ENHANCED PERFORMANCE ANALYSIS OF P-CHANNEL TUNNEL FETS USING HIGH-K DIELECTRICS AND WKB APPROXIMATION

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ABSTRACT

This paper presents the detailed performance of p-channel tunnel field-effect transistors (TFETs) using high-quality gate dielectrics and the Wentzel-Kramers-Brillouin (WKB)[1] method to calculate the probability of tunneling. The use of high-k materials[3], especially hafnium oxide (HfO2), increases the gate control over the channel, thereby improving the lower threshold and lowering the flow rate. In addition, the WKB approach provides a more accurate modeling of the quantum mechanical tunneling process and shows the barrier effect on the transporters. The electric field distribution across the device is determined using Poisson's equation and the effect of high-k dielectric. The obtained I-V characteristics show better performance compared to conventional gate dielectric components. This comprehensive analysis demonstrates the potential of high-quality dielectrics and advanced quantum mechanical modeling to optimize TFET[2] performance, making it a promising approach for future low-power electronics applications.

Keywords: WKB, HfO2

1. INTRODUCTION

Tunnel Field-Effect Transistors (TFETs) have been the subject of extensive research due to the pursuit of improved performance in semiconductor devices, especially for applications that need high speed and low power. Comparing TFETs to conventional MOSFETs, there are a number of benefits, such as smaller sub-threshold swing and lower power consumption, due to their utilization of quantum mechanical tunneling for carrier transport.P-channel TFETs are one of the more promising TFET[2] architectures when it comes to complementary logic circuits because of their ability to operate at high speeds and with better energy efficiency. While silicon (Si) and germanium (Ge) are commonly employed as channel materials in traditional TFETs[21], new developments have concentrated on using high-k gate dielectrics to further improve device performance.When compared to conventional silicon dioxide (SiO2), high-k dielectrics like halogen oxide (HfO2) offer better gate control over the channel. In order to achieve low-power operation, this leads to enhanced sub-threshold slope, decreased leakage currents, and more effective electrostatic control. Accurately estimating and comprehending the carrier tunneling probability via the potential barrier is a major difficulty in TFET modeling.For this reason, the Wentzel-Kramers-Brillouin (WKB) approximation has shown to be a potent tool, providing a more accurate computation of tunneling rates by taking into account quantum mechanical factors. The WKB approximation offers important insights into device performance by breaking down the difficult challenge of tunneling through a potential barrier into a more understandable form.To grasp the electric field distribution throughout the device, Poisson's equation must be solved in conjunction with the WKB approximation. Poisson's equation explains how the electric potential changes in response to boundary conditions and charge distributions, which has a direct impact on the likelihood of tunneling and the general behavior of the device. For the purpose of forecasting TFET[2] performance under varied operating conditions, accurate modeling of the electric field is also essential.This work intends to improve the p-channel TFET performance analysis by the incorporation of high-k dielectrics and the use of the WKB approximation in tunneling probability computations. Through the integration of these sophisticated methodologies into the simulation framework, the work offers an all-encompassing assessment of TFETs with enhanced gate control and quantum mechanical precision.

Tunnel Field-Effect Transistor (p-TFET)

A low-power semiconductor device is called a tunnel field-effect transistor (TFET). TFETs use quantum tunneling to regulate the current flow, as opposed to conventional Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs), which rely on thermionic emission. TFETs can achieve much lower power consumption than MOSFETs because of this fundamental difference. The electric field the gate produces when a voltage is applied to it modifies the width of the energy barrier between the source and the drain. A current can be produced when electrons from the n-type source tunnel through this energy barrier and enter the p-type drain. Because of this tunneling process' extreme sensitivity to gate voltage, current flow may be precisely controlled. Because TFETs have a subthreshold swing (SS) that is far lower than MOSFETs', they use less power and produce less leakage current.

Model: The current is modeled as $I_d = I_{off} \cdot \exp\left((V_g - V_{th})/S\right)$. Here, I_{off} is the off-state leakage current, and S is the subthreshold slope.

