

# Research of Field Effect Transistors and Their Applications

## Zhengyu Lu

Shanghai HD school, Shanghai,  
China

\*Corresponding author: lu.chun@  
phichem.com.cn

### Abstract:

This article explores the evolution of Field Effect Transistor (FET) technology, from early Metal-Oxide-Semiconductor FETs to modern Gate-All-Around FETs. It explains FET's fundamental principles, highlighting its importance in electronics due to high input resistance, low noise, and precise current control. The text traces the progression from planar MOS FETs to three-dimensional FinFETs, which addressed current leakage issues. As semiconductor manufacturing advanced to 3nm processes, new challenges led to GAA FET development, offering improved electrostatic control and further miniaturization. Emerging technologies like Quantum Well FETs and Graphene FETs are mentioned, promising higher performance and broader applications. The article emphasizes FETs' crucial role in both analog and digital circuits, driving electronic device miniaturization. Looking ahead, it predicts continued breakthroughs in FET technology, stressing the need for innovative structures and materials to create smaller, faster transistors. These developments are expected to impact fields like AI, IoT, and quantum computing, shaping the future of electronics and computing.

**Keywords:** Field Effect Transistors; GAA; FinFETs.

## 1. Introduction

Field Effect Transistor (FET) is a semiconductor device that utilizes the electric field effect of the control input circuit to regulate the output circuit current [1]. This innovative electronic component operates on the principle of field effect, whereby the number of electrons in the conductive channel between the source and drain is manipulated by controlling the gate voltage, thus achieving precise current control. This unique control method has led to FET's widespread adoption in various electronic devices, including amplifiers, switches, and oscillators, among others.

One of the key advantages of FET is its high input resistance and low noise characteristics, which make it particularly effective in amplifying small signals and in high-frequency applications. These properties have contributed significantly to the advancement of sensitive electronic equipment and communications technology. Furthermore, the controllable current feature of FET has made it an indispensable component in digital circuits, playing a crucial role in the development of modern computing and digital systems. The structure of a FET comprises three essential electrodes: the source, drain, and gate. Between the

source and drain, a conductive channel is formed using semiconductor materials. The gate, through the application of an external voltage, controls the flow of electrons within this channel. This control mechanism is at the heart of FET's functionality. When the voltage at the gate is altered, it can create an inversion region that either facilitates or impedes the flow of electrons through the channel, thereby providing precise control over the current.

There are several types of FETs, each with its own unique characteristics and applications. Metal oxide semiconductor field-effect transistors (MOSFETs), junction field-effect transistors (JFETs), and enhancement field-effect transistors are among the most common varieties. Of these, MOSFETs have gained particular prominence due to their excellent performance characteristics and versatility, making them suitable for a wide range of applications [2][3].

As technology continues to advance, new types of FETs are being developed to meet the ever-increasing demands of modern electronics. Quantum well field-effect transistors (QFETs) and graphene field-effect transistors (GFETs) are examples of these cutting-edge developments. These innovative FET designs offer the potential for even higher performance and broader application areas, pushing the boundaries of what is possible in electronic circuit design. QFETs, in particular, represent a significant leap forward in FET technology. By leveraging quantum mechanical effects, these devices achieve current control by manipulating the movement of charge carriers within conductive channels at the quantum level. This approach opens up new possibilities for ultra-high-speed and low-power electronic devices, potentially revolutionizing fields such as telecommunications and computing.

The importance of FET in the field of electronics cannot be overstated. As a voltage-controlled semiconductor device, it offers unique advantages that have made it an essential component in modern electronic technology. Its ability to provide precise current control with high efficiency has led to its incorporation in a vast array of electronic systems, from simple consumer devices to complex industrial equipment and advanced scientific instruments.

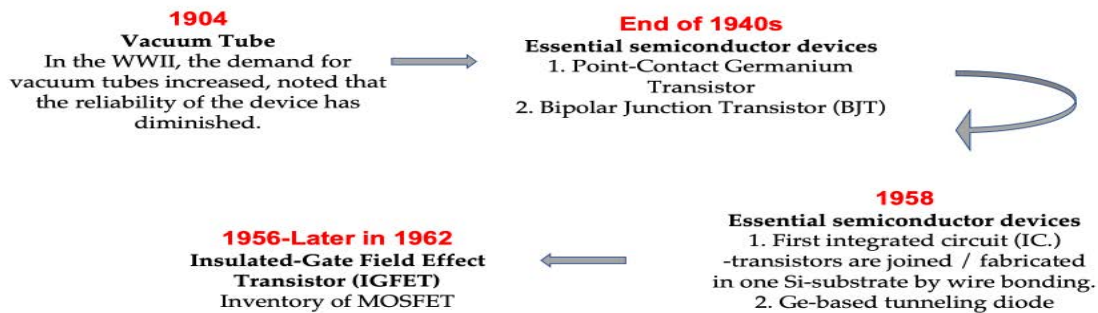
The versatility of FET extends to its use in both analog and digital circuits. In analog applications, FETs are crucial for signal amplification, frequency modulation, and voltage regulation. Their low noise characteristics make them ideal for use in sensitive audio equipment and medical devices where signal integrity is paramount. In the digital realm, FETs form the basis of logic gates and memory cells, serving as the building blocks for microprocessors and other complex integrated circuits that power this paper digital world.

