristics (n-Channel)

Relationship with Drain Characteristics

The transfer curve can be derived from the saturation points of the drain (output) characteristics. While the drain curve shows I_D vs V_{DS}, the transfer curve highlights the control aspect of the gate voltage.

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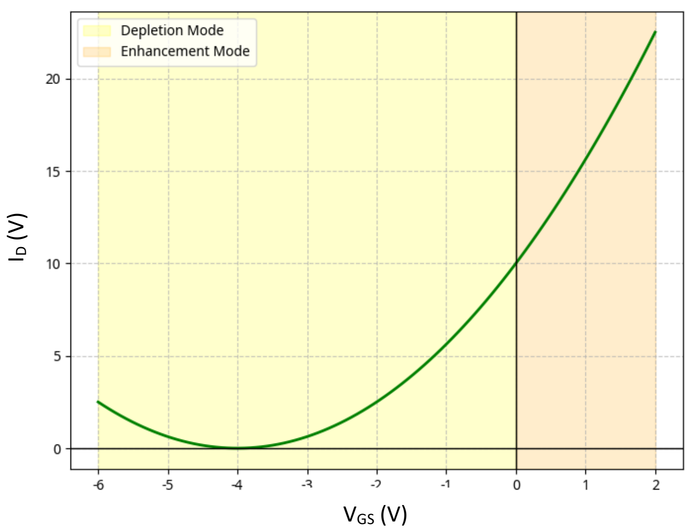
4. MOSFET Transfer Characteristics

4.1. Depletion-type MOSFET (D-MOSFET)

D-MOSFETs can operate in both **Depletion Mode** (negative V_{GS}) and **Enhancement Mode** (positive V_{GS}). Shockley's equation still applies across both regions.



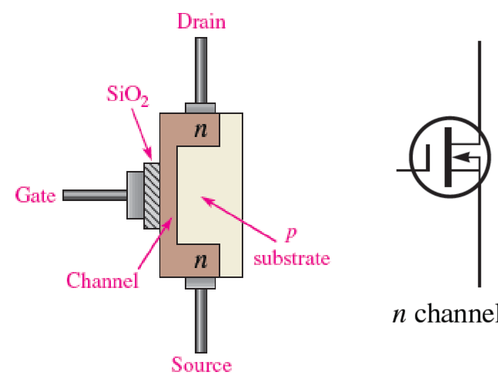


Figure 2 D-MOSFET Transfer Characteristics (n-channel)

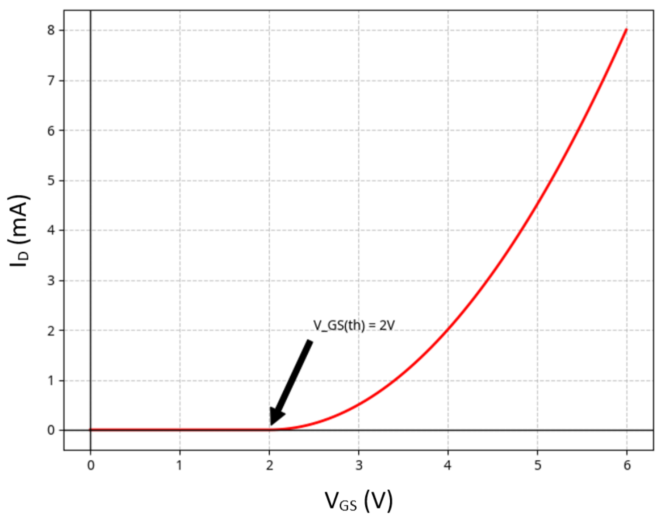
4.2. Enhancement-type MOSFET (E-MOSFET)

E-MOSFETs do not have a pre-formed channel. They require a minimum threshold voltage (**$V_{GS(th)}$**) to create a channel and begin conducting. The equation for E-MOSFETs is:

$$I_D = k(V_{GS} - V_{GS(th)})^2$$

$$k = \mu_n C_{ox} \frac{W}{L}$$

μ_n	Electron mobility in the channel (how fast electrons move)
C_{ox}	Gate oxide capacitance per unit area
W	Channel width
L	Channel length



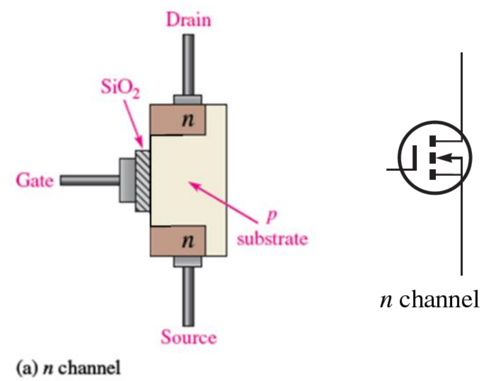


Figure 3 E-MOSFET Transfer Characteristics (n-channel)

Problem 1: A JFET has $I_{DSS} = 12$ mA and $V_P = -4$ V. Calculate the drain current (I_D) for $V_{GS} = -2$ V.

Solution:

Identify the given values: $I_{DSS} = 12$ mA, $V_P = -4$ V, $V_{GS} = -2$ V.

Apply Shockley's Equation:

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$$

$$I_D = 12\text{ mA} \times \left(1 - \tfrac{-2\text{ V}}{-4\text{ V}}\right)^2$$

$$I_D = 12\text{ mA} \times (1 - 0.5)^2$$

$$I_D = 12\text{ mA} \times (0.5)^2 = 12\text{ mA} \times 0.25 = 3\text{ mA}$$

Problem 2: For the same JFET ($I_{DSS} = 12$ mA, $V_P = -4$ V), find the V_{GS} required to achieve $I_D = 6$ mA.

HOMEWORK

7. Summary

- **Shockley's Equation** defines the non-linear relationship in JFETs and D-MOSFETs.
- **Transfer Characteristics** provide a visual representation of how input voltage controls output current.
- **High Input Impedance** is the primary advantage of FETs over BJTs.
- **Square-law behavior** is a fundamental characteristic of FET operation in the saturation region.

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