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Design and Performance Analysis of Gate Overlap Dual Material Tunnel Field Effect Transistor

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ABSTRACT

This study introduces a biosensor employing a dielectric-modulated dual material gate tunnel field effect transistor (DM-DMG TFET) in 10 nanometer technology. To detect diverse bio molecules, the biosensor incorporates a nano gap cavity formed through gate overlap on the drain side. The variation in ambipolar current serves as the sensing parameter, influenced by altering the dielectric constants of immobilized bio molecules within the nano cavity. In this paper, the simulation results of biosensor employing a dielectric-modulated dual material gate tunnel field effect transistor with different dielectric constants imposed in nano cavity. A comprehensive examination of the biosensor's performance is conducted, exploring various positions and filling factors of bio molecules within the nano cavity region. This analysis involves a thorough investigation into the device's performance, considering a range of parameters such as drain current, electric field distribution, variations in surface potential, configurations of energy bands, behaviors of carrier concentration, and the Ion/Ioff ratio. The simulations are done using the Silvaco TCAD Atlas tool.

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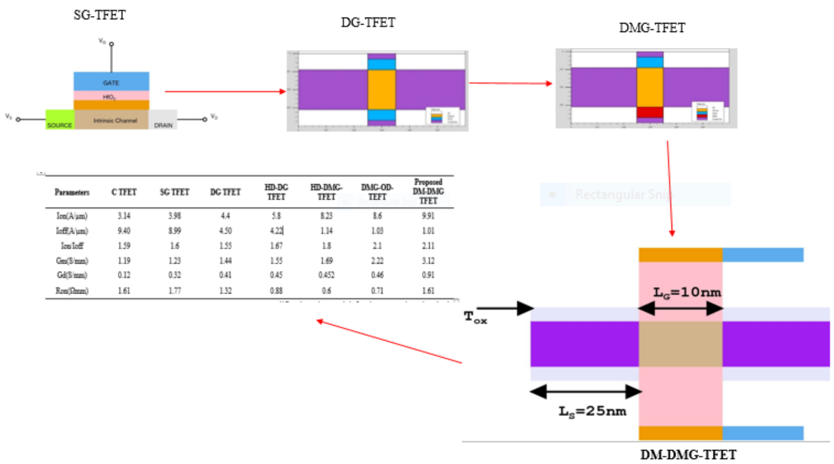
Graphical Abstract



Parameters	C TFET	SG TFET	DG TFET	HD-DG TFET	HD-DMG-TFET	DMG-OD-TEFT	Proposed DM-DMG TFET
Ion(A/μm)	3.14	3.98	4.4	5.8	8.23	8.6	9.91
Ioff(A/μm)	9.40	8.99	4.50	4.22	1.14	1.03	1.01
Ion/Ioff	1.59	1.6	1.55	1.67	1.8	2.1	2.11
Gm(S/mm)	1.19	1.23	1.44	1.55	1.69	2.22	3.12
Gd(S/mm)	0.12	0.32	0.41	0.45	0.452	0.46	0.91
Ron(Ωmm)	1.61	1.77	1.32	0.88	0.6	0.71	1.61

1. INTRODUCTION

Dielectric modulated Tunnel Field-Effect Transistors (TFETs) have been recently used as a novel method in biosensor. Unique properties of TFETs have been used in a novel technology which is extremely sensitive to small changes in charge distribution. Researchers have introduced modulator in their TFET structures that makes

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the device more sensitive and specific for detecting the most minor amounts bio molecules at once (1). Dielectric modulation is a central feature of the bio sensing process, enabling detection of bio analytes with regulated charge interactions. The combination of dielectric modulation and TFETs led to the creation of highly sensitive ultrasensitive and highly efficient biosensors that have the potential to be used in clinical diagnosis and biotechnology due to their ability to detect disease markers at very low concentration units. The dielectric modulated TFET is one of the major steps in biosensor technology that could be used as an instrument for developing healthcare service delivery and research in biology (2, 3).

