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## Performance Analysis of BJT and MOSFET in Amplifier Configurations

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## Abstract

This reading project presents a detailed comparative study between Bipolar Junction Transistors (BJT) and Metal Oxide Semiconductor Field Effect Transistors (MOSFET) when used in different amplifier configurations. The analysis focuses on their **voltage gain**, **input–output impedance**, **frequency response**, **power dissipation**, and **linearity characteristics**. Drawing upon established research and simulation results, this work investigates the performance of common-emitter and common-source amplifiers, as well as advanced configurations such as Darlington pairs and multi-stage MOSFET amplifiers.
The findings highlight that **BJTs generally provide higher transconductance and voltage gain for low-frequency signals**, while **MOSFETs exhibit superior high-frequency response, thermal stability, and efficiency**, making them ideal for integrated circuit (IC) and low-power applications.
A proposed new circuit model using two MOSFETs and a BJT in a **Triple Darlington configuration (Circuit-2)** was shown to successfully amplify small-signals of 1–10mV range. This circuit provides high voltage gain (**311.593**) and current gain (**13.971K**) with a low distortion percentage (**1.28%**). The MOSFET-dominant nature of this unit motivates the extraordinarily high current gain.

## Introduction

Amplifiers are fundamental building blocks in analog electronics, designed to increase the amplitude of electrical signals without altering their waveform characteristics. Most electronic systems require amplifiers for scaling signals to a useful level when output signals are too small to be processed reliably. The performance of these circuits is heavily dependent on the type of active device—typically a BJT or MOSFET—used as the main amplifying element.

• **BJT Amplifiers** are **current-controlled devices** that rely on base current modulation, providing high transconductance and gain. However, a major drawback is that they suffer from **higher power losses and lower input impedance**. The maximal voltage gain for a passive load Common-Emitter (CE) stage cannot exceed an upper barrier related to the ratio $V_{CC}/V_T$.

• **MOSFET Amplifiers** are **voltage-controlled devices**, offering **higher input impedance**, **better thermal stability**, and **smaller leakage currents**. They dominate in modern **VLSI** and **low-power analog systems**. The maximal gain for a passive load Common-Source (CS) stage is limited by the ratio $0.5V_{DD}/V_{OV}$.

This project systematically examines the roles of these two devices in different amplifier configurations—Common Emitter (CE) and Common Source (CS)—and provides insight into their advantages, limitations, and application domains.

## Literature Review

The project synthesizes findings from various studies comparing BJT and MOSFET characteristics.

1. **Small-Signal Amplifier with MOSFET and BJT in Triple Darlington Configuration:** This research introduced a hybrid amplifier design (Circuit-2) combining BJT and MOSFET devices in a Triple Darlington configuration. This model demonstrated high input impedance and voltage gain suitable for **low-frequency audio amplification**. The finding was that the hybrid BJT-MOSFET combination improved gain and reduced distortion compared to a conventional BJT amplifier. The qualitative performance of this proposed amplifier (Circuit-2) was compared with a reference circuit (Circuit-1) that uses a BJT-MOSFET in a Darlington pair configuration.

2. **Analysis and Design of MOSFET-Based Amplifier in Different Configurations:** This research explored the characteristics of Common Source, Common Drain, and Common Gate configurations using NMOS transistors. The findings indicated that the **Common Source amplifier provided the highest voltage gain** (e.g., a practical gain of 10.11). In contrast, the **Common Drain amplifier (source follower) excelled in impedance matching and signal buffering**.

3. **A Comprehensive Study of Gain Characterization in MOSFETs:** This study focused on the voltage gain dependence on MOSFET transconductance ($g_m$) and channel length modulation ($\lambda$). The finding emphasized that gain increases with **higher $g_m$ and lower $\lambda$** (channel length modulation), stressing the influence of biasing and device geometry on overall amplifier efficiency. This research systematically varied parameters like transistor area, temperature, and mobility to understand their impact on gain.

4. **RF-LNA Comparison:** A simulation comparing Cascode CMOS LNA and Cascode BJT LNA at 1.0 GHz concluded that the use of **low-cost and high integration CMOS technology results in a penalty in the power dissipation and frequency response**, which are much better in bipolar technology.

## Objective of the Study

The key objectives of this reading project, adopted from the preliminary framework, are designed to conduct a thorough comparative analysis:

1. **To study the operational principles** of BJTs and MOSFETs in amplifier applications.
2. **To compare their performance metrics**—gain, bandwidth, impedance, and efficiency.
3. **To analyze the effect of biasing and device configuration** on amplification.
4. **To interpret findings from simulation-based and theoretical analyses** available in the literature.

5. **To derive conclusions regarding the optimal choice of transistor type** for various amplifier applications.