Moreover, the scalability of FET technology has been a

key factor in the ongoing miniaturization of electronic devices. As manufacturers have been able to produce smaller and more efficient FETs, it has become possible to create increasingly compact and powerful electronic systems. This trend has driven the development of portable devices such as smartphones, tablets, and wearable technology, fundamentally changing how people interact with and use technology in this paper daily lives.

## 2. The Invention And Development Of MOS FET

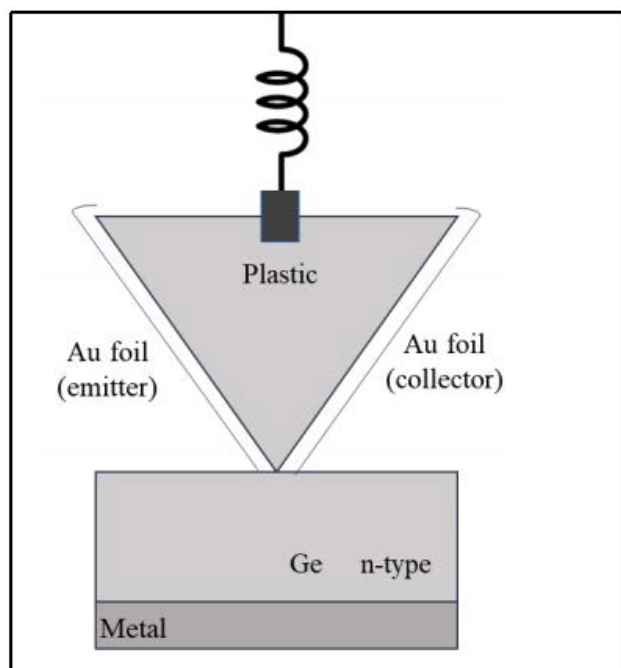
The first seed of the electronics industry, called the vacuum tube, launched in 1904 [4]. The vacuum tube controls the flow of electrons in the vacuum. However, in the Second World War, the demand for vacuum tubes increased. It was noted that the reliability of the device has diminished, owing to the growth in power consumption, manufacturing expenses, and overall size. At the end of the 1940s, the electronic industry invented the two most essential semiconductor devices, Point-Contact Germanium Transistor and Bipolar Junction Transistor (BJT). In 1947, the Point contact transistor was built by a team of William Shockley, John Bardeen, and Walter Brattain shown in Fig. 1. In 1948, BJT was invented by William Shockley. Point contact transistors and BJTs are more power-efficient and reliable than vacuum tubes. In 1958, Jack Kilby developed the first integrated circuit (IC.), where several transistors are joined or fabricated in one silicon substrate by wire bonding. On the other hand, Leo Esaki studied and noticed that a narrow junction would introduce tunneling. In 1957, Leo Esaki first invented a Germanium-based tunneling diode. On the other hand, he invented silicon\_x0002\_based in 1958. After developing the transistors, Shockley and Brattain focused on designing field-effect devices. In bipolar transistors, various unwanted problems have been noticed. The researchers did not correctly clear the semiconductor surface in bipolar transistors. In 1956, M.M Atalla presented the issues regarding surface, and Silicon dioxide can be considered a solution for semiconductor surfaces. During this period, he designed the Insulated-Gate Field Effect Transistor (IGFET), which is now called MOSFET. Later in 1962, F.P. Heiman and S.R Hofstein modified the IGFET structure. In 1963, Steven Hofstein and Fredic Heiman published their work on silicon MOSFET, which was acknowledged by the semiconductor industry. MOSFET has been the driving engine of the digital World. This was the most famous invention of the 20th century due to its successful incorporation into IC.



**Fig. 1 History of FinFETs [4].**

## 2.1 The origin of MOS FET

At the end of the 1940s, the electronic industry invented the two most essential semiconductor devices, Point-Contact Germanium Transistor and Bipolar Junction Transistor (BJT). In 1947, the Point contact transistor was built by a team of William Shockley, John Bardeen, and Walter Brattain (Fig. 2).

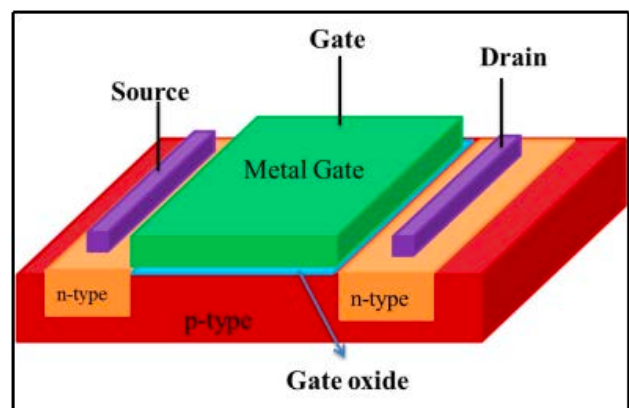


**Fig. 2 Point contact transistor [4].**

## 2.2 The planar MOSFET semiconductor device.

MOSFET has been the driving engine of the digital World.