However, one of the large electronics which is widely utilized in the manufacturing of semicondcutor circut integraded circut as well as other electronic systems is the metal oxide semiconductor field effect transistor (MOSFET) (4). It is used as a switch off/on and to amplify digital and analog circuits. A thin layer of oxide separates them from the semiconductor substance, which is in contact with metallic gate. This electric field is created when gate terminal is applied with certain voltage and a controlled current passes through source and drain terminals. MOSFETs come in two main types. These devices are of two types namely – n-channel and p-channel (5). These are crucial components of modern electronic gadgets like microprocessors, Random Accessed Memory (RAMs) and power amplifiers. This makes MOSFET very important today and used as basis of almost every single modern electronic with lower power consumption, fast switching, and small size (6).

The Tunnel Field-Effect Transistor represents an evolutionary development from the Metal-Oxide-Semiconductor Field-Effect Transistor, addressing some of the challenges associated with power consumption in traditional MOSFET designs. MOSFET's have been the main of electronic devices for decades, offering high performance and scalability (7, 8). However, as technology advanced, MOSFET's faced limitations related to sub-threshold swing and power efficiency. TFET's leverage quantum tunneling for their operation, introducing a new mechanism to control the flow of charge between the source and drain terminals. Unlike MOSFET's, TFET's take advantage of band to band tunneling, allowing carriers to pass through the energy barrier without the thermal activation required in traditional transistors. This characteristic results in lower sub-threshold swing, enabling TFET's to operate at lower voltages and potentially reducing power consumption (9).

The shift from MOSFET to TFET signifies the semiconductor industry dedication to detect issues related to power efficiency, particularly in the realm of energy efficient and low power electronics (10). Despite TFET's being in the research and development phase. They offer potential solutions to the power consumption challenges associated with MOSFET's in upcoming electronic devices. This move from MOSFET to TFET highlights the continuous seek to advance semiconductor technology, aiming for improved performance and energy efficiency (11).

The evolution of dielectric modulated Tunnel Field Effect Transistors represents a significant advancement in semiconductor device technology. TFET's are the type of transistor that influence quantum tunneling for electron transport, offering potential advantages over conventional transistors in terms of reduced power consumption and improved performance (12, 13). Dielectric modulation in TFETs involves manipulating the properties of the insulating material in the transistors structure to improve its overall efficiency. Over the time, researchers have detected various dielectric materials and configurations to optimize the TFET's performance (14). This evolution has led to the development of innovative designs and fabrication techniques, aiming to overcome challenges such as low ON state current, achieve better control over the tunneling process. The dielectric modulated TFET's hold promise for future generations of low-power electronic devices contributing to the ongoing efforts to advance the field of nano-electronics (15).

This research introduces a biosensor that utilizes a dual material gate tunnel field-effect transistor (DM-DMG_TFET) with dielectric modulation. The biosensor incorporates a nanogap cavity created through gate overlap on the drain side to detect various biomolecules. The sensing parameter is the variation in ambipolar current, which is influenced by changes in the dielectric constants of immobilized biomolecules within the nano cavity (16). The study comprehensively examines the biosensor's performance, exploring different positions and filling factors of biomolecules in the nano cavity region (17).

The DMGTFET has two different materials for the gate structure to enhance its performance and suitable for low power electronics due to their ability to operate at lower supply voltages compared to conventional MOSFET and TFET. While the DMGTFET offers advantages in terms of improved subthreshold swing and lower leakage current compared to SG TFET, and it still faces certain challenges and limitations. The implementation of dual material gate structure can increase the complexity of the fabrication process, making it more challenging and expensive and the selecting appropriate materials for the dual gate that are compatible with semiconductor technology can be challenging. The materials must be compatible with the overall device fabrication process and should provide the desired electronic properties. The dielectric-modulated tunnel field-effect transistor that utilizes a modulated dielectric material in the gate region to control the tunneling of carriers. Therefore to addressing these limitations and improving the overall performance and reliability of this proposed DM-DMG TFET for potential integration with gate length of 5 nanometer and to reduce the device length.

The proposed dielectric modulated TFET offer several advantages such as enhanced performance and low-power operation and employed with dielectric materials being HfO_2 and SiO_2, there are challenges related to fabrication complexity, and development efforts.