# Theory Background

Unified Gain Relations (BJT vs. MOSFET)
Although BJT and MOSFET have different device equations, surprising similarities can be highlighted in terms of voltage gain expressions. This unified perspective simplifies the learning process.
The voltage gain can be expressed as a ratio between a voltage determined by the load (equivalent Early voltage or supply voltage) and a characteristic voltage inherent to the transistor.
• **Characteristic Voltage Replacement:** The **thermal voltage (**$V_T$**)** in BJT amplifier relations can be replaced by **half of the overdrive voltage (**$0.5V_{OV}$**)** to obtain valid and similar relations for MOSFET amplifiers.
• **Transconductance (**$g_m$**)**: For BJT, $g_m = I_C/V_T$. For MOSFET, $g_m = 0.5 I_D/V_{OV}$.
• **Maximal Passive Load Gain:** This is expressed as a ratio between the voltage supply ($V_{CC}$ or $V_{DD}$) and the characteristic voltage ($V_T$ or $0.5V_{OV}$).
• **Active Load (Current-Source) Gain:** The voltage gain is a ratio between the equivalent Early voltage ($V_{Aeq}$) and the characteristic voltage ($V_T$ or $0.5V_{OV}$). This topology is attractive for analog ICs as the gain is no longer dependent on the supply voltage and has better values.

**MOSFET Parameter Impact on Gain**

Voltage gain is a crucial parameter in circuit design. In MOSFETs, gain is represented as the ratio of output voltage to input voltage. Since gain is primarily a function of transconductance, load resistance, and drain resistance, it is highly sensitive to several parameters:

• **Length (L) and Width (W):** Length and Width constitute the transistor area. Since gain is dependent on the $W/L$ ratio, **larger width values correlate with higher gain**, while **smaller lengths tend to correlate with higher gain**.
• **Mobility (**$\mu$**):** Mobility is an extremely sensitive parameter. **Higher values of mobility correlate to higher values of gain**. Mobility is strongly impacted by temperature.
• **Temperature (T):** As temperature increases, the mobility of majority carriers decreases due to higher collision rates between them and the ions. This leads to a **decrease in voltage gain, current gain, and bandwidth** for the proposed amplifier (Circuit-2).
• **Oxide Thickness (**$t_{ox}$**):** A thicker oxide would correspond to a lower permittivity, which would likely correlate to a **smaller gain**.
• **Capacitance:** Parasitic capacitances (gate-source, gate-drain) primarily impact device qualities such as speed. Variations in these overlap capacitances were found to have **no impact on gain**.

# Amplifier Configurations

The analysis covers both single-stage MOSFET configurations and complex hybrid BJT-MOSFET composite units.
Single-Stage MOSFET Configurations

| Configuration | Input/Output Connection | Primary Characteristic | Example Gain (Simulation) |
|---|---|---|---|
| **Common Source (CS)** | Input: Gate, Output: Drain | **Highest Voltage Gain Potential**. Most widely used configuration. | Practical gain of **10.11**. |
| **Common Drain (CD)** | Input: Gate, Output: Source | **Voltage buffer** (gain near unity). Used for **impedance matching and signal buffering**. | Practical gain of **0.785**. |
| **Common Gate (CG)** | Input: Source, Output: Drain | Used as a **current buffer or voltage amplifier**. Desirable in CMOS RF receivers due to ease of impedance matching and low noise. | Practical gain of **8.8**. |

Composite BJT/MOSFET Configurations

• **Darlington Pair (Circuit-1):** A composite unit of two similar transistors, consisting of a BJT and a MOSFET in this case. It has superior characteristics regarding current gain but a major drawback is its **poorer response at higher frequencies** than that of a single transistor amplifier. Circuit-1 generally behaves like a BJT dominating Darlington unit due to the BJT acting as the driver device.

• **Triple Darlington (Circuit-2):** Uses two identical MOSFETs and one BJT in 'Triple Darlington topology'. This configuration, which is MOSFET dominant due to the driver MOSFET, is proposed as a new circuit model suitable for those applications where **high voltage and current gain would be the prime requirement of amplification in narrow-band low frequency region**.

## Simulation Setup

The quantitative data reviewed originated from different simulation environments appropriate for the analysis scope (device physics vs. circuit performance).

Hybrid Darlington Simulation

• **Tool: PSpice simulation (Student version 9.2)** was performed to investigate the hybrid Darlington circuits.

• **Input Conditions:** Observations were procured by feeding the circuits with a 1V AC input signal source, from which a **small-distortion-less AC signal of 1mV at 1KHz frequency** was drawn as input for amplification purposes.

• **Biasing:** The reference amplifier (Circuit-1) was biased with **+15V DC** supply, while the proposed amplifier (Circuit-2) was biased with **+18V DC** supply.

