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Performance research and analysis of MOSFETs and TFETs

Lekun Li

Department of Arizona College of Technology, Hebei University of Technology , Tianjin, China

*Corresponding author: lekunli@arizona.edu

Abstract:

As an important part of the chip, MOSFET plays a vital role in integrated circuits, but with the continuous reduction of chip size, the energy consumption problem that cannot be ignored has been paid attention to, and TFET came into being. Thanks to its special tunneling mechanism, it can operate at low voltages and has lower leakage currents. This paper illustrates the basic principles of MOSFET and TFET, and uses tables and elaboration methods to intuitively show that TFET has more advantages in terms of short channel effect, subthreshold swing and switching speed. However, in industrial manufacturing, MOSFETs have more mature and stable processes, which is often one of the main factors affecting yield. Therefore, it can be concluded that MOSFETs will continue to be one of the major periods in the recent industrialization process, and MOSFETs have a more mature process and more stable performance for device manufacturing. However, TFET has great potential in terms of energy consumption, so the research and process improvement of TFET will also be one of the main research tasks in the future.

Keywords: MOSFET, TFET, Consumption.

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1. Introduction

Chips are the core components of modern electronic equipment, the core driving force to promote technological innovation, and also play an important role in the realization of high-speed data transmission in future communication technology. FETs, on the other hand, are important components on the chip, which control the current through switches to perform calculations. The significant advantage of the MOSFET is the high input impedance (the input end of the FET is insulated, which means that it has a very high input impedance. In integrated circuits, this can reduce the current consumption at the input and allow more transistors to share the same input signal), good scaling (as technology advances, MOSFETs can be manufactured smaller and smaller, which makes them ideal for high-density integrated circuit designs), low power consumption (MOSFETs consume little to no current in the closed state (cut-off state), which helps reduce the power consumption of integrated circuits, especially in portable devices that require battery power), and fast switching speeds(FETs can be turned on and off quickly, which is important for high-speed digital circuits) and manufacturing compatibility (FETs are manufactured with a manufacturing process that is compatible with existing semiconductor manufacturing technologies, which allows them to be easily integrated), among others. Since the advent of the MOSFET (Metal Oxide Field Effect Transistor) concept in 1960, bipolar transistors have been developed. As Montoro et.al 2007 said, from the 1970s to the early 1980s to the present, the leading technology of MOS technology from NMOS to CMOS and has been used so far, the scope of application of CMOS is very wide and has a strong flexibility [1]. However, with the development of science and technology, the size of chips has even reached 3nm, so that more and more transistors must be carried on a very small panel, and the requirement to reduce the size of MOSFETs is very urgent. However, side effects such as the short channel effect are also challenges that cannot be ignored, and these side effects can lead to huge defect rates. Therefore, the concept of TFET emerged and has been studied and discussed

Compared to traditional MOSFETs, low energy consumption, efficient current control, and no leakage current are the significant advantages of TFET. However, there are still many people who do not think that TFET can replace MOSFET, because MOSFET has been developed for about 50 years, and the process technology is far more stable than TFET, and the tunneling mechanism is not as stable as the principle of MOSFET. In order to objectively evaluate the performance and energy consumption of these two MOSFETs, this research paper introduces the structure, principle, advantages and disadvantages of MOSFET and TFET in detail, and then shows their performance more intuitively by comparison.

The first chapter of the paper is the introduction, which first introduces the research background and research significance of the paper, the second chapter is the principle and structure of MOSFET, and gives the working principle, device structure, main working performance and current-voltage relationship diagram of MOSFET, and the third chapter is the principle and structure of TFET, which introduces the main working principle and device structure of TFET, and explains the relevant basic concepts. Finally, the conclusion section summarizes the full text.

2. MOSFET

2.1 Semiconductors

N-type semiconductors: In intrinsic semiconductors, pentavalent elements such as phosphorus (P), arsenic (As), etc., the atoms of pentavalent elements have one more valence electron than semiconductor atoms, and these excess electrons (i.e., polytons) can move freely in the material, so most of the carriers of N-type doping are electrons.

