Analysis and Simulation Study on the Impact of MOSFET Second-Order Effects on Common-Source Amplifier Performance

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Abstract. This paper analyzes the generation mechanism of channel length modulation and body effect from the perspective of device physics, as well as their impact on key parameters. Subsequently, using the Cadence Spectre simulation platform and the controllable variable method, the characteristic curve was extracted at the device level. At the circuit level, the influence mode of these second-order effects on voltage gain and static working points is studied. Finally, the co-source co-grid configuration is introduced to verify its effectiveness in reducing the channel length modulation effect. With the decrease in the channel length, the output resistance decreases significantly, resulting in a decrease in the voltage gain of the common source amplifier. The body effect will increase the threshold voltage and reduce the on resistance, thus further reducing the circuit gain and destroying the bias stability. The cascade structure effectively improves the equivalent output resistance, thus improving the voltage gain performance.

Keywords: MOSFET second-order effects, Channel length modulation effect, Body effect, Common-source amplifier, Cascode structure.

1 Introduction

With the continuous development of integrated circuit technology to submicron and nanoscales, the role of analog integrated circuits in high-performance electronic systems has become more and more important [1]. From high-speed communication and precision sensing interfaces to data conversion and radio frequency front-end systems, analog circuits have always undertaken the key tasks of signal amplification and adjustment [2]. In the process of development, the circuit performance is increasingly dependent on the physical characteristics of the device, so that the traditional idealized modeling method cannot accurately describe the actual circuit behavior [3]. Especially under advanced technological conditions, the non-ideal characteristics of MOSFET increasingly limit the gain, linearity and stability of analog circuits [4]. Therefore, it is of great theoretical significance and engineering value to systematically study the impact of MOSFET non-ideal effects on the performance of typical analog circuits from the perspective of device physics [5].

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Existing studies have comprehensively explored the channel length modulation (CLM), body effect and other short channel effects in MOSFET, thus achieving mature results in device modeling and parameter extraction [6]. At the same time, in the design of analog circuits, in order to improve the amplifier gain, enhance the output resistance and improve the stability of the bias, the structural optimization method has been extensively studied [7]. However, most of the work focuses on improving the accuracy of the device model or the modification of the circuit structure itself. It lacks a comprehensive research framework that can systematically analyze how the second-order effects in specific circuits propagate internally and quantitatively affect key performance parameters [8], starting from the physical mechanism of the device. Especially in the basic amplification circuit structure, there is still room for further deepening the theoretical analysis and simulation verification between the second-order effect of the device and the circuit performance. Therefore, it is necessary to select a representative circuit structure as a research platform to establish a systematic link between device non-ideality and circuit performance.

In response to these problems, this paper conducts a systematic study on the channel length modulation effect and body effect of MOSFET, aiming to build a unified analysis framework covering the physical and circuit performance of the device. First of all, from the perspective of device physics, the formation mechanism of the second-order effect and its impact on key parameters such as output resistance, threshold voltage and on resistance are analyzed. Subsequently, a common source amplifier with a simple structure and high sensitivity to device parameters was selected as a research platform. By introducing the non-ideal characteristics of the device at the circuit level, the study systematically explores the impact of these non-ideal characteristics on voltage gain and static working points. In addition, the effectiveness of this method in reducing the modulation effect of channel length is compared and analyzed by introducing a co-source co-gate structure to improve the equivalent output resistance. Through the combination of theoretical analysis and Cadence Spectre simulation verification, this paper clarifies the specific performance of the second-order effect of MOSFET in analog circuits and its engineering significance. It provides theoretical basis and practical guidance for equipment selection and structure optimization in actual circuit design.

2 MOSFET second-order effects

2.1 Channel length modulation effect

In the ideal MOSFET model, once the device enters the saturation state, the leakage current will no longer be affected by the leakage-source voltage [9]. However, in actual devices, with the increase of the leakage-source voltage, the leakage exhaustion area will expand in the direction of the channel, thus shortening the effective channel length. This phenomenon is called the channel length modulation effect [6].