Single-Stage CMOS Amplifier Simulation

• **Tool: TSpice tool** was used to compute voltage gain and frequency response for Common Source, Common Drain, and Common Gate configurations.
• **Technology:** These simulations used the **2-$\mu$m CMOS technology** and Spice level-1 parameters.
• **Common Source VTC:** For the CS amplifier, the analysis included observing the Voltage Transfer Characteristics (VTC) to ensure the transistor works in the **saturation region** (e.g., $V_{GS}$ $=1.3$V was chosen where the saturation region lies between 1V to 1.4V).

**MOSFET Parametric Gain Measurement**

• **Configuration:** The **Common Source configuration** was implemented to measure gain variation, as it has the potential for the highest gain.
• **Methodology:** The $g_m/I_D$ **methodology** was used to analyze intrinsic behavior and measure the intrinsic gain (theoretical maximum gain). This methodology is considered superior for comparison research in deep submicron CMOS processes.
• **Parameter Variation:** Parameters were varied individually through Cadence ADE (Length, Width, Area, Temperature) and through modifications to the SPICE model (Mobility, Zero-Bias Threshold, Oxide Thickness, Capacitances).

## Performance Parameters

Hybrid Darlington Amplifiers (Low Frequency)

| Metric | Reference Amplifier (Circuit-1) | Proposed Amplifier (Circuit-2) |
|---|---|---|
| **Max Voltage Gain ($A_{VG}$)** | 115.522 | **311.593** |
| **Max Current Gain ($A_{IG}$)** | 35.242 | **13.971K** |
| **Bandwidth (BW)** | 22.258 KHz | 9.665 KHz |
| **Lower Cut-off Freq ($f_L$)** | 443.567 Hz | 151.056 Hz |
| **Upper Cut-off Freq ($f_H$)** | 22.702 KHz | 9.817 KHz |

| | | |
|---|---|---|
| **THD Percentage** | 3.48% (8 harmonics) | **1.28%** (10 harmonics) |

RF Cascode LNA (1.0 GHz)

| Metric | CMOS LNA Cascode | BJT LNA Cascode |
|---|---|---|
| **Voltage Gain ($S_{21}$)** | **21.64 dB** | 14.3 dB |
| **DC Current ($I$)** | 11.55 mA | 2.3 mA |
| **Power Dissipation ($P_D$)** | 23.1 mW | **4.6 mW** |
| **Noise Figure (NF)** | 1.786 dB | 1.876 dB |

# Comparative Analysis

The comparative analysis reveals distinct trade-offs between BJT and MOSFET technology across different performance domains.

Gain and Bandwidth Trade-Offs

The proposed amplifier (Circuit-2) produces **higher voltage and current gain on the cost of reduced bandwidth** compared to the reference amplifier (Circuit-1). Circuit-2 achieved a gain approximately $2.7$ times higher than Circuit-1, but its bandwidth was reduced by roughly $57\%$. Both the hybrid BJT-MOSFET amplifier and the Triple Darlington amplifier effectively remove the problem of poor response of conventional Darlington pair or Triple Darlington amplifiers at higher order frequencies in the prescribed frequency-response range.

Power and Frequency Response

In high-frequency RF Cascode LNA simulations (1.0 GHz), the use of low-cost and high integration **CMOS technology results in a penalty in the power dissipation and frequency response** compared to bipolar technology. The power dissipation of the CMOS-LNA (**23.1 mW**) is significantly larger than that of the BJT LNA (**4.6 mW**). This disparity arises because MOSFET devices require a higher bias current to provide comparable performance to bipolar devices, due to the different transconductance relationships ($g_m \propto I_C$ for BJT versus $g_m \propto \sqrt{I_D}$ for MOSFET).

Effect of External Resistances

• **Additional Biasing Resistances ($R_A$, $R_{AD}$):** The presence of $R_A$ and/or $R_{AD}$ is **essential to maintain the high voltage and current gain features** of both amplifiers, as without them, the respective gains dip below unity. For Circuit-2, increasing $R_A$ and $R_{AD}$ results in the average voltage gain (AVG) finally acquiring a state of saturation beyond $50K\Omega$.

• **Source Resistance ($R_{SR}$):** The increasing values of source resistance $R_{SR}$ barely affect the voltage gain for the reference BJT-dominant amplifier (Circuit-1). However, for the proposed MOS driven composite unit (Circuit-2), the average voltage gain (AVG) decreases almost exponentially with $R_{SR}$. This fall is forced by the **source degeneration property of the common source MOSFET amplifier**.

## Observations and Discussion

### Linearity and Distortion

The proposed amplifier (Circuit-2) exhibits a significantly reduced Total Harmonic Distortion (THD) of **1.28%** compared to 3.48% for the reference amplifier (Circuit-1). This reduction is attributed to the **fast switching property** of the MOS driven composite unit, which virtually acquires the property of a MOSFET and reduces the propagation delay between the positive and negative half cycles of the output waveform.