P-type semiconductors: In intrinsic semiconductors, trivalent elements such as boron (B), gallium (Ga), etc., are doped, and when the atoms of the trivalent elements are combined with the semiconductor atoms, they leave holes in the crystal lattice, and the holes become the majority of the carriers of p-type semiconductors.PN Junction

PN Junction: When P-type semiconductors come into contact with N-type semiconductors, Some free electrons from the n region diffuse to the p region and fill the hole, and the holes in the P region diffuse to the N region to capture electrons. Due to diffusion, the side of the p-type semiconductor in contact with the N-type semiconductor loses its holes, the corresponding N-type semiconductor loses electrons, forming a depletion region, and the PN junction interface forms a built-in electric field, and the direction is N-type pointing to P-type. The electric field, which prevents the carriers from spreading further, is in the opposite direction to the external electric field of the PN junction and is the main contributor to the threshold voltage.

2.2 MOSFET

2.2.1 Components and principle

MOSFET is a key component that constitutes a digital logic circuit, CMOS (Complementary MOSFET) is the main component of digital logic gates such as AND gates, OR gates, NAND gates, etc. MOSFET’s full name is Metal Oxide Semiconductor Field Effect Transistor. The MOSFET structure can be divided into several key parts: source, drain, gate, gate oxide layer, channel, body. Fig 1 is N-type MOSFET’s structure.

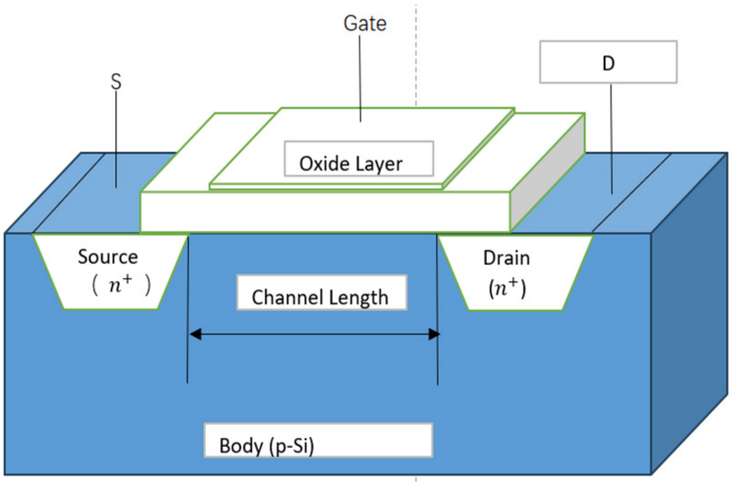

Fig. 1 N-channel MOSFET structure diagram

The source is the main source of supply of carriers for MOSFETs. The drain is the terminal on the MOSFET where the carrier flows out, and the potential is usually higher than the source. The gate is the terminal that controls the conductive state of the MOSFET and is isolated from the channel by an insulating oxide layer. The voltage applied to the gate usually determines the formation of the channel. The gate oxide layer is one of the main parts of the MOSFET and is usually made of silicon dioxide, which isolates the channel from the gate to avoid current leakage. At the same time, the thickness of the gate oxide and the dielectric constant determine the threshold voltage of the MOSFET (the minimum voltage required to form a channel). Channel: The conductive region that connects the source and drain and is the main flow path for the carriers. The length and width also usually determine the current carrying capacity of the MOSFET. The body is the basic material that constitutes the MOSFET, usually made of semiconductor materials, which determines the electronic characteristics of the transistor, provides mechanical support for the transistor, and ensures the stability of the transistor in the packaging and use of the composition. MOSFETs are mainly divided into enhanced MOSFETs and depletion MOSFETs. Their main differences are the channel formation mechanism and the initial state at zero gate voltage. Enhanced MOSFETs have no conductive channel formation at zero gate voltage and the transistor is in a cut-off state, while depletion MOSFETs already have a conductive channel in the channel region at zero gate voltage. Due to the low input impedance and stability of depletion-type MOSFETs, only enhanced MOSFETs are used in this article, and the subsequent MOSFETs are also defaulted to enhanced MOSFETs.

2.2.1 MOSFET Working Principle

In the case of NMOS, an N-type channel is formed when a positive voltage is applied to the gate and is greater than the threshold voltage to attract enough electrons from the substrate (p-type semiconductor) to the insulating layer (gate oxide). However, drain current is often defined in circuit analysis as moving from source to drain. The difference in direction is often ignored because the circuit analysis is consistent with the current direction used in the design. In the relationship between drain current and drain voltage, there are linear region, saturation region and sub-threshold region respectively. In the Linear region (the difference between gate and source voltage is slightly higher than the threshold voltage, and the channel begins to form but is not fully formed), the drain current is linearly with the drain voltage. In the saturation region (where the gate and source voltage difference is large enough for the channel to be fully opened), the channel length and conductivity no longer vary with the gate voltage. And Threshold Voltage is the minimum gate voltage required to form a channel, and the transistor is in a cut-off state before the gate voltage is less than the threshold voltage. The following formula is the calculation of the threshold voltage.