The direct result of the channel length modulation effect is that MOSFET will also show a certain degree of leakage current change rate in the saturation region [5], which is equivalent to introducing a limited output resistance. This effect is usually described by the parameter λ, and the corresponding output resistance can be approximated as:

$$r_0 = \frac{1}{\lambda I_D} \tag{1}$$

where λ is the channel length modulation coefficient.

In analog circuits, finite output impedance limits the achievable gain of amplifiers, a phenomenon particularly pronounced in short-channel devices.

2.2 Body effect

The body effect refers to a phenomenon that when there is a voltage difference between the source electrode of the MOSFET and the body region, its threshold voltage will change. In actual integrated circuits, due to the limitations of process and structure, the body area cannot be completely in an equiposition state with the source pole, so the body effect will inevitably occur.

The body effect causes the threshold voltage to increase with rising source-body voltage, and this relationship can be expressed as:

$$V_{TH} = V_{TH0} + \gamma(\sqrt{|2\Phi_F + V_{SB}|} - \sqrt{|2\Phi_F|}) \tag{2}$$

γ: Body effect coefficient (related to doping and oxide layer capacitance)

φ_F: Fermi potential

V_SB: Source voltage

The increase of the threshold voltage will reduce the overdrive voltage of the device, thus reducing the on-on resistance (gm), which will ultimately adversely affect the performance of the amplifier.

3. The common-source amplifier is used as the research platform

The common source amplifier is one of the most basic structures in MOS analog amplifiers, which is characterized by high voltage gain and simple architecture [10]. Under ideal conditions, the voltage gain of the common source amplifier can be expressed as:

$$\mathrm{A}_v = \frac{v_{out}}{v_{in}} = -g_m R_D \tag{3}$$

The gain of the common source amplifier directly depends on the crossconduct and output resistance of the device, which makes it very sensitive to the second-order effect of MOSFET. Based on this characteristic, this paper selects a common source amplifier as a research platform to observe and verify the specific performance of the non-ideal characteristics of the device at the circuit level.

4. Performance analysis of common-source amplifier under second-order effect

After considering the influence of channel length modulation, the output resistance of the MOSFET is no longer infinite. The actual voltage gain of the common source amplifier can be approximated as:

$$A_v = -g_m \cdot (R_D \parallel r_0) \tag{4}$$

It can thus be seen that the channel length modulation effect directly limits the amplifier's gain by reducing the output resistance.

On the other hand, this overall effect will increase the threshold voltage and reduce the conduction resistance, thus reducing the gain under the same bias conditions and possibly causing the shift of the working point. Therefore, in the actual circuit design, the second-order effect must be included in the analysis.

5. Simulation environment and methods

In order to systematically analyze the impact of the second-order effect of MOSFET on the performance of common source amplifiers, this paper adopts the circuit-level simulation method based on the Cadence Virtuoso platform. Using the Spectre emulator and calling the standard MOSFET device model provided by the process PDK, all simulations are carried out under unified process angles and temperature conditions to ensure the comparability and consistency of the results. All simulations are carried out under unified process parameters and temperature conditions to ensure the comparability and consistency of the results. In the simulation process, the effects of the channel length modulation effect and the body effect on the device characteristics and circuit performance were studied respectively by adopting the single-variable control method.

First, conduct a characteristic analysis at the device level. By constructing a single transistor test circuit, DC scanning simulation of NMOS is carried out to obtain the ID-VDS output characteristic curve under different channel length conditions. Under the condition that the gate source voltage and bias conditions are kept constant, change the channel length parameter L to observe the change trend of the current slope in the saturation area and extract the change of the output resistance ro. This process realizes the quantitative analysis of the channel length modulation effect enhanced with the change of device size.

Then, in order to explore the influence of the body effect, it introduced a controllable voltage difference VSB between the source pole and the body pole, and carried out parameter scanning. Through direct current and working point (OP) analysis, it extracted the change trend of key parameters (including leakage current, threshold voltage and cross-conducting gm) under different VSB conditions, thus verifying the impact mechanism of the body effect on the electrical characteristics of the device.

