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Third generation semiconductor device research: Optimizing CMOS and HEMT designs

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Abstract. The third-generation semiconductor device known as High Electron Mobility Transistors (HEMT) has found extensive applications in high-frequency and high-speed electronic systems. Its widespread usage in critical technologies such as radio telescopes, satellite broadcast receivers, and cellular base stations has established HEMT as a foundational technology underpinning our information and communication society. This paper provides an in-depth exploration of these semiconductor advancements. Firstly, the paper utilizes the CMOS inverter as a representative example to elucidate the fundamental structure of Complementary Metal-Oxide-Semiconductor (CMOS) technology. Additionally, it employs Gallium Arsenide (GaAs) HEMT as an illustrative instance to expound upon the architecture of HEMT devices. Furthermore, the paper delves into the optimization of CMOS technology, focusing on topics such as Multi-Threshold CMOS and the impact of the Width/Length (W/L) ratio. These discussions shed light on ways to enhance the performance of CMOS-based components. Additionally, the paper explores strategies to optimize HEMT devices, including the introduction of carbon doping and the application of the Grey-Wolf optimization technique. These approaches are critical in achieving higher efficiency and performance in HEMT-based applications.

Keywords: Carbon Doping, Grey-Wolf Optimization, Multi-Threshold CMOS, Width/Length Effect.

1. Introduction

For nowadays, the EEers are required not to make addition to the electronic device but make subtractions, because the pursuing of high performance of modern electronic devices is the question and the solution to the society, beginning from the development of the world first Electronic Computer to the modern Supercomputer Arrays [1]. There supposed to be two ways to "level up" the structure, either from material side or from composition side. The bad news is that the new research of high-performance material may not leading to a result, it may use up to generations to wait for the critical development from material science, to make a tiny effort. To avoid the situation, this paper may try another approach, which is from the compositional components to make improvements. Thus, as the commonly used basic components, the importance Complementary Metal-Oxide-Semiconductor (CMOS) and High Electron Mobility Transistors (HEMTs) becomes increasingly evident, since these two technologies play essential roles in driving innovation and meeting the demands of modern electronics. In this paper, they will be first introduced with their structures, characteristics, application scenarios, and then their optimization direction will also be shortly introduced. With the new technology, those basic components are supposed to get a better high performance.

2. Structural characteristics of CMOS and HEMT

CMOS is the second-generation semiconductor device, which is a crucial technology in the field of electronics and digital integrated circuits. It plays a vital role in various electronic devices, including computers, smartphones, digital cameras, and many other consumer electronics. CMOS technology's importance lies in its low power consumption, high integration density, compatibility with digital logic, noise immunity, and scalability. These characteristics make CMOS an essential technology for the advancement of modern electronics and the development of innovative devices [2].

HEMT is the third-generation semiconductor device, which is a type of field-effect transistor. HEMTs are known for their excellent performance in terms of high gain, low noise, and high-power handling capabilities. HEMTs are high-performance transistors that offer high electron mobility, low noise, and high-power processing capability. HEMTs are widely applied to high-frequency applications, power amplifiers, and microwave devices, contributing to advancements in wireless communication, radar systems, and other high-speed electronic systems.

2.1. Working Principle of CMOS Inverter

CMOS inverter is the basic component of digital integrated circuit which is a type of logic gate that converts input signals into complementary output signals. The CMOS inverter is composed of several complementary MOSFETs (Metal-Oxide-Semiconductor Field-Effect Transistors) connected in series between the power supply and ground. There are two MOSFETs which are known as the P-channel MOSFET and N-channel MOSFET. The Structure of NMOS Inverter is shown in figure 1.

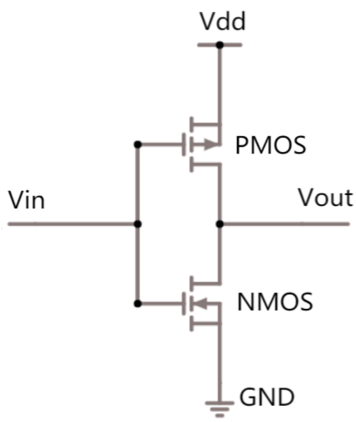

Figure 1. Structure of NMOS Inverter (Photo/Picture credit: Original).