2. DEVICE STRUCTURE AND SIMULATION PARAMETERS

Figure 1 shows the two-dimensional cross-sectional view dielectric modulated biosensor, highlighting its unique nanogap embedded overlapped gate-on-drain configuration. To comprehensively understand the device's behavior, the Silvaco ATLAS TCAD simulator, a commercially available tool, for the simulation and characterization of its electrical properties (18). The simulation takes into account non-local band-to-band tunneling (BTBT) by incorporating a relevant model. The analysis involves the utilization of various models, such as Shockley-Read-Hall (SRH), Auger recombination, Fermi Dirac, and field-dependent mobility, to delve into the intricate characteristics of the biosensor. Additionally, the band gap narrowing (BGN) model is considered, particularly for the highly doped source and drain regions (19). The biosensor's sensitivity is a focal point of evaluation, measured by observing changes in ambipolar current resulting from variations in the dielectric constant of specific biomolecules immobilized within the nanogap cavity beneath the overlapped gate. Notably, as the gate electrode experiences variations in the dielectric constant within the overlapped region, it amplifies the effective coupling capacitance near the drain side, enhancing the overall performance of the biosensor (20).

The source section is doped with a p-type material at a concentration of 1e20, while the drain segment incorporates an n-type material with a concentration of 1e19. Additionally, the channel is enriched with an n-type material at a concentration of 1e17. The relationship between the coupling capacitance and barrier width establishes a proportional connection, leading to an increase in the barrier width at the channel-drain junction (21). This heightened barrier width imposes limitations on the number of carriers tunneled through the channel-drain junction, consequently causing a reduction in the ambipolar current. To further diminish this ambipolar current, a dual material gate configuration proves effective, especially when a high work function gate is positioned toward the drain side ($\phi G2 > \phi G1$). While a gate underlapped drain exhibits favorable outcomes, it encounters challenges in cases of equally doped source and drain regions. The introduction of a dual material gate structure with $\phi G2 > \phi G1$ successfully overcomes this limitation, demonstrating an efficient reduction in ambipolar current (22). The spatial arrangement of biomolecules significantly influences the sensitivity of the device for the proposed dielectric modulated dual material gate structure. The simulation of the biosensor as shown in Figure 2 shows the conduction and valance band energy representation of proposed device. The complete filling of the nanogap cavity by biomolecules andpractical challenges arise due to difficulties in the binding association of biomolecules, preventing the complete filling of the nanogap with electron hole concentration shown in Figure 3.

The gate overlap on drain side TFET, the gate structure extends beyond the active region of the device toward the drain side. This gate overlap on the drain side enhances the control of the electric field, influencing the tunneling process and improving overall device characteristics. The gate overlap on the drain side provides enhanced control over the tunneling mechanism, resulting in improved drain current characteristics such as on current and reduced leakage current and improved switching characteristics. The DM-DMG TFET is an innovative structure design that combines the principles of tunneling with a dual gate structure and dielectric modulation for improved performance in electronic devices. This transistor type operates based on quantum tunneling, where charge carriers move through a barrier, allowing for low-power and high-speed applications. The dual gate configuration provides enhanced control over carrier flow, and

