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Analytical Evaluation of MOSFET Secondary Effects

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Abstract. MOSFET is a field effect transistor that can be used in a wide range of analog and digital circuits. It has the advantages of low power consumption, high speed and high integration. Its abbreviation is MOS. During the operation of MOS tubes, there are some secondary effects that cannot be ignored in circuit analysis and there is a research gap in analyzing and evaluating these effects. Therefore, in this paper, we will analyze and evaluate the body effect, channel length modulation effect, subthreshold conductivity effect, and short channel effect among the secondary effects by reviewing the related literature and give some methods to minimize the impact of secondary effects on circuits. In this study, the secondary effects of MOS tubes are discussed in depth. In the combing of previous related studies, the above several common secondary effects of MOS tubes are summarized and inductively analyzed, and the effects of reduced body effect and channel length modulation effect on circuits are summarized and evaluated. These results provide important theoretical support and practical guidance for MOSFET research.

Keywords: MOSFET, secondary effects, body effect, channel length modulation effect.

1. Introduction

Metal Oxide Semiconductor Field Effect Transistors (MOSFETs for short), a central semiconductor with remarkable input and minimal output impedance [1], finds extensive application across diverse electronic gadgets. Comprising a source, drain, and gate, the creation or non-creation of the channel is governed by a voltage beneath the gate, which subsequently regulates the current's movement between the source and drain. As technology evolves, the design of MOSFETs keeps evolving to accommodate the shrinking size of equipment and the heightened performance demands of electronic systems.

In the operating process of MOSFETs, in addition to the basic MOSFET operating principle, a series of phenomena caused by factors such as device size reduction and changes in electric field strength that have a significant impact on the performance of the device are known as secondary effects. In modern electronic technology, the study of MOSFET secondary effect is of great significance. The investigation of the secondary effect of MOSFET holds considerable importance in contemporary electronic technology. As the semiconductor process evolves, MOSFETs are increasingly shrinking in size, their operational speed accelerates, and the integration degree escalates progressively. Here, the escalating significance of the secondary effect, if overlooked, could result in a decline in circuit efficiency and a breakdown in design. For example, in high-speed digital circuits, the channel length modulation effect

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affects the switching speed and power consumption of transistors; in analog circuits, the body effect and subthreshold effect affect the amplifier's gain, noise, and other performance metrics.

These effects cannot be ignored in circuit analysis, and there is still a research gap in analyzing and evaluating these effects. Therefore, this paper will analyze and evaluate the body effect, channel length modulation effect, subthreshold conductivity effect, and short channel effect in the secondary effects by reviewing the related literature and summarizing them. Finally, a method to reduce the influence of some secondary effects on circuit analysis is given.

2. Body effect

The body effect is also known as the back-gate effect. In MOSFETs, the impact of the body is significantly influential. This primarily stems from the voltage variance between the source and the substrate. The occurrence of this voltage variance influences the charge distribution across the semiconductor's surface, resulting in an alteration of the threshold voltage [2].

The mechanism of the body effect is more intricate. In the case of MOSFETs, the bias voltage of the liner operates straight between the source and the substrate, leading to a wider depletion layer at the field-sensing junction and a rise in the density of the space charge surface. Consequently, there's a rise in the device's threshold voltage, impacting its operational properties. Maintaining a steady gate voltage leads to a reduction in the carrier surface charge density within the channel due to the liner bias voltage, causing a rise in channel resistance, a drop in current, and a decline in transconductance [3]. In dynamic operation, the constant change of the source potential will cause the liner bias voltage to change accordingly, resulting in back gate modulation, presenting a function similar to the JFET. In addition to this, a liner bias capacitance is generated, which affects the switching speed of the device.

There are differences and commonalities in the body effect in different types of MOSFETs. The manifestation of the body effect varies between N-channel and P-channel MOSFETs, attributable to the diverse types of semiconductors. In N-channel MOSFETs, the body effect typically results in a heightened threshold voltage and a reduced on-state capacity, whereas in P-channel MOSFETs, the body effect can cause a drop in threshold voltage and a rise in on-state capability. However, their commonality lies in the fact that the body effect will have a moderating effect on performance parameters such as threshold voltage and current, affecting the overall performance of the device. In practical applications, these differences and commonalities need to be fully considered to optimize circuit design and improve system performance.

3. Channel length modulation effect

Channel length modulation effect plays a crucial role in MOSFETs, significantly influencing their performance and features. From the physical nature, the modulation effect on channel length stems from how the drain-source voltage affects the channel's length. In the operation of MOSFET, when the drain-source voltage rises, the lower gate channel is removed and the pin-off point moves toward the source. This implies a reduction in the actual effective length of the channel [4]. This change is not due to a change in the physical length of the channel itself, but to a change in the equivalent channel length due to the action of the electric field.