When the input is logic 0, the PMOS is at ON state, and the NMOS is at OFF state This creates a path between Vdd and the output, resulting in logic 1 as the output. When the input is logic 1, the PMOS is at OFF state, and the NMOS is at ON state. This creates a path between the output and ground, resulting in a low output voltage (logic 0). The Voltage Characteristic Curve of CMOS Inverter is shown in figure 2.

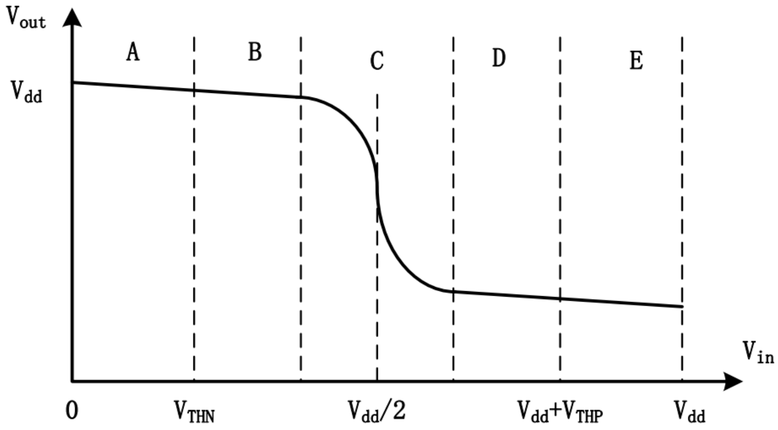

Figure 2. Voltage Characteristic Curve of CMOS Inverter (Photo/Picture credit: Original).

Area A: $0 < V_{in} \leqslant V_{THN}$. In this area, the NMOS is turned off, the PMOS is in the linear area, and the output voltage equals Vdd. Area B: $V_{THN} \leqslant V_{IN} < V_{DD/2}$, p-MOSFET in linear region, n-MOSFET in saturated state,p-MOSFET is equivalent to a resistor and n-MOSFET is equivalent to a current source. Area C: $V_{in}=V_{dd/2}$, n-MOSFET and p-MOSFET are turned on at the same time and are in a saturated state, and the characteristic curve drops rapidly. Area D: region:$V_{dd/2}\leqslant V_{in}<V_{dd}+V_{THP}$, p-MOSFET is saturated, and n-MOSFET is in linear region. Area E: $V_{dd}+V_{THP} \leqslant V_{in} < V_{dd}$, in this area, the p-MOSFET device is turned off, the n-MOSFET works in the linear region, and the output voltage Vout≈0V [3].

2.2. Working Principle of GaAs HEMT

GaAs HEMT has attracted much attention because of its high work efficiency, high current density, and high electron saturation speed [4]. HEMT is a type of field-effect transistor that operates at high frequencies. There are several types of HEMTs, including: GaAs HEMT, InP HEMT, AlGaN/GaN HEMT and SiC(Silicon Carbide) HEMT [5].

2.2.1. Characteristics of GaAs

Gallium Arsenide (GaAs) is a compound semiconductor material with unique characteristics that make it suitable for various applications [6]. Here are some of the key characteristics of GaAs: 1. Bandgap: GaAs has a direct band gap, which means that it can effectively absorb and emit light. This characteristic is an ideal choice for photovoltaic devices such as led or laser diode. 2.High electron mobility: GaAs has a high electron mobility compared to other semiconductors like silicon. This property allows for faster electron movement, making GaAs suitable for high-frequency and high-speed applications such as wireless communication devices. 3.High breakdown voltage: GaAs has a high breakdown voltage, which means it can handle higher voltages without experiencing electrical breakdown. This characteristic makes GaAs suitable for power electronics applications. 4.Thermal stability: GaAs shows good thermal stability and can work at high temperature without significantly reducing its performance. This property is advantageous for applications that require high-temperature operation, such as power amplifiers and high-power devices. 5.Low noise: GaAs has low noise characteristics, making it suitable for low-noise amplifiers and high-frequency applications where signal integrity is crucial. 6.Radiation resistance: GaAs is relatively resistant to radiation damage, making it suitable for use in space and nuclear applications. 7.Integration with other materials: GaAs can be integrated with other semiconductor materials, such as silicon, to create hybrid devices that combine the advantages of both materials. This property enables the development of advanced integrated circuits and optoelectronic devices.