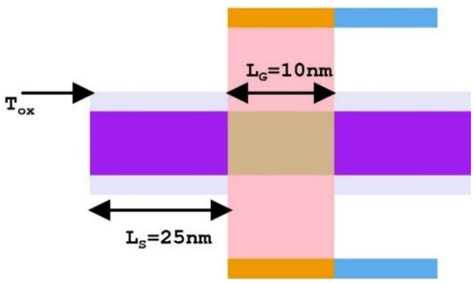

Figure 1. Proposed DM DMG TFET

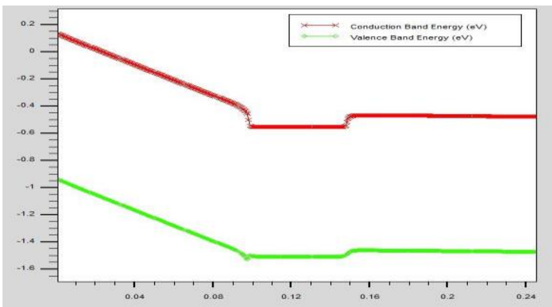

Figure 2. Conduction and valance band energy of device

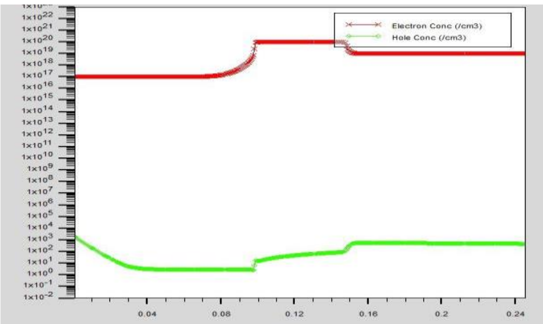

Figure 3. The electron and hole concentration of device

dielectric modulation involves adjusting the properties of the dielectric material, contributing to improved transistor efficiency, speed, and power consumption. This technology is particularly promising for applications requiring low-power operation and high-speed performance, such as in portable electronics and energy-efficient computing systems.

3. RESULTS AND DISCUSSION

Investigations on TFET show interesting variations of drain current when there are K due to differnt biomolecules involved (23). This study examined the effect that biomolecule immobilisation has on the transistors nanocavity. Different dielectric constants were utilised –K=1, K=3 and K=7. Dielectric modulation strongly affects ambipolar current, with subsequent changes in drain current acting as a most sensitive indicator of the biomolecular interaction events (24). A smaller dielectric constant (K=1), denotes lesser polarization forces while larger one indicates strong interactions with electric fields e.g., K=3, K=7. Thus, the TFET dielectric modulation proves ability to detect changes in biomolecular qualities, which points towards a perspective for bio-sensors application (25, 26). Investigation of various dielectric constants provide for an all-rounded knowledge of how the TFET responds towards different biomolecules towards development of customized designs in bioelectronic apparatuses. Figure 4 illustrates the variation of drain current against gate voltage in a given biomolecule (27).

In particular, TFET demonstrates diverse voltage shifts during its interaction with different biological molecules that have distinct K values. In this study, the changes in biomolecule (such as K=1,K=3,K=7) biomolecule affect the potential across the TFET (28, 29). The variation of dielectric constant of the immobilized biomolecule significantly affects the local electric field in nano cavity of the TFET. Subsequently altering the potential distribution. The variation of potential versus position along the channel for various biomolecules is illustrated in Figure 5.

The proposed DM-DMG TFET is considered novel due to its innovative approach in incorporating dielectric modulation to enhance the device performance. The novelty lies in the specific utilization of dielectric modulation, which involves varying the properties of the dielectric material such as hafnium oxide (HfO_2) and silicon dioxide (SiO_2) within the transistor structure. This modulation plays a crucial role in controlling the electric field and, consequently, the tunneling process of charge carriers. By leveraging dielectric modulation, the model aims to achieve improved on current, reduced leakage current, efficiency, speed, and power consumption in comparison to traditional TFET, making it a distinctive and advanced transistor design in 10 nanometer technology.

These variations are largely driven by the dielectric modulation principle that provides a flexible biological sensing surface. These variations in potential due to different dielectric values, demonstrate the specificity and responsiveness of the dielectric-modulated TFET as a biosensor. It is essential in designing TFET- based biosensor, which are specialized biomolecular interaction specific (30).

The dielectric constants differ between various biomolecules and this influences the change in energy bands for a dielectric modulate TFET operating mode

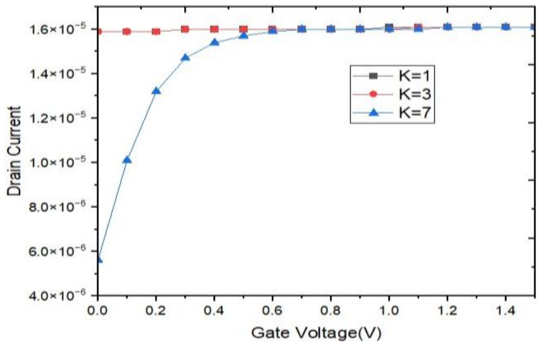

Figure 4. The change in drain current with respect to gate voltage for different biomolecules(K=1,3,7)