The channel length modulation effect behaves differently under different operating conditions. When the drain-source voltage is low, it leads to negligible effects, thereby aligning the device's output characteristics more closely with the ideal situation. However, an increase in drain-source voltage leads to a more pronounced modulation impact on the length of the channel. Consequently, this leads to multiple modifications in the characteristics of the MOSFET. Concerning the current parameter, reducing the length of the channel results in an increase in the drain current. Considering the link between a channel's resistance and its length, shortening it leads to decreased resistance and an increase in current at the same voltage [5]. Specifically, in the saturation area, there's a noticeable fluctuation in the drain current, which gradually rises as the drain-source voltage increases, resulting in a clear gradient within the saturation zone of the output characteristic curve. For voltage parameters, the threshold

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voltage is affected by how channel length modifies voltage parameters. Moving the pinch-off point reduces the gate's control over the channel, causing a significant change in the threshold voltage.

In conclusion, although the channel length modulation effect is a non-ideal characteristic in MOSFETs, its effects need to be fully understood and considered in practical applications in order to design and optimize circuits more accurately and improve system performance and stability.

4. Subthreshold effect

The subthreshold effect is an important effect in MOSFETs. Even if the gate-source voltage falls below the threshold voltage, a minor current persists between the source and drain, known as the subthreshold current. As the voltage from the gate-source diminishes, there's an exponential rise in the subthreshold current. Within MOSFET devices, the gate voltage regulates the introduction of charge carriers. Despite the gate voltage being below the threshold, carrier injection can still occur via a thermally activated mechanism or a gap state, leading to a leakage current. This effect has an impact on both the static and dynamic performance of the device and the impact of subthreshold behavior on power consumption becomes more significant as the process size shrinks.

In low-power applications, the subthreshold effect is of great importance. On the one hand, it allows a certain amount of current conduction at lower supply voltages, which helps to reduce the overall power consumption. For example, in some mobile devices and IoT devices with extremely stringent power consumption requirements, the rational use of the sub-threshold effect can extend the battery life. On the other hand, potential problems cannot be ignored. The presence of subthreshold currents can lead to an increase in static power consumption, especially in large-scale integrated circuits, which may significantly affect the performance and stability of the system.

5. Short-channel effect

The short-channel effect occurs when the channel length of a MOS transistor is equal to the thickness of the depletion layer at the junction of the drain and source. The short-channel effect leads to various phenomena that are different from those of long channel MOS tubes [6]. Specifically, the short-channel effect includes the threshold voltage change, mobility field correlation effect, hot carrier effect, subthreshold characteristic degradation and leakage barrier reduction in five aspects.

The threshold voltage change indicates that with the reduction in channel length, the area where the source-drain junction depletes takes up a greater part of the channel. The electrical charge needed to create the antipattern layer beneath the gate on the silicon surface lessens, resulting in a lowered threshold voltage [7]. Furthermore, the sideways expansion of the substrate's depletion area influences the threshold voltage.

The mobility field correlation effect means that at low fields, the carrier mobility is constant and the carrier velocity increases linearly with the electric field. However, in a strong electric field, the mobility decreases. The carrier velocity saturates and is no longer correlated with the electric field [8]. This effect leads to a decrease in the saturation current on the drain side and makes the saturation current linearly related to the gate voltage.

The hot carrier effect is the amplification of the electric field strength within an instrument as the size of the instrument decreases, particularly when a potent electric field is present near the drain junction. In the intense electric field, carriers acquire greater energy and transform into hot carriers [9]. The hot carriers have the ability to penetrate the Si-SiO2 barrier and penetrate the oxide layer, altering the threshold voltage and impacting the lifespan of the device.

Subthreshold characteristic degradation refers to the increase of leakage current in the subthreshold region of a short-channel device, resulting in poorer device off-state characteristics and higher static power consumption. It may lead to confusion in logic states.

Leakage-induced barrier degradation means that when a high voltage is added to the drain, the source is simultaneously affected by the drain electric field due to the shorter gate, resulting in a lower source junction barrier. This may cause the device to fail to turn off [7].

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6. Methods to reduce the effect of secondary effects on circuits

6.1. Methods for minimizing the effects of body effects on circuits

Common methods to reduce the MOSFET body effect include using long channels, reducing the substrate doping concentration, and reducing the thickness of the oxide layer, all of which are briefly analyzed below.

Employing extended channels serves as a method to diminish the MOSFET body effect. The concept here is that extending the length of a channel can lead to a more even distribution of the electric field within it, thereby diminishing the influence of the body effect. As the length of the channel extends, the gap between the source and drain widens, leading to a comparatively reduced influence of the potential variance between the source and the substrate on the channel. Long channel design is relatively simple and does not require complex process improvements. Moreover, in some applications with low-frequency requirements, long channels can effectively minimize the body effect and improve the stability of the circuit. However, long channels also have significant drawbacks. Longer channels lead to increased on-resistance, which increases power loss. In addition, long channels take up more chip area, which is not conducive to integration, which is a factor to be weighed in modern integrated circuit design.