GaAs provides a unique performance combination, which is very suitable for a wide range of applications such as telecommunications, aerospace, optoelectronics, and power electronics.

2.2.2. Basic Structure and Working Principle of GaAs HEMT

In 1978, Dingle et al. of Bell Laboratories put forward the concept of two-dimensional electron gas, and used it to explain their discovery that doped GaAs/AlxGa1-xAs superlattices have high electron mobility. In 1980s, based on this discovery, Mimura of Fujitsu Company of Japan developed HEMT and successfully applied it. GaAs HMET has shorter channel, larger saturation current and larger trans-conductance. The Basic structure of GaAs HEMT is shown in figure 3.

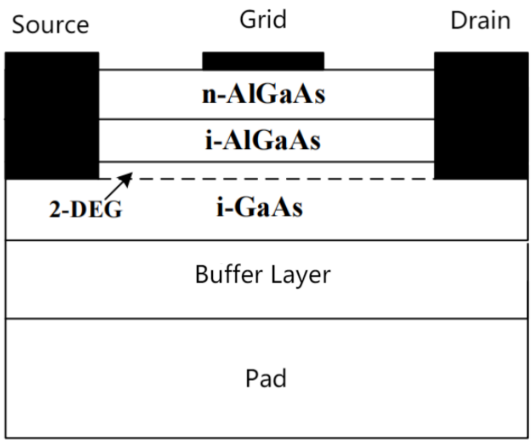

Figure 3. Basic structure of GaAs HEMT (Photo/Picture credit: Original).

HEMT controls the concentration and movement of 2-DEG through Schottky barrier under the gate, and then controls the channel current [7]. The function of buffer layer is to prevent substrate defects from entering the trench layer, and the function of undoped AlGaAs layer is to reduce the influence of impurities on two-dimensional electron gas. There are two working modes of GaAs HEMT, namely, enhancement mode and depletion mode, and the one with 2-DEG at zero gate voltage is depletion mode. This mode of HEMT will form a certain concentration of 2-DEG when the source-drain voltage is applied under-door zero voltage. However, when negative gate pressure is applied, the depletion layer of schottky junction expands, the barrier on the heterojunction decreases, and the 2-DEG decreases and approaches zero.

3. Application Scenario of HEMT

HEMT is widely used in various industries. The following are some usage scenarios of HEMT. Wireless Communication: HEMT is extensively used in wireless communication systems, such as cellular networks, satellite communication, and radar systems. They are employed as power amplifiers to boost signals for transmission over long distances.

Microwave and Millimeter-Wave Systems: HEMT is well-suited for high-frequency applications, 0making them ideal for microwave and millimeter-wave systems. They are used in radar systems, microwave links, and satellite communication systems operating in these frequency ranges.

Low Noise Amplifiers (LNAs): HEMT is commonly used as LNAs in communication systems. LNAs are crucial for receiving weak signals with minimal noise interference. HEMT, with its low noise characteristics, is well-suited for applications where signal sensitivity is important, such as in radio astronomy and sensitive communication receivers.

Optical Communication: HEMT finds applications in optical communication systems as well. It is used in optoelectronic devices, such as photo-detectors and modulators, to convert optical signals into electrical signals and vice versa.

High-Speed Digital Circuits: HEMT is employed in high-speed digital circuits, such as in high-speed data communication and digital signal processing. Its high switching speeds and low power consumption make it suitable for these applications.

Power Electronics: HEMT is used in power electronics applications, such as in power converters and motor drives. It can handle high voltages and currents, making them suitable for high-power applications.

Aerospace and Defense: HEMT is utilized in various aerospace and defense applications, including radar systems, electronic warfare, and satellite communication. Its high-frequency capabilities and reliability make them valuable in these demanding environments.