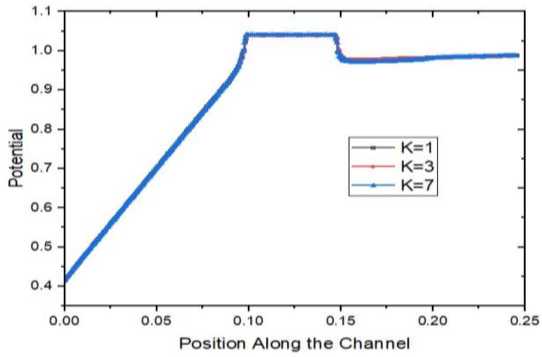

Figure 5. The change in potential with respect to position along the channel for different biomolecules(K=1,3,7)

used as biosensor. Dielectric modulation generates a sensitive environment for sensing biomolecular interactions in TFTs. The change in dielectric constant affects the energy band of the device as it assumes values K=1, 3, and 7 for different biomolecules. Shifts in the energy band lead to adjustments with respect to movement probability of charges by means of dielectric modulation. The biomolecules at low dielectric constant (K=1) may demonstrate an exclusive behavior while a unique tendency will be observed with higher K values such as K=3 and 7. The knowledge of these modifications is crucial for interpretating the device's behavior in respect of various biomolecules and basis for adjusting the biosensors performance depending on the target molecule. This fine understanding of energy bands deviation due to different dielectric constants is essential for optimization of dielectric-modulated TFETs for biosensing designs. Figure 6 displays how biomolecular energy bands vary across the space through a channel.

Observed changes in the drain current, energy bands, and potential in a dielectric-modulated Tunnel Field Effect Transistor (TFET), for different biomolecules where the dielectric constant is K equal to one, three and seven shed light on the response of the The dielectric modulation is instrumental towards shaping the device properties. The dielectric constant of the immobilized biomolecules within the nano cavity changes. It has a direct impact on the dielectric area of the TFETs and thereby determines their capacitance. As a result, this affects the tunneling probability and ultimately the drain current. Lower dielectric constants such as K=1 reduce capacitive coupling resulting in low tunneling probabilities yielding reduced drain current. However, lower dielectric constants such as (K = 7) improve the capacitive coupling providing for more tunneling and increased drain current. The changes in the dielectric environment will also alter the positions of the energy bands, as well as the potential profile inside the TFET device. Because the change in dielectric constant straight influences the electrostatics of this device, it leads to variations in electronic energy levels and potential profiles. The subtle comprehension of intertwinement between dielectric modulation and biological environments gives us vital information in designing effective dielectric-modulated TFETs applicable for various biosensors. Tables 1-3 present the device design performance parameters and electric parameters.

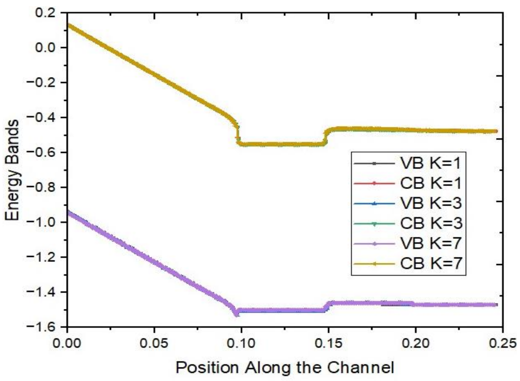

Figure 6. The change in energy bands with respect to position along the channel for different biomolecules

TABLE 1. The dimensions of the proposed device

Parameter	Value
Channel Length	50 nm
Device Length	100 nm
Source Length	30 nm
Channel Thichness	10 nm
(HfO_2) Tox	3 m
(TiO_2) Tox	3 nm
Cavity thickness	6 nm
Gate Work Function	4.3eV
Source doping	10^{18} cm^{-3}
Drain doping	10^{18} cm^{-3}
Channel doping	10^{20} cm^{-3}