Biasing and Operational Range

The selection of DC supply voltage ($V_{CC}$) critically impacts gain. While the voltage gain of the reference BJT amplifier (Circuit-1) rises almost linearly with increasing $V_{CC}$, the gain for the proposed MOSFET amplifier (Circuit-2) increases non-linearly from 10V to 30V of $V_{CC}$ and then drops at $V_{CC}=40V$. The permissible operating range for Circuit-2 is **substantially reduced to 15-30V**, primarily due to the MOSFET driven Triple Darlington unit, which has a threshold voltage of $2.831V$. When $V_{CC}$ increases beyond 30V, the channel region pinches-off because the drain absorbs more electrons than the channel can supply, leading to a roll-off in voltage gain.

The maximum voltage gain highly depends on the drain resistance ($R_D$ or $R_{CD}$), attaining a maximum at $10K\Omega$ for both circuits before producing a distorted output.

### Temperature Sensitivity

For the proposed amplifier (Circuit-2), the **voltage gain, current gain, and bandwidth all decrease with rising temperature**. This effect is severe for the MOSFET-dominant circuit because the decreasing mobility of majority carriers at elevated temperatures reduces the drain current, and thus reduces current and voltage gains. Additionally, the effective contribution to the source capacitance increases with increasing temperature, which reduces the bandwidth.

Parameter Intersectionality

The systematic variation of MOSFET parameters showed that, despite achieving optimized individual results (e.g., small length, large width, high mobility), combining these variations did not result in the maximum possible gain achieved during testing. This suggests a complex **interconnectedness of parameters** that requires further investigation for true optimization.

## Applications

The performance characteristics dictate the primary application domains for BJT and MOSFET architectures:
• **Integrated Circuits (IC) and VLSI:** MOSFETs are crucial components in modern electrical engineering. They are suitable for developing **high speed switching circuits, memory segments, logic gates, buffer amplifiers, power amplifiers and trans-conductance amplifiers**. They dominate in modern **VLSI and low-power analog systems** due to their superior efficiency, high input impedance, and better thermal stability.
• **RF and High-Speed Systems:** Common Gate amplifiers are useful in **CMOS RF receivers**, especially when operating near the frequency limitations of the FETs. However, when power dissipation is critical, BJT technology offers better performance for RF-LNAs.
• **High-Gain Audio/Low-Frequency Systems:** The proposed **Triple Darlington amplifier (Circuit-2)**, with its high voltage gain (311.593) and low distortion (1.28%), is suitable for applications where **high voltage and current gain would be the prime requirement of amplification in the narrow-band low frequency region**.
• **Impedance Matching and Buffering:** The Common Drain amplifier is typically used as a **voltage buffer** because it excels in transforming impedances.

# Conclusion

This reading project established a detailed comparative framework for analyzing BJT and MOSFET performance in amplifier configurations, synthesizing data from fundamental theory to advanced hybrid designs.
The core findings confirm the fundamental roles of the devices: **BJTs (current-controlled) offer high gain and better power efficiency in specific RF topologies, while MOSFETs (voltage-controlled) are essential for highly integrated, low-power IC solutions**.
The unified theoretical approach highlights that voltage gain can be determined using the same relation for any type of load or active transistor, based on the principle that the thermal voltage ($V_T$) and half of the overdrive voltage ($0.5V_{OV}$) fulfill similar roles.
The proposed **Triple Darlington configuration (Circuit-2)** successfully combines hybrid devices to yield extraordinarily high voltage gain ($A_{VG}=311.593$) and remarkably low harmonic distortion (1.28%) for processing small signals in the 1-10mV input range. The presence of additional biasing resistances ($R_A$and $R_{AD}$) is crucial for maintaining these high gain features. Collectively, these features make the proposed circuit fabulously unique in the category of small-signal amplifiers based on Darlington’s topology.

# Future Scope

Future work for this study could be extensive, particularly by expanding the analytical scope to address complex parameter interactions and emerging technologies.
1. **Investigation of Parameter Interconnectedness:** A crucial area of research is the **interconnectedness of the parameters** in the SPICE model. Since optimized individual parameter changes did not yield the maximum gain when combined, further investigation into these synergistic effects is necessary.
2. **Extended Device and Threshold Analysis:** Only 1 V supply devices were used in the systematic MOSFET gain study. The library supports different supply (e.g., **2 V supply devices**)

and threshold devices (high, low, and nominal threshold voltage devices) which should be investigated thoroughly.
3. **Advanced Multi-Gate Architectures:** An interesting avenue for gain variation investigation would be **multi-gate device investigations**, which could be done through **double-gate devices, FINFETs, or GAAFETs**.

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