After completing the device-level analysis, the extracted non-ideal characteristics are incorporated into the common source amplifier circuit for system verification. First, use operational amplifier analysis to determine the static working point of the circuit to ensure that the transistor works in the saturation zone. Then, AC small signal analysis is carried out to extract the voltage gain, and the gain changes under different channel lengths and VSB conditions are compared. Throughout the stage, the principle of single-variable control is always valid to eliminate the interference caused by parameter coupling.

Following the completion of device-level analysis, the extracted non-ideal characteristics are incorporated into a common-source amplifier circuit for systematic validation. Initially, operational amplifier analysis is employed to determine the circuit's static operating point, ensuring the transistor operates within the saturation region. Subsequently, AC small-signal analysis is conducted to extract the voltage gain, with comparisons made between variations in gain under different channel lengths and VSB conditions. Throughout this stage, the single-variable control principle remains in effect to eliminate interference arising from parameter coupling.

Finally, in order to verify the effectiveness of the engineering improvement method, a cascode common source amplifier structure was constructed according to the same device parameters and bias conditions, and multiple operational amplifiers and AC analysis were carried out. By comparing the differences in voltage gain and output resistance between the traditional co-source structure and the cascode structure, the improvement effect of the cascode structure in suppressing the channel length modulation effect is evaluated.

Through the above-mentioned hierarchical and step-by-step simulation methods, this paper constructs a comprehensive analysis path from the change of device characteristics to the response of circuit performance, thus clearly demonstrating the impact of the second-order effect of MOSFET at the circuit level.

6. Simulation results and analysis (i): channel length modulation

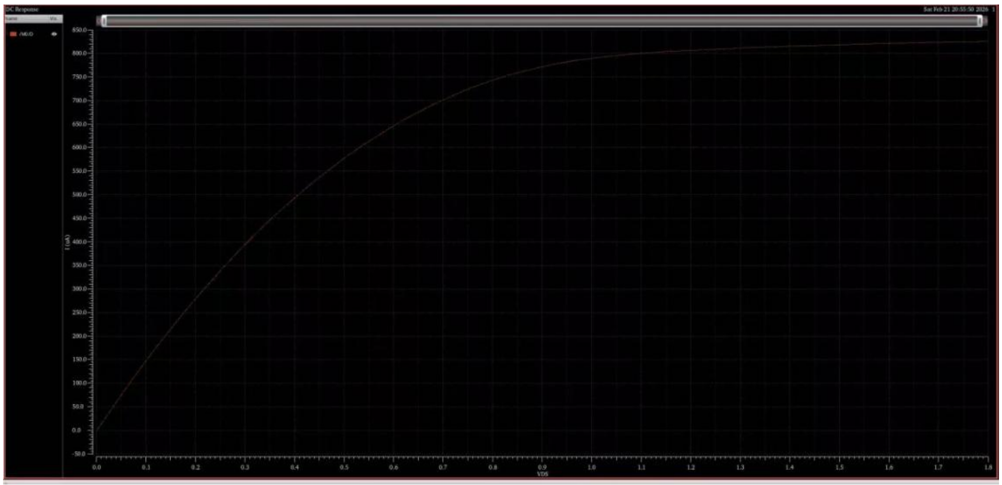

Figure. 1. ID–VDS characteristics of NMOS under different channel lengths(Picture credit : Original)

As shown in Figure 1, under the same gate source voltage conditions, NMOS devices of different channel lengths show significantly different output characteristics. With the decrease of the channel length L, the slope of the output characteristic curve of the device in the saturation zone gradually increases, indicating that the dependence of the leakage current on the leakage source voltage is increased. This shows that with the decrease of the length of the ditch, the modulation effect of the length of the ditch is significantly enhanced.

From the perspective of the small signal model, the increase in the slope of the saturation zone curve means that the output resistance ro of the device is significantly reduced. Because the voltage gain of the co-source amplifier is closely related to its output resistance, the strong channel length modulation effect directly limits the voltage gain that the amplifier can achieve.

