Journal of Nano- and Electronic Physics
Vol. **18** No 2, 02018(5pp) (2026)

Журнал нано- та електронної фізики
Том **18** № 2, 02018(5cc) (2026)

OPEN ACCESS

REGULAR ARTICLE

Material-Engineered DGTFET: An Enhanced Sensitivity Method for Label-Free Biosensing

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(Received 02 February 2026; revised manuscript received 17 April 2026; published online 29 April 2026)

This work investigates a Material-Engineered Double Gate Tunnel Field Effect Transistor (ME-DGTFET) engineered for ultra-sensitive, label-free biosensing applications. The suggested structure with n^+ pocket dual-layer gate dielectric GaSb-AlGaAs-GaAs heterostructure has been implemented to improve the efficiency of band-to-band tunnelling (BTBT) and electrostatic control. Silvaco-ATLAS was used to run device simulations that took into account non-local BTBT, SRH, Auger and BGN models. The modified DGTFET has a subthreshold swing (SS) of 9.2 mV/dec, an I_{on}/I_{off} ratio of 4×10^{13} and a threshold voltage (V_{th}) of 0.32 V. These numbers show that it is much better than traditional Si-based designs. Sensitivity analysis with different dielectric constants (K = 5-12) and biomolecular charge densities ($N_{bio} = \pm 1 \times 10^{12}$ C/cm²) showed that higher dielectric constants and positively charged biomolecules greatly improve ON-current and sub-threshold performance. Moreover, complete surface coverage (100 %) increases sensitivity by over twofold in comparison to partial coverage (50 %). So the proposed ME-DGTFET could be a great choice for next-generation biosensing platforms that need low power and high sensitivity.

Keywords: ME-DGTFET, GaSb-AlGaAs-GaAs heterostructure, Band-to-band tunnelling, Dielectric and electrostatic modulation sensitivity.

DOI: 10.21272/jnep.18(2).02018 PACS numbers: 73.40.Kp, 73.40.Gk, 73.43.Jn

1. INTRODUCTION

In today's world, biosensors have achieved enormous significance in the fields like food industry, medical sector, agriculture, environmental monitoring and forensic sciences [1]. Bio-sensor is an analytical device that uses biological components (e.g. enzymes, antibody, DNA etc) coupled to a transducer (electrical, optical, mechanical etc) to convert a specific biological interaction into a measurable signal. The earliest bio-sensor was introduced in 1962 by Leland C. Clark and Champ Lyons [2], known as father of bio-sensor. After that scientists have started to design well-grounded and error free biosensor for offering label free detection, high sensitivity, scalability & less power consumption [3].The advantages of field effect transistor (FET) based biosensors including label free operation, high sensitivity, low-power consumption, CMOS compatibility and the potential for large-scale integration, have drawn a lot of interest in recent years for the detection of biomolecules [4-6]. These devices use bio-receptors to functionalise the oxide layer or dielectric cavity. The interaction of biomolecules creates a gating effect that modifies the electrical properties of the device, allowing for detection. Short Channel effects (SCEs), leakage current, subthreshold slop (SS) restricted to > 60 mV/dec by the thermionic emission limit and weak detection of neutral biomolecules are some of the disadvantages of conventional FET biosensor [7]. In real world applications, these problems limit their maximum sensitivity and selectivity. Because of their subthreshold slope below 60 mV/dec, ultra-low leakage current and steep switching characteristic, TFETs have become a promising option for next generation biosensing applications [8]. TFETs rely on the band-to-band tunnelling (BTBT) mechanism [9], which allows for quick response times, low voltage operation and better sensing performance than MOSFETs which use thermionic emission to control current flow.

TFET biosensors have limitations despite these advantages. Practical implementation is hampered by their ambipolar conduction and relatively low ON current [I_{on}] [10]. Multiple engineering techniques, such as hetero-gate architectures, high-K dielectric stacks, high band gap channel material. Moreover, dielectrically modulated TFET biosensors have been developed as a result of the integration of DM with FET structure [10-12]. Because it can identify both charged particles as well as neutral biomolecules, operate at lower supply voltages and achieve higher sensitivity, DM-TFET biosensor [12]. To ensure accurate and robust detection of a broad range of biomolecules, there is still plenty of scope to improve sensitivity and selectivity. Based on these designs, this work suggests and investigates sophisticated DM-TFET architectures designed for high-performance biosensing uses.