Overall, HEMT is versatile device that finds applications in wireless communication, microwave systems, optical communication, high-speed digital circuits, power electronics, and aerospace and defense industries. Its high-frequency performance, low noise characteristics, and power handling capabilities make it essential components in many advanced technologies.

4. Optimization Direction

According to the previous discussion about CMOS performance, attributes, and applications, we can clearly find out the importance of such objects. However, together with the technology development on new software and hardware, the CMOS components also require some adjustments to be applied with different usage. Our topic is about one way we may approach to adjust the CMOS performance, which is reducing delay in VLSI circuits.

Come back with how CMOS works properly, we can find two ways to improve the efficiency, one is about material, and the other one is about Width Length ratio (W/L). According to the research, the way to improve CMOS performance is about the W/L, which can also be changed with applying different material [8]. In the paper, it demonstrates the Si-only interface together with SiGe interface. Besides, the thickness ratio of Sicap and SiGe also determines the performance.

To find out the relationship between the width and length of CMOS, we should first find out the relationship of the ratio between each N-channel and P-channel. After experiment, the numerical value of the dimension interference can be calculated, which suggests that the higher value of Width makes degradation in P-channel, and the lower value of Width leads to enhancement [8]. It also observed that a shift of Threshold Voltage exists while changing the dimensions. For the NMOS, the changing is positive according to the changing Width, while for the PMOS the changing is negatively related. This phenomenon also stands up the conclusion of W/L ration and Performance. Here is the figure 4 that represents the situation they test.

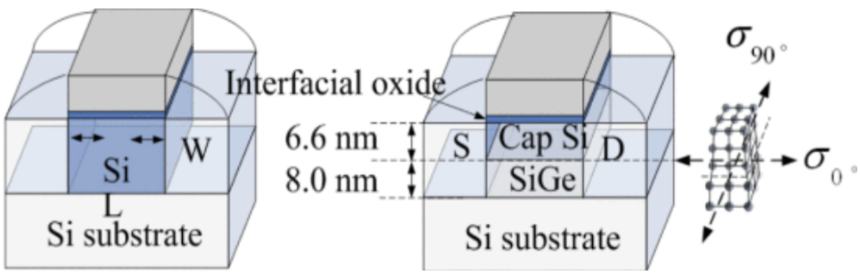

Figure 4. Test of W/L Effect [8].

Also, there is a new idea about to decrease the delay for CMOS in VLSI circuits without large changes in power dissipation, which is called Multi-Threshold CMOS [9]. It discusses the usage of High threshold CMOS devices for low threshold requirements, and the usage of Low threshold CMOS devices for high threshold requirements. Here is the relative graph for power and delay with such Transmission Gate based flip flop configuration shown in figure 5.

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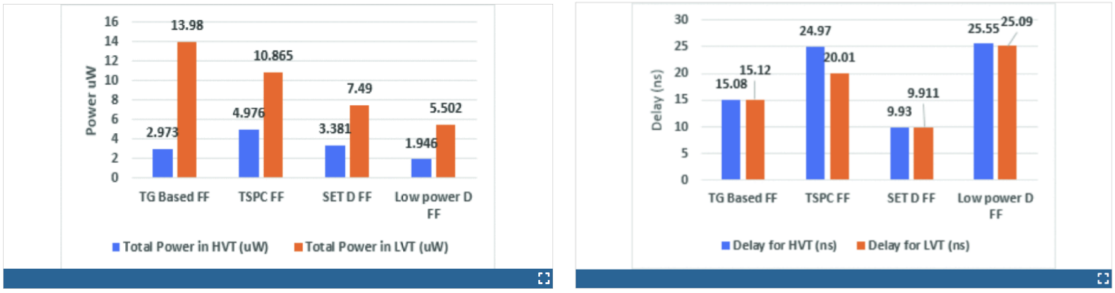

Figure 5. Comparison for different voltage threshold [9].

