1. MOSFET Overview

Structure and Types: MOSFETs have four terminals: Gate (G), Source (S), Drain (D), and Body (B). The two main types are:

- **nMOS**: n-channel, p-type substrate, electrons as majority carriers.
- **pMOS**: p-channel, n-type substrate, holes as majority carriers.

Operating Regions:

- **Cutoff**: $V_{GS} < V_t$, no channel, $I_D = 0$.
- **Triode**: $V_{GS} > V_t, V_{DS} < V_{OV}$, MOSFET acts as a resistor.
- **Saturation**: $V_{GS} > V_t, V_{DS} \geq V_{OV}$, MOSFET acts as a current source.

Body Effect: Threshold voltage V_t changes with body-to-source voltage V_{BS}:

$$V_t = V_{t0} + \gamma(\sqrt{|2\phi_F + V_{BS}|} - \sqrt{|2\phi_F|})$$

where V_{t0} is V_t at $V_{BS} = 0$, γ is the body-effect coefficient, and ϕ_F is the Fermi potential.

2. Amplifier Configurations

Key Configurations:

1. **Common-Source (CS)**:
   - High gain, inverts signal, moderate input impedance.
   - Voltage gain: $A_v = -g_m(R_D||r_o)$.
2. **Common-Gate (CG)**:
   - No signal inversion, low input impedance, high gain.
   - Voltage gain: $A_v = g_m R_D$.
3. **Source Follower (SF)**:
   - Unity gain, high input impedance, low output impedance.
   - Voltage gain: $A_v \approx 1$.

3. MOSFET Characteristics

Drain Current (Saturation):

$$I_D = \frac{1}{2}k_n\frac{W}{L}(V_{GS} - V_t)^2(1 + \lambda V_{DS})$$

where λ accounts for channel-length modulation. **Transconductance** g_m:

$$g_m = \frac{\partial I_D}{\partial V_{GS}} = \frac{2I_D}{V_{OV}}, \quad V_{OV} = V_{GS} - V_t$$

4. Small-Signal Model

Components:

- **Controlled current source** $g_m v_{gs}$: Models gate control over drain current.
- **Output resistance** r_o: Models channel-length modulation.
- **Parasitic capacitances**: C_{gs}, C_{gd}, limiting high-frequency performance.

Gain-Bandwidth Trade-Off: Increasing gain reduces bandwidth due to the constant gain-bandwidth product.

5. Practical Design Notes

Biasing Methods:

- **Fixed bias**: Simple, sensitive to parameter variations.
- **Voltage-divider bias**: Stable, adds resistors.
- **Current-source bias**: High precision, complex design.

Coupling Capacitors: Allow AC signals while blocking DC, enabling independent biasing of stages.

6. MOSFETs in Digital Circuits

Applications: Operated as switches in cutoff ($V_{GS} < V_t$) and saturation ($V_{GS} > V_t, V_{DS} > V_{OV}$) regions for digital logic.

7. Amplifier Analysis Procedure

1. Determine DC operating point (biasing). 2. Develop small-signal model. 3. Solve for gain, input resistance, and output resistance. 4. Verify assumptions (small-signal conditions, operating region).

8. Key Parameters

- **Voltage Gain** (A_v): Ratio of output to input voltage.
- **Input Resistance** (R_{in}): Determines loading on input source.
- **Output Resistance** (R_{out}): Affects ability to drive loads.

9. Definitions and Notes

- **Channel-Length Modulation** (λ): Causes I_D to depend on V_{DS} in saturation.
- **Process Transconductance Parameter** (k_n'): Depends on carrier mobility and oxide capacitance.
- **Threshold Voltage** (V_t): Gate voltage needed to form a conducting channel.

10. Summary

MOSFET amplifiers leverage the transistor's operation in saturation for signal amplification. CS, CG, and SF configurations serve different purposes, balancing gain, impedance, and signal characteristics. Proper biasing and small-signal modeling are critical for effective amplifier design.