$$V_T(V_{SB}) = V_{T0} + \gamma * (\sqrt{|2\phi_f| + V_{SB}} - \sqrt{|2\phi_f|}) \tag{1}$$

In the subthreshold region (the difference between the gate and source voltages is lower than the threshold voltage), the drain current in the subthreshold region is almost 0 in the ideal state. But in practice, the transistor in the subthreshold region is not fully turned off, it still has a part of the leakage current, which is called subthreshold leakage. This may be due to the quantum tunneling effect. The quantum tunneling effect is that in quantum mechanics, the state of the particle is represented by the wave function (a mathematical function that calculates the probability distribution of a particle at a specific location and time, usually calculated by the Schrödinger equation), when the particle encounters a barrier higher than its own energy, its wave function will have a non-zero value in the outer barrier (the other side of the barrier), which means that the particle has a certain probability that it will appear on the other side of the barrier. With the process of shrinking the MOSFET, as the channel becomes shorter, the barrier becomes thinner and thinner, resulting in a greater probability of quantum tunneling, which increases the tunneling current(the leakage current), resulting in energy consumption that cannot be ignored. Sze et.al (2006) plotted the possible tunneling situation and derived the tunneling current formula for the tunneling diode. As below. (Since the field is not constant, E is some average field inside the junction) [2]

$$J_t = \frac{\sqrt{2m}*q^3V_RE}{4\pi^2h^2\sqrt{E_g}}\exp(-\frac{4\sqrt{2m}*E_g^{\frac{3}{2}}}{3qEh}) \qquad (2)$$

It is also possible that because of the diffusion movement of the carriers, Hojabri et Al 1985 describes this phenomenon as an increase in the gate voltage in the subthreshold region only increases the width of the depletion region and does not produce any transverse electric field, thus producing drift currents. As a result, MOSFETs are almost unable to maintain high efficiency at low energy consumption [3]

3. TFET

TFET, short for tunneling field-effect transistor, is a semiconductor device that uses the quantum tunneling effect to control the current. Its device structure is a gated junction with a p-i-n structure, unlike traditional CMOS, TFET works in reverse mode, and depending on the type of semiconductor of the p-i-n junction, TFET is divided into homojunction (usually implemented on silicon materials) and heterojunction (usually using InAs and other III-V materials). In the case of NTFETs, the source is doped with P+ and the drain is doped with N+, while the source and drain doping of PTFETs is the opposite of the doping type of NTFETs. As Tiwari recounts, in NTFET, Particles (electrons) from the source tunnel into the channel. Whereas in P-TFET, the principle is the same, but carriers are holes [4]. As below, Fig 2 is a structural diagram of N-TFET

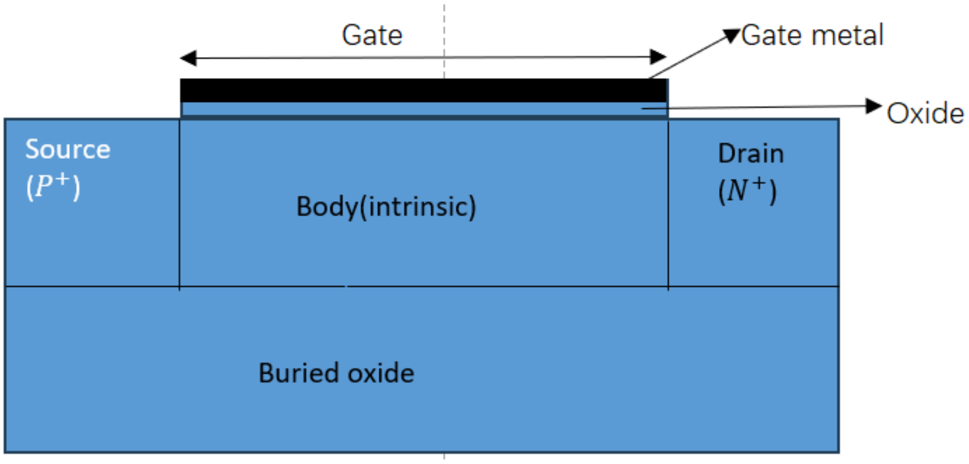

Fig. 2 N-channel TFET

The source region is usually heavily doped, which can increase the carrier concentration in the source region, thereby increasing the tunneling current and increasing the tunneling probability. The intrinsic region, i.e., the i region, is usually lightly doped or undoped, and due to the lower doping concentration, the electric field strength under the applied voltage is stronger, which helps to improve the probability of interband tunneling. The doping level and width of the intrinsic area directly affect the width of the tunneling barrier, which can effectively form the tunneling barrier.