TABLE 2. Electricl Parameters of Proposed device

Parameter	Value
Ion (Amps)	1.3
Ioff (Amps)	5.5
Ion/Ioff	2.1

TABLE 3. Comparison of device performance parameters of DM-DMG TFET

Parameters	C TFET	SG TFET	DG TFET	HD-DG TFET	HD-DMG-TFET	DMG-OD-TEFT	Proposed DM-DMG TFET
Ion(A/µm)	3.14	3.98	4.4	5.8	8.23	8.6	9.91
Ioff(A/µm)	9.40	8.99	4.50	4.22	1.14	1.03	1.01
Ion/Ioff	1.59	1.6	1.55	1.67	1.8	2.1	2.11
Gm(S/mm)	1.19	1.23	1.44	1.55	1.69	2.22	3.12
Gd(S/mm)	0.12	0.32	0.41	0.45	0.452	0.46	0.91
Ron(Ωmm)	1.61	1.77	1.32	0.88	0.6	0.71	1.61

The Dielectric Modulated TFETs holds great potential for employing high-k dielectric material such as Titanium dioxide (TiO_2) and this material are compatible, scalable. The fine-tuning and optimizing the dielectric modulation TFET will be important and can reduce the channel length of 5 nanometer node. Therefore, Dielectric Modulated TFET to smaller nodes is essential for integration into advanced semiconductor technologies. This can lead to more compact and energy-efficient electronic devices in future.

4. CONCLUSION

Thus, as shown in this paper, the device in fact utilizes DM-DMG_TFET as the basis of its operation for detecting different biomolecule. A sensor that has improved flexibility by incorporating the nanogap cavity formed between the gate and the drain provides a higher resolution to sense changes in resistance over the time. Therefore, the biosensor manifests sensitivity since the ambipolar current depends on the permittivity of immobilized biomolecules in the nanocavity. The assessment of the sensor performance in various areas and concerning diverse concentrations of molecules in a nanobox provides some data about the applicability aspect. A thorough investigation (drain current, electric field distribution, surface potential variations, energy band configurations, carrier concentrations, and I/O ratios) enlightens a user how the device behaves. The use of the appropriate tool made simulation results reliable with high precision level. As such, this study brings about an important advance in the field of biosensing technology and lays the basis for new methods of production of ultrasensitive and flexible bioelectronics.

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Persian Abstract

چکیده

این مطالعه یک حسگر زیستی را معرفی میکند که از یک ترانزیستور اثر میدان تونل دروازه‌ای دو ماده مدولهشده با دی الکتریک (DM-DMG TFET) در فناوری 10 نانومتری استفاده میکند .برای شناسایی مولکولهای زیستی متنوع، حسگر زیستی یک حفره نانو شکاف تشکیل میدهد که از طریق همپوشانی دروازه در سمت تخلیه تشکیل شده است .تغییر در جریان دوقطبی به عنوان پارامتر سنجش عمل می کند که تحت تأثیر تغییر ثابت های دی الکتریک مولکول های زیستی تثبیت شده در حفره نانو قرار دارد. در این مقاله، نتایج شبیه‌سازی حسگر زیستی با استفاده از ترانزیستور اثر میدان تونلی دروازه دو ماده مدوله‌شده با دی‌الکتریک با ثابتهای دی‌الکتریک متفاوت اعمال شده در حفره نانو انجام میشود .یک بررسی جامع از عملکرد حسگر زیستی انجام میشود و موقعیتهای مختلف و عوامل پرکننده مولکولهای زیستی را در ناحیه نانو حفره بررسی میکند.این تجزیه و تحلیل شامل بررسی کامل عملکرد دستگاه، با در نظر گرفتن طیف وسیعی از پارامترها مانند جریان تخلیه، توزیع میدان الکتریکی، تغییرات پتانسیل سطح، پیکربندی باندهای انرژی، رفتارهای غلظت حامل، و نسبت یون / یون است .شبیه سازی ها با استفاده از ابزار Silvaco TCAD Atlas انجام می شود.