2. PROPOSED METHOD
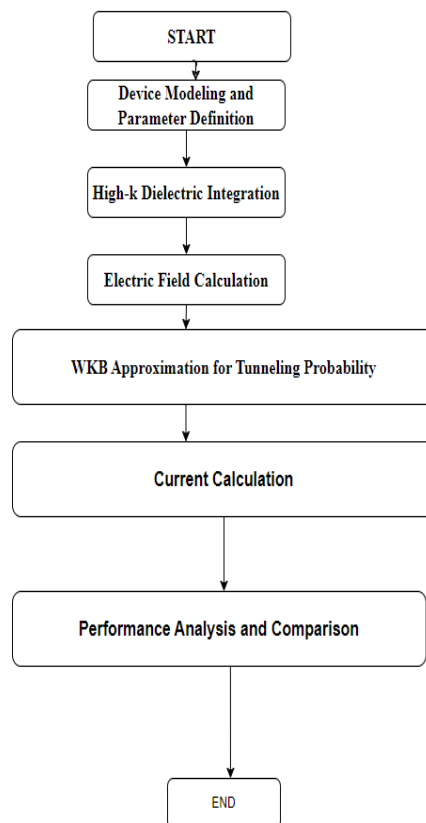
Using expert tunneling probability modeling with the WKB approximation and integrating high-k gate dielectrics[10] are the two methods suggested to improve the performance of p-channel TFETs. The process can be divided into multiple crucial steps:

Device Modeling and Parameter Definition:

A. Specify the geometric dimensions, gate dielectric, and channel material of the p-channel TFET.

B. Establish the material's characteristics and physical constants, such as oxide thickness, dielectric constants, and effective mass of carriers.

High-k Dielectric Integration:

Replace traditional silicon dioxide (SiO2) with a high-k dielectric material, such as hafnium oxide (HfO2), to enhance gate control and lower leakage currents

Electric Field Calculation:

To find the distribution of the electric field throughout the device, solve Poisson's equation. To solve the potential distribution, this entails discretizing the device into a spatial grid and using finite difference techniques.

WKB Approximation for Tunneling Probability:

To get the carrier tunneling probability via the potential barrier, use the WKB approximation. In order to do this, the energy difference over the barrier width must be integrated squarely.

Current Calculation:

Utilizing the tunneling probability derived from the WKB approximation along with additional device parameters, compute the drain-source current (Ids).

Performance Analysis and Comparison:

• Examine and contrast the I-V characteristics of the high-k dielectric TFET with those of conventional devices.

• Assess performance indicators like on-current, off-current, and sub-threshold slope.

WKB Approximation

The Schrödinger equation in quantum physics is solved using the semi-classical WKB Approximation (Wentzel-Kramers-Brillouin Approximation). Understanding quantum tunneling processes, as those seen in Tunnel FETs (TFETs), is very helpful. In situations where the potential fluctuates slowly over space in relation to the particle's de Broglie wavelength, the WKB technique approximates the wavefunction of a quantum system.

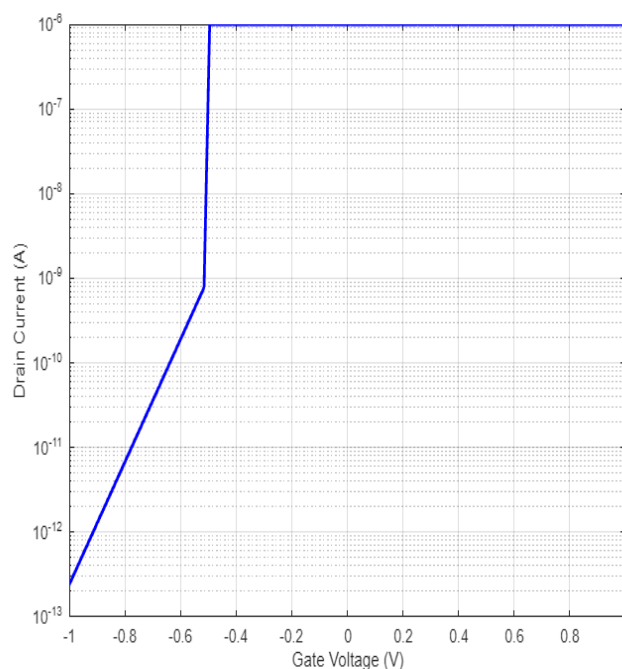## 3. RESULTS -DISCUSSION

V-I Characteristics of p-Channel TFET :

Figure-1-V-I Characteristics of p-hannel Tunnel FET

Figure-1: Displays Exponential behavior below the threshold voltage, highlighting the TFET's subthreshold steepness and its ability to conduct with low gate voltages. Saturation behavior above the threshold voltage, where the current becomes relatively constant as the device turns on. These characteristics illustrate the TFET's unique ability to operate with a low subthreshold slope, making it potentially useful for low-power and high-speed applications.