The working principle of TFET is based on the interband tunneling effect, which changes the energy level of the band gap position in the intrinsic region relative to the source and drain. For example, applying a positive voltage to the gate of an NTFET makes the band gap narrow enough to allow tunneling to occur.

4. Comparison of TFET and MOSFET

4.1 Switching speed

The switching speed determines the response time of the logic gate in the digital logic circuit, i.e., the delay of a single digital logic gate from input to output. This also indirectly determines the effectiveness of a device in terms of energy consumption. In addition, Switching speed is also one of the key factors for increasing integration, as it means that the transistor can perform more switching actions per unit of time, which allows designers to use higher clock frequencies. The high-speed switch can respond quickly to signal changes. It allows more functions to be integrated on the same chip, increasing the level of integration. Fast switching transistors help improve signal integrity and they respond faster to signal changes and reduce signal propagation delay and distortion

Comparison: Theoretically, the switching speed of a TFET may be higher than that of a MOSFET, because the quantum tunneling technology of a TFET does not rely on thermal excitation like a MOSFET (a barrier transition requires energy, and the thermal excitation of a MOSFET requires a carrier to obtain energy from a substrate or channel, which takes a long time), and the tunneling mechanism can respond quickly to gate voltage changes because it does not require the carriers to cross the barrier, reducing the transport time of the charge carriers from the source to the drain.

But despite the potential for fast switching, TFETs typically have lower tunneling current densities than MOSFETs, which means that at the same size, TFETS may have lower drive currents (as shown in the figure) as Gupta et.al 2021 wrote, and lower TFETs than any MOSFET, which may reduce the response speed of the circuit, increase propagation delay, and reduce switching speed. On the other hand, because TFETs do not receive subthreshold slope limitation like MOSFETs, it also has a smaller turn-off current I_{ON} [5]

4.2 Short channel effect

The tunneling mechanism also reduces the short-channel effect [6-8], which is one of the unavoidable challenges for MOSFETs. One of the main manifestations of the short channel effect is that it will cause the threshold voltage to decrease, resulting in the transistor not being able to turn off completely in the shutdown state, which will increase the leakage current, increase the power consumption, and more likely to cause the chip to heat up and consume serious power, which will affect the service life.

Combining 2D materials with MOSFETs and TFETS would theoretically be effective in mitigating the short-channel effect. Common 2d materials such as black phosphorus, MoS2 and other materials have a good effect on overcoming this problem, 2d materials have a high electron mobility, which means that under a given electric field, the carriers can move quickly and can quickly switch transistors to quickly switch between conduction and cut-off, reducing the duration of the conduction state, which also reduces the leakage current, reduces the static power consumption, and reduces the thermal effect caused by long-term conduction. As Zhou explains, the MOSFET with a 2D crystal channel exhibits stable and excellent electrostatic and transmission characteristics, and the surface roughness of the 3D crystal channel deteriorates greatly when the channel becomes thinner, and the need for gate control capabilities increases dramatically, so 2D materials are needed to enhance gate control [9,10].

Another manifestation of the short-channel effect is that it reduces gate-to-channel control, affecting the switching characteristics of the transistor, but the high electron mobility of 2D materials enables fast switching and more precise control of the threshold voltage, because fast switching reduces the delay of the gate signal and ensures that the gate voltage can be transferred quickly and accurately to the channel region of the transistor. This also contributes to the optimization of latency for the entire circuit.

For example, the extremely thin thickness of the 2D material can make the gate electric field penetrate the channel region more effectively and better realize tunneling. Of course, these are only theoretical, and technology is needed to support the realization of ideas.

4.3 Subthreshold swing

Subthreshold swing is a parameter to measure the performance of a field-effect transistor in the subthreshold region, as described by Kumar et.al 2017, the subthreshold swing of a MOSFET is defined as:

$$\mathrm{SS}=\frac{dlog\left(I_{DS}\right)}{dV_{GS}} \tag{3}$$

MOSFET subthreshold swing is constant with V_{GS}.

In TFET, the drain current is the same as that of $e^{\frac{-1}{E}}$. Proportionally, E is a function of the lateral electric field in the channel and the lateral electric field is a function of V_{GS}, so in TFET, subthreshold swing varies with V_{GS}, and does not have a constant value.