This was the most famous invention of the 20th century due to its successful incorporation into IC. MOSFET device improves the packing density while maintaining the low fabrication cost. These devices also improved the operating frequencies with better speed. The MOSFET device has ruled above 40 years in the semiconductor industry due to its robustness (Fig. 3) [5].



**Fig. 3 Planar MOSFET semiconductor device [5].**

In particular five different short-channel effects can be distinguished: 1. drain-induced barrier lowering and punch through 2. surface scattering 3. velocity saturation 4. impact ionization 5. hot electrons. The short-channel effects are attributed to two physical phenomena: 1. the limitation imposed on electron drift characteristics in the channel, 2. the modification of the threshold voltage due to the shortening channel length..

## 3. GAA FET Technical Overview

GAA FET (Surrounding Gate Field Effect Transistor)

is a novel transistor technology aimed at addressing the limitations encountered by traditional FinFET technology in nanoscale chip manufacturing. GAA FET technology improves the performance and efficiency of chips by changing the structure of transistors, allowing them to carry more current while maintaining a relatively small size. This technology breaks through the performance limitations of FinFET by reducing the power supply voltage level and enhancing performance through boost, and performs well in driving current capability. Specifically, the advantages of GAA FET technology include:

1. Improving performance: By optimizing the design, GAA FET provides greater freedom, allowing the design team to better control the flow of current, thereby increasing the operating frequency of the chip and reducing switching losses.
2. Reduce energy consumption: GAA FET technology can operate more stably at extremely low voltages, while reducing power and space occupation, which is of great significance for improving energy efficiency and reducing device size.
3. Optimization design: Due to the changes in the GAA FET structure, the design team has more design freedom to better optimize their designs to meet the constantly evolving demands of electronic devices.

In addition, GAA FET technology is considered one of the most feasible transistor technologies in the post FinFET era. As the chip industry gradually shifts from FinFET technology to GAA FET technology, this transformation brings new opportunities and challenges to the chip industry. In the temporary final decision to increase export restrictions disclosed in the Federal Register by the Bureau of Industry and Security (BIS) of the US Department of Commerce, the EDA software necessary for GAA FET structure integrated circuits was specifically mentioned, demonstrating the importance of this technology in advanced chip manufacturing.

## 4. Conclusion

The Metal-Oxide-Semiconductor Field-Effect Transistor (MOS FET), also referred to as planar FET, functions by manipulating gate and source voltages to regulate drain current magnitude and modify circuit performance. As MOS FET technology advanced, its current control efficacy diminished considerably, resulting in unwanted current leakage. To address these issues, the three-dimensional FinFET was conceived.

FinFET technology has experienced rapid progress, evolving from 22nm to 5nm chip fabrication, and has become the industry standard. This advancement marked a significant improvement in transistor design, offering enhanced

current control and reduced leakage compared to conventional planar MOSFETs. The distinctive structure of FinFETs, featuring a channel formed as a thin, vertical fin encircled by the gate on multiple sides, enables superior electrostatic channel control, yielding improved performance and reduced power consumption.

However, as semiconductor manufacturing processes approached the 3nm threshold, static current leakage re-emerged as a critical concern. The challenges once faced by MOSFETs resurfaced in FinFETs at these extreme scales, prompting the development of Gate-All-Around (GAA) FET technology. GAA FET represents the next evolutionary step in transistor design. In this configuration, the gate material completely envelops the channel, providing even more precise electrostatic control than FinFETs. This design facilitates further transistor size reduction while maintaining excellent current flow management and minimizing leakage. The progression from MOS FET to FinFET and subsequently to GAA FET demonstrates a clear trend in transistor development. Each iteration has resulted in smaller transistor sizes, improved current-carrying capacity, and more accurate current control, paving the way for enhanced future performance.

Looking ahead, it is anticipated that FET technology will continue to experience breakthroughs in key technologies and applications. The development of innovative structures and novel semiconductor materials will be crucial in creating FETs that are smaller, faster, and more resilient. Potential areas of innovation include the exploration of new semiconductor compounds, advanced packaging techniques, and the incorporation of quantum effects in transistor design.

Through ongoing innovation and technological advancements, people can expect to witness the emergence of new device structures that push the boundaries of electronic design. These developments will not only propel the advancement of information technology but also enable new applications in fields such as artificial intelligence, Internet of Things (IoT), and quantum computing. As FET technology evolves, it will play a pivotal role in shaping the future of electronics and computing. The continuous miniaturization and performance enhancements of FETs will facilitate the creation of more powerful, energy-efficient, and compact electronic devices. This progress will contribute to advancements across various sectors, including healthcare, transportation, and communication, ultimately improving this paper daily lives and fostering a better future for society as a whole.

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