As we see how HEMT are widely used in various applications. It is particularly important to improve its efficiency. First way is carbon doping, Carbon doping can be used to alter the electronic properties of materials and improve device performance [10]. Carbon doping involves the intentional introduction of carbon impurities into the GaN semiconductor lattice. Elevating the carbon-doping concentration within the buffer layer of GaN HEMTs can result in enhancements in subthreshold slope and breakdown voltage, accompanied by a reduction in transit frequency. This phenomenon occurs due to the traps present in the buffer layer, which can function as origins of leakage current, thereby compromising the performance of the device. Through carbon-doping-induced reduction in trap density, the device can attain improved subthreshold slope and breakdown voltage characteristics.

What's more, augmenting the carbon-doping concentration can result in a decrease in the device's transit frequency. This occurs because the heightened doping can result in a greater abundance of free carriers within the channel, causing the device's capacitance to rise and its transit frequency to decrease. As a result, a balance exists between the advantages of diminishing trap density via carbon doping and the disadvantages of elevated doping concentration affecting the transit frequency. Besides that, The effectiveness of carbon-doping in enhancing device characteristics is influenced by the thickness of the channel. When the channel thickness is decreased while maintaining the carbon-doping level unchanged, enhancements occur in subthreshold slope, ION/IOFF ratio, and breakdown voltage, yet the transit frequency experiences a notable reduction [11]. This outcome arises from the thinner channel layer's ability to decrease device access resistance, thereby improving subthreshold slope and breakdown voltage. Nevertheless, the diminished channel thickness also prompts a higher electric field within the device, leading to an elevated impact ionization rate and diminished transit frequency. Similarly, elevating the carbon-doping level within a given channel thickness also results in better subthreshold slope and breakdown voltage, albeit with a decrease in transit frequency. As previously mentioned, this underscores the trade-off between the advantages of reducing trap density through carbon doping and the disadvantages of increased doping concentration affecting the transit frequency.

The second way is the Grey-Wolf optimization technique [12]. It first have to know that the suitability of GaN HEMTs for high-frequency and high-power applications stems from several advantages they offer. These benefits encompass elevated electron velocity, robust breakdown voltages, and excellent thermal characteristics. These characteristics enable GaN HEMTs to efficiently handle high power levels and operate at higher frequencies, which is beneficial for communication development. The Grey-Wolf optimization method is employed for deriving optimal values of the model components pertaining to GaN HEMT substrate/buffer loading. This approach is applied to fine-tune the Z-parameter measurements of the open de-embedding structure associated with the given device. To validate the models, their simulated outcomes are compared against the actual measurements. The accuracy and convergence speed of the extraction results are assessed.

To summarize, this study explores the effect of carbon-doping and channel thickness on GaN-based HEMTs. Carbon-doping in the buffer layer decreases trap density, thereby enhancing subthreshold slope and breakdown voltage. However, higher carbon-doping levels can decrease the device's transit frequency. Channel thickness also influences the effectiveness of carbon-doping: a thinner layer reduces access resistance, improving subthreshold slope and breakdown voltage, but also increases the electric field and decreases transit frequency. GaN HEMTs possess versatility and value in high-frequency and high-power applications due to attributes such as high electron velocity, breakdown voltages, and thermal capabilities. Accurate models are vital for computer-aided design (CAD), and the Grey-Wolf optimization method refines GaN HEMT models by enhancing equivalent circuit elements linked to substrate/buffer loading. This optimization enhances model accuracy and convergence rate, ultimately strengthening GaN HEMT performance in high-frequency and high-power scenarios.

5. Conclusion

This paper work offers valuable insights into the realm of third-generation semiconductor device design and optimization, with a specific focus on CMOS and HEMTs. It underscores the critical imperative of sustained research and development efforts in these domains to enhance both performance and efficiency. Central themes covered in our study encompass the utilization of Si-only and SiGe interfaces, considerations related to gate length and doping concentration, and the pivotal role of minimizing delay in VLSI circuits. Moreover, the exploration extends to the intricacies and potential in the design of HEMTs for applications demanding high-frequency and high-power capabilities. Looking ahead, it is recommended that future research in this field places a strong emphasis on refining device design and delving into innovative materials and technologies. In summary, Our research underscores the pivotal role of third-generation semiconductor devices in advancing innovation and fulfilling the evolving requirements of contemporary electronics. It stands as an invaluable resource for professionals and researchers actively engaged in this domain.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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