7. Simulation results and analysis (ii): volume effect

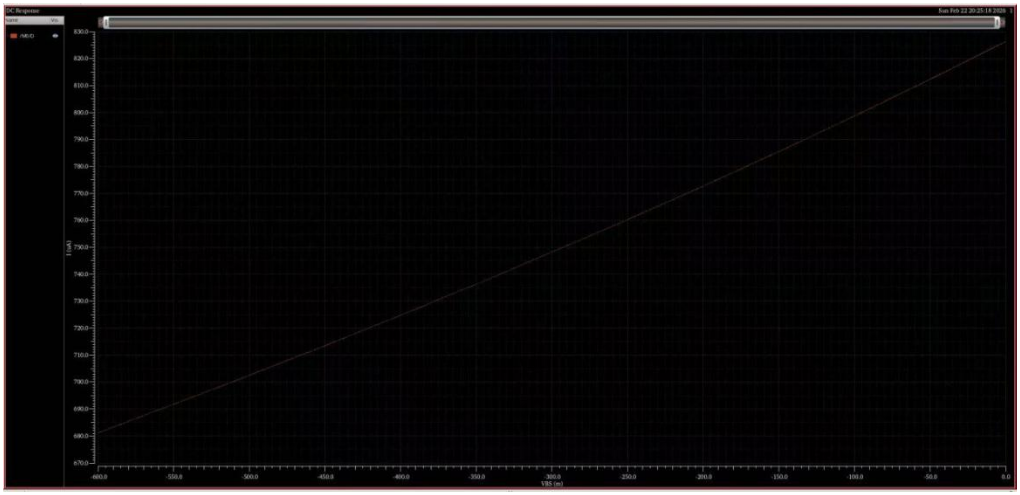

Figure. 2. Variation of drain current under different source–body voltages.(Picture credit : Original)

As shown in Figure 2, when the source voltage VSB gradually increases, the leakage current of the NMOS device decreases significantly. This is because the body effect causes the threshold voltage to rise with the increase of VSB, thus reducing the overdrive voltage of the device, thus reducing the leakage current.

In addition, since the transconductor (gm) is closely related to the leakage current, the reduction of the leakage current will also lead to a decrease in the cross-conductivity of the device. This trend shows that the body effect not only affects the current characteristics of the device, but also further affects the voltage gain and linear performance of the analog amplifier.

8. Engineering improvement method: cascode structure

In order to reduce the impact of the channel length modulation effect on the amplifier performance, this paper introduces a co-source cross-conducting amplifier structure. This cross-conducting structure effectively reduces the dependence of gain on the output resistance of the device by increasing the equivalent output resistance.

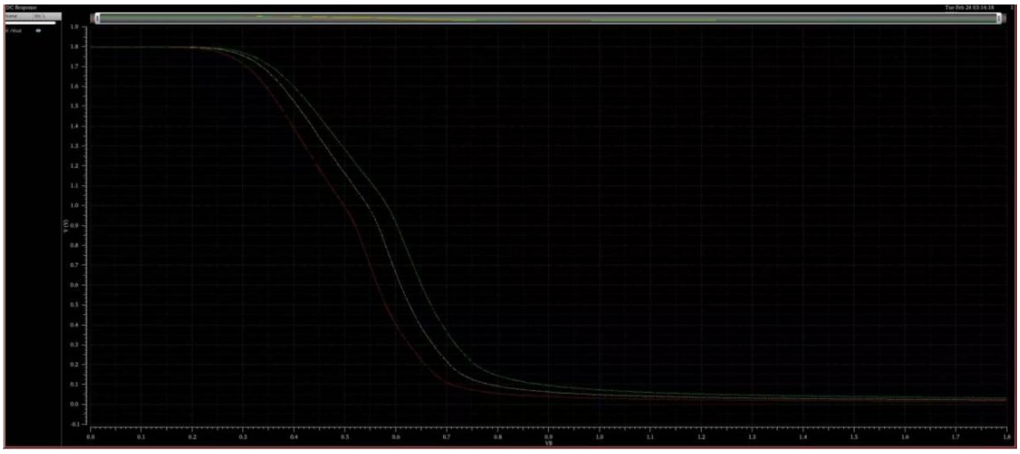

Figure 3. DC Transfer Characteristics of the Common-Source Amplifier for Different Channel Lengths.(Picture credit : Original)