Reducing the substrate doping concentration is also an effective means. The principle is to reduce the conductivity of the substrate by reducing the impurity concentration in the substrate, thereby reducing the bulk effect. Employing this technique can markedly diminish the body effect's influence and enhance the efficacy of MOSFETs. At the same time, it has relatively low process requirements and is easier to realize on the basis of existing manufacturing processes. However, lowering the substrate doping concentration may lead to an increase in substrate resistance, affecting the on-state characteristics of the device. Moreover, lower doping concentration may reduce the interference immunity and stability of the device.

Reducing the thickness of the oxide layer is also a crucial strategy to lessen the MOSFET body effect. The fundamental concept involves diminishing the oxide layer's thickness to improve the gate's control over the channel, consequently lessening the body's impact. Reduce the thickness of the oxide layer can effectively improve the performance of the device, such as reducing on-resistance, improve switching speed. And can be adapted to the requirements of modern integrated circuits for high performance. However, reducing the thickness of the oxide layer will increase the gate leakage current, which has a certain impact on the reliability of the device. At the same time, the precision requirements of the manufacturing process are higher, increasing the production cost.

In summary, the advantages and disadvantages of these methods need to be considered in the actual circuit design according to the specific application requirements and process conditions. Select the most appropriate scheme to reduce the MOSFET body effect to achieve the optimization of circuit performance.

6.2. Methods to reduce the channel length modulation effect affecting circuits

Common methods to minimize the channel length modulation effect of MOSFETs include optimizing the device structure, selecting more suitable materials, and improving the process, and the following is a brief analysis of the three methods.

Optimizing the device structure can effectively reduce the channel length modulation effect by adjusting the structure of the MOSFET. For example, a multi-gate structure, such as a double-gate or wrap-around gate structure, is used. This structure can better control the electric field distribution in the channel and enhance the control ability of the channel, thus reducing the channel length modulation effect. Optimizing the device structure can significantly improve the performance and stability of the device, but the manufacturing process is complex and costly, and is suitable for high-end circuit design with very high performance requirements.

Another approach involves choosing a dielectric material with a high dielectric constant gate. A gate dielectric material with a high dielectric constant can enhance the equivalent oxide thickness without

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altering the gate capacitance, thereby diminishing the gate leakage current and boosting the modulation effect of channel length [10]. Choosing gate dielectric substances with elevated dielectric constants enhances the device's efficiency and dependability, yet the emergence of novel materials may lead to compatibility and developmental challenges in processes, often suitable for sophisticated IC designs.

Process improvements include the use of more advanced lithography to precisely control channel lengths, or optimization of ion implantation processes to adjust channel doping distributions. Advanced lithography allows for smaller channel lengths and higher precision, thereby reducing channel length modulation effects. Improved processes can increase device performance and consistency, but this requires high equipment investment and complex process control for large-scale IC production.

In short, different methods to reduce the channel length modulation effect have their own advantages and disadvantages and applicable scenarios. Circuit designers need to be based on specific design requirements and cost and other factors for comprehensive consideration and selection.

7. Conclusion

In summary, this review centers on an in-depth discussion of the secondary effects of MOS tubes. In the combing of previous related studies, several common secondary effects of MOS tubes are summarized and inductively analyzed, including the body effect, channel length modulation effect, subthreshold conductivity effect, and short-channel effect. And a number of methods for reducing the effects of body effects and channel length modulation effects on circuits are summarized and evaluated. These results provide important theoretical support and practical guidance for MOSFET research. However, the key point of MOSFET secondary effect is that multiple effects are intertwined and jointly affect the performance of MOSFET. Therefore, it is necessary to focus on comprehensively analyzing the joint influence of each secondary effect in the real research.

In the future, the research and application of MOSFET secondary effect is expected to usher in a broader development. As the semiconductor process continues to progress, the requirements for device performance continue to improve, in-depth study of the secondary effect will help optimize circuit design and improve chip performance. For example, in the field of low-power and high-speed communication, how to better control the subthreshold effect and channel length modulation effect to achieve lower power consumption and higher transmission speed will be one of the focuses of research.

In terms of application prospects, an in-depth understanding of the MOSFET secondary effect will promote the birth of more high-performance, low-power electronic devices. In the Internet of things, automatic driving, intelligent medical and other fields, the performance and power requirements of the chip is extremely demanding, accurate control of the secondary effect will help meet these needs. In addition, in aerospace and other special fields, the reliability and stability of the device is extremely high, in-depth study of the secondary effect will also provide strong technical support.

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