The formula for the average subthreshold swing is:

$$SS_{AVG}=\frac{V_{Th}-V_{eff}}{log(I_{DS}(V_{Th})-I_{DS}(V_{OFF}))} \tag{4}$$

V_{Th} is the threshold voltage of TFET, V_{OFF} is the gate voltage at OFF-state [10].

The subthreshold swing directly affects the switching speed of the transistor. A smaller subthreshold swing means that a larger leakage current variation can be achieved with the same voltage variation, resulting in higher transistor switching speeds.

Power consumption: In digital logic circuits, the subthreshold swing determines the leakage current of the transistor in the turned off state. The small subthreshold swing helps to reduce leakage current, which reduces quiescent power consumption.

Circuit design: Subthreshold swing is an important consideration in circuit design, especially when designing low-power and high-performance circuits. The small subthreshold swing contributes to faster circuit response and lower power consumption.

According to thermodynamic theory, the minimum subthreshold swing of MOSFETs at room temperature is limited to 60 Mv/dec, while TFET can achieve a lower subthreshold swing by using the interband tunneling mechanism, because TFET does not require thermal excitation to cross the barrier. Table 1 shows a comparison of MOSFETs and TFETS in these three aspects.

Table 1. MOSFET vs TFET

Numble	Short channel effect	Subthreshold swing	Switching speed
TFET			Faster
MOSFET	Significantly	Higher	

5. Conclusion

The purpose of this study is to analyze the performance advantages of MOSFETs and TFET, and through the comparison of short-channel effect, subthreshold swing and switching speed, it is found that TFET has obvious advantages in the ideal state, which means that the TFET will have excellent performance in energy consumption in the ideal state. This discovery not only promotes the theoretical development of TFETs in terms of energy consumption, but also provides an alternative for MOSFETs in circuits. In view of these performances, I suggest that future research further explore how to solve the problems of TFET in large-scale production and circuits. It should be noted that this study is limited to theoretical elaboration, and its performance in the real state has not been verified. In conclusion, this paper introduces the performance and performance of MOSFETs and TFETS in terms of energy consumption, and lays the foundation for subsequent scientific research and technological improvement.

References

[1] Galup-Montoro, C., & Schneider, M. C. (2007). MOSFET modeling for circuit analysis and design (1st ed.). World Scientific.

[2] Sze, S.M. and Ng, K.K. (2006). p-n Junctions. In Physics of Semiconductor Devices (eds S.M. Sze and K.K. Ng).

[3] Hojabri, Pirooz.-. (1985). Introduction. In NOISE AT SUBTHRESHOLD CURRENT IN MOS DEVICES, (pp. 4). The Univercity of Arizona.

[4] Tiwari, & Saha, R. (2022). Methods to Reduce Ambipolar Current of Various TFET Structures: a Review. SILICON, 14(12), 6507–6515. https://doi.org/10.1007/s12633-021-01458-w

[5] Gupta. (2021). State-of-the-Art TFET Devices. In Gupta, Makosiej, Amara, Vladimirescu, Anghel (Ed) , TFET Integrated Circuits From Perspective Towards Reality (1st ed. 2021.), (pp. 5-15) Springer Nature Switzerland

[6] Björkqvist, K. and Arnborg, T. (1981). Short channel effects in MOS-transistors. Physica Scripta 24 (2): 418–421.

[7] Sarkar, A., De, S., Nagarajan, M. et al. (2008). Effect of fringing fields on subthreshold surface potential of channel engineered short channel MOSFETs. TENCON 2008 – 2008 IEEE Region 10 Conference. 1–6

[8] Pal, A. and Sarkar, A. (2014). Analytical study of dual material surrounding gate MOSFET to suppress short-channel effects (SCEs). Journal of Engineering Science and Technology https://doi.org/10.1016/J.JESTCH.2014.06.002.

[9] Walia. (2018).Tunneling Field-Effect Transistors Based on Two-Dimensional Materials. In Zhou (Ed.) , Low Power Semiconductor Devices and Processes for Emerging Applications in Communications, Computing, and Sensing (1st edition.), (pp. 157-180) Boca Raton, FL : CRC Press, an imprint of Taylor and Francis

[10] Kumar, Vishnoi, R., & Pandey, P. (2017). The tunnel FET. In Kumar , Vishnoi, and Pandey (Ed.) , Tunnel field-effect transistors (TFET) : modelling and simulations (1st ed.), (pp. 39-77) John Wiley & Sons, I