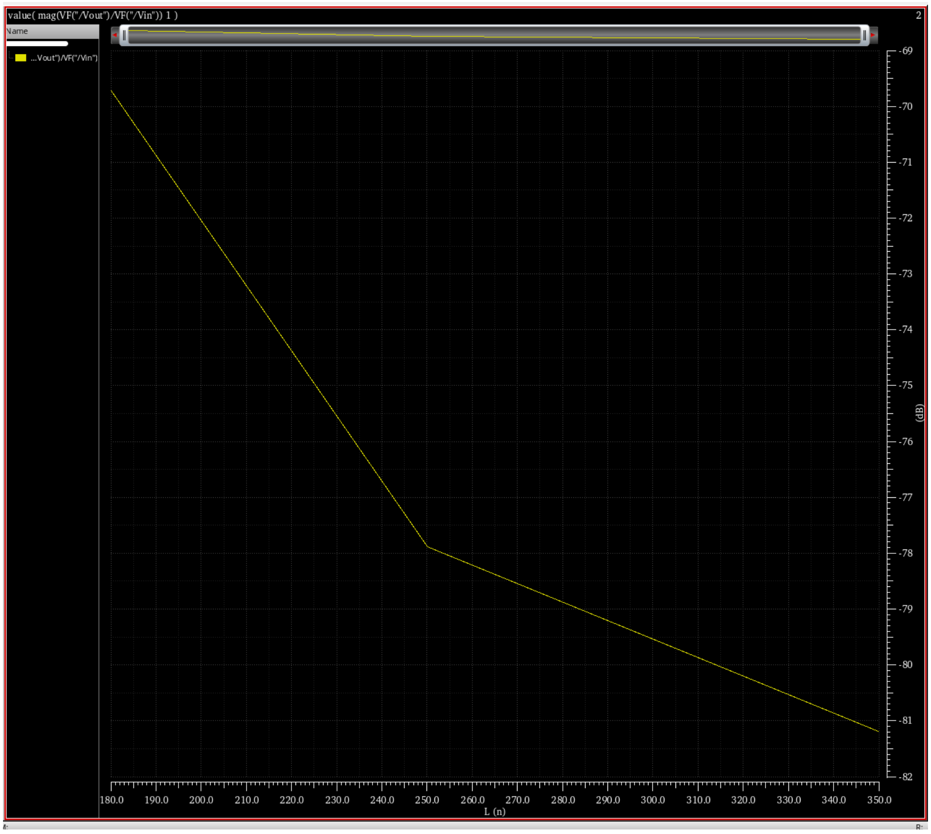

Figure 4. Voltage Gain of the Common-Source Amplifier as a Function of Channel Length.(Picture credit : Original)

As shown in Figures 3 and 4, under the same device parameters and bias conditions, the voltage gain of the common source amplifier is significantly higher than that of the traditional common source amplifier. This is because the common source pole structure introduces a cascode transistor at the output node, thus effectively increasing the equivalent output resistance of the circuit. Therefore, the limiting effect of channel length modulation on the amplifier gain has been alleviated.

It can also be observed that the gain change trend of the common source common gate structure is relatively more stable, which shows that this configuration is more robust in suppressing the non-ideal effect inside the device. This is also the key reason why the co-source co-gate structure is widely adopted in the design of high-gain analog amplifiers.

9. Discussion and engineering insights

Through theoretical analysis and circuit-level simulation results, it can be clearly seen that under modern CMOS process conditions, the channel length modulation effect and body effect of MOSFET have a significant impact on the performance of the analog circuit. With the reduction of the channel length, the output resistance of the device is significantly reduced, which directly limits the voltage gain of the common source amplifier. At the same time, when there is a voltage difference between the source pole and the body pole, the body effect will lead to an increase in the threshold voltage and a decrease in the cross-conductivity of the device. This further weakens the amplification ability and may cause the work point to drift. These phenomena show that under the deep submicron process, it is difficult to accurately predict the circuit performance by traditional analysis methods based on ideal device models. In the circuit design stage, the second-order effect of the device must be fully considered.