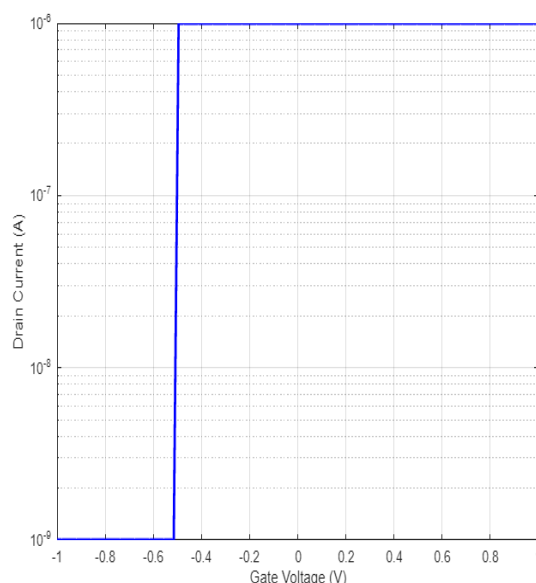**V-I Characteristics of p-Channel TFET with High-k Dielectric and WKB Approximation:**

Figure-2-V-I Characteristics of p-Channel TFET with High-k Dielectric and WKB Approximation

Figure-2: Subthreshold Region (Gate Voltage < Threshold Voltage): demonstrates how, as the gate gets closer to the threshold voltage, the current grows exponentially with increasing gate voltage. Tunneling is made easier by the high-k dielectric, which might lead to an increase in current. Because the WKB approximation takes into account the intricate tunneling mechanism in the Subthreshold Region (Gate Voltage < Threshold Voltage), it yields an exponential increase in current that is more realistic.In the subthreshold area, a device with a high-k dielectric usually exhibits a larger drain current than one with a conventional dielectric.This is due to tunneling has a lower effective barrier height.The current calculation accurately captures the genuine quantum mechanical tunneling process thanks to the WKB approximation. As a result, the current rise in the subthreshold zone may be represented more accurately.
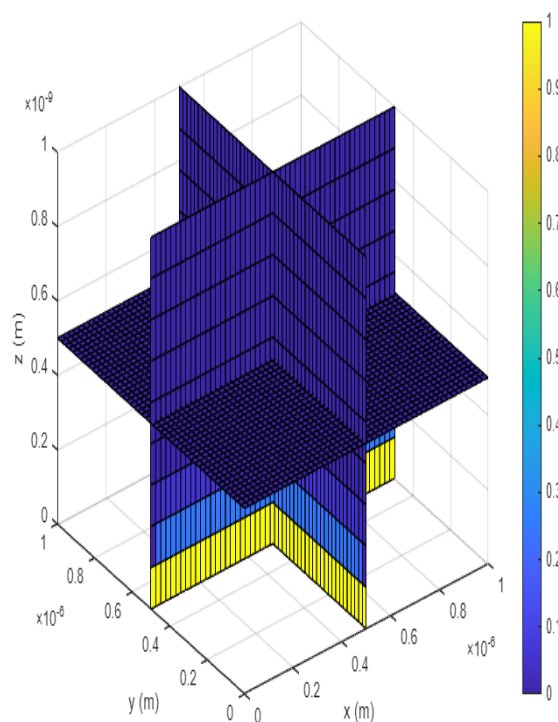
Figure-3 Potential Distribution in the TFET

Potential Distribution: Figure-3- The plot illustrates the variations in electric potential inside the three-dimensional TFET volume. Generally speaking, the potential values inside the device will drop from the applied voltage at the boundary to lower values.

- **x = Lx/2:** This slice shows the potential distribution in the yz-plane (midplane of the device).
- **y = Ly/2:** This slice shows the potential distribution in the xz-plane (midplane of the device).
- **z = Lz/2:** This slice shows the potential distribution in the xy-plane (midplane of the device).

Potential Gradient: As you go away from the boundaries where the voltage is applied, the potential usually drops. Higher potential values are displayed at these boundaries.

Device Behavior: The distribution facilitates comprehension of possible modifications inside the device that may have an impact on the TFET's overall efficiency and switching characteristics.

4. CONCLUSION

In the final analysis, by improving gate control and significantly lowering leakage currents, the integration of high-k dielectrics, namely Hafnium Oxide (HfO2), into p-channel Tunnel Field-Effect Transistors (TFETs) represents a notable gain in device performance. A more accurate description of quantum mechanical tunneling is possible through the use of the Wentzel-Kramers-Brillouin (WKB) approximation, which also offers deeper insights into the effects of the potential barrier on carrier transport. Moreover, Poisson's equation is used to solve the electric field distribution, which confirms the greater performance gains made. Taken together, these advancements demonstrate how high-k dielectrics and sophisticated quantum mechanical modeling can propel TFET technology forward, making it an attractive option for next-generation low-power electronic applications. .

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