From the perspective of engineering practice, the conclusions drawn in this paper provide valuable guidance for the design of analog circuits. First of all, when designing a high-gain analog amplifier, the channel length of the MOSFET should be carefully selected to achieve a balance between the chip area, speed performance and output resistance. A shorter channel length can increase the speed of the device and reduce the parasitic capacitance, but an overly short length will significantly enhance the channel length modulation effect, thus reducing the voltage gain of the amplifier. Therefore, appropriately increasing the length of the channel is a common and effective design strategy when high gain is required in analog circuits.

Secondly, at the circuit structure level, the impact of the channel length modulation effect on the circuit gain can be mitigated by increasing the equivalent resistance of the output node. For example, the common source common gate configuration significantly improves the equivalent output resistance through cascade transistors, so it is widely used in operational amplifiers, conductive current amplifiers (OTA) and radio frequency front-end amplification circuits. The simulation results shown in this paper show that compared with the traditional common-source configuration, the common-source co-gate structure achieves a higher and more stable voltage gain under the same device parameters. This further proves its effectiveness in reducing the channel length modulation effect.

In addition, in the design of analog front-end and bias circuits, the voltage difference between the source pole and the body pole must be reduced as much as possible to reduce the threshold voltage change caused by the body effect. For example, the use of appropriate body pole connection method or the use of deep N base pole technology to achieve independent body pole control can significantly reduce the impact of the body effect on the stability of device parameters.

In general, as the CMOS process continues to advance to the nanoscale, the non-ideal characteristics of MOSFET will have a more significant impact on the performance of analog circuits. By comprehensively considering the second-order effects in device selection, circuit topology and bias strategy, it is possible to mitigate the adverse impact of these factors on circuit performance to a certain extent. This method improves the stability and reliability of analog circuits in practical engineering applications.

10. Conclusion

This paper systematically studies the impact of the second-order effect on the performance of the common source amplifier, focusing on the channel length modulation effect and the body effect in MOSFET. First, the generation mechanism of second-order effects is analyzed from the perspective of device physics, and their impact on key parameters such as output resistance, threshold voltage and on resistance is discussed. On this basis, the circuit-level simulation conducted by the Cadence Spectre platform verified the influence mode of the second-order effect on the voltage gain and bias stability of the common source amplifier, and the device characteristics and circuit performance were examined at the same time. The simulation results show that as the channel length decreases, the channel length modulation effect is enhanced, resulting in a significant decrease in the output resistance, thus reducing the voltage gain of the common source amplifier. At the same time, the body effect leads to an increase in threshold voltage and a decrease in conduction resistance, which further reduces the circuit gain and may damage the stability of the static working point. In addition, the cascade structure can significantly improve the equivalent output resistance, thus alleviating the limitations on the amplifier gain caused by the channel length modulation effect to a certain extent.

It should be noted that this study still has certain limitations. First of all, the analysis of the secondary effect of MOSFET is mainly based on circuit-level simulation. Although these simulation models are based on process PDK and can reasonably reflect the characteristics of the device, they lack confirmation through actual chip testing or layout-level verification. Therefore, its performance under actual process conditions needs further experimental research. Secondly, this article mainly focuses on two typical quadratic effects: channel length modulation and body effect. However, in the deep submicron CMOS process, there are other short channel effects, such as velocity saturation, leakage-induced potential barrier reduction (DIBL) and sub-threshold conductivity. These factors may also have a significant impact on the performance of analog circuits.

Future research may unfold in many directions. For example, the integration of device models from more advanced process nodes can achieve a comprehensive analysis of the coupling effect of a variety of short-channel phenomena, so as to establish a more complete device-circuit performance-related model. At the same time, the scope of research can also be extended to more complex analog circuit structures, such as operational conduction amplifiers (OTA), multi-level operational amplifiers and radio frequency front-end amplifier circuits, to evaluate the impact of second-order effects in actual systems. In addition, combining layout parasitic parameter extraction with temperature change analysis to conduct joint research on layout parasitism, power supply noise and process changes will also help improve the accuracy and engineering practicality of analog integrated circuit design.

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