2. MODELS AND METHODS

The standard silicon-based Tunnel FET (TFET) has low tunnelling efficiency and poor performance in the

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Cite this article as: P. Pahari et al., *J. Nano- Electron. Phys.* 18 No 2, 02018 (2026) https://doi.org/10.21272/jnep.18(2).02018

sub threshold range. The concept for Material Engineered Double Gate TFET (ME-DG-TFET) fixes these problems by using a hetero structure comprising three compound semiconductors as shown in Fig 1. The channel is made out of a ternary compound semiconductor ($Al_{0.47}Ga_{0.53}As$). The source is Gallium Antimonide (GaSb) with a low bandgap of 0.72 eV to make band-to-band tunnelling easier, while the drain is Gallium Arsenide (GaAs). The doping concentration of source, channel, and drain are p^{++} (1×10^{20} cm^{-3}), n (1×10^{17} cm^{-3}), and n^+ (5×10^{18} cm^{-3}), respectively. A 3 nm n^+ pocket with a doping of 5×10^{19} cm^{-3} is added near the source-channel junction to make the tunnelling width smaller and the ON-current stronger. The 50 nm long channel is covered by a bilayer gate dielectric stack made up of 0.5 nm SiO_2, which protects against leaks and makes the gate more sensitive, and 1.5 nm HfO_2, which makes the gate more powerful. Both gates have a work function of 4.0 eV. There are also 15 nm × 1.5 nm cavities made near the source-channel junction which can sense biomolecules, which allows for biosensing. In general, this method of material and structural engineering using GaSb-AlGaAs-GaAs heterostructures, pocket doping, dual-gate control, and bilayer dielectrics greatly improves tunnelling efficiency, ON-current, and sensitivity. This makes the ME-DG-TFET better than the regular Si-based TFET. Silvaco Atlas [13] was used for all of the simulations. The simulations use a very fine mesh in the area where the tunneling happens to figure out the energy band profiles and the energies that allow band-to-band tunneling. We use non-local band-to-band tunneling (BTBT) and the band gap narrowing (BGN) model to figure out the tunneling current. These models take advantage of the device's heavily doped areas. The Shockley-Read-Hall (SRH) and Auger models are used in the simulation to look at generation and recombination. The simulation also uses the Fermi-Dirac distribution function model and the drift-diffusion carrier transport model. Conmob includes a mobility mode that depends on concentration, and consrh includes a lifetime mode that depends on concentration.

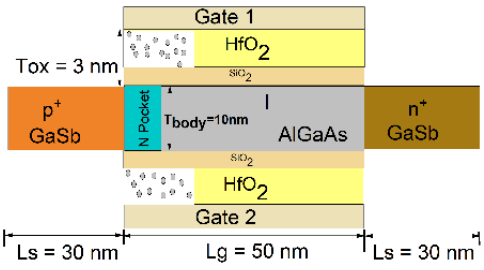

Fig. 1 – Modified DGTFET structure with cavity

Table 2 shows that the gate control is better and the switching is sharper among the two structures shown in Fig. 3. The ON-state current (I_{on}) goes up far from 1.48×10^{-6} in the silicon version to 5.9×10^{-5} A in the designed version respectively. I_{off} is significantly decreased from 2.68×10^{-16} A to 8.8×10^{-18} A, which is essential for low-power functionality. So, the I_{on}/I_{off} ratio goes up from 2.2×10^{11} to 4×10^{13}, which is over two orders of magnitude better.

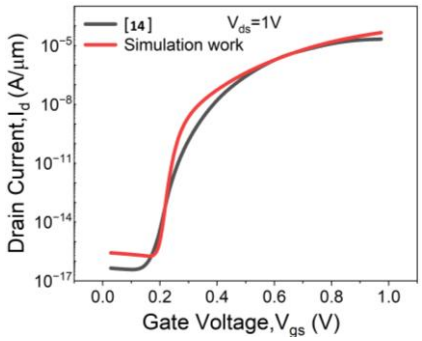

Fig 2 – Calibration of TFET structure through ref [14]

Table 1 – Performance comparison between two different structures

Parameters	Modifications of DGTFET structure with L_G = 50 nm	
	Silicon based	This work
SS (mV/dec)	31.4	9.2
I_{on} (A/μm)	5.91×10^{-5}	3.5×10^{-5}
I_{off} (A/μm)	2.68×10^{-16}	8.8×10^{-18}
I_{on}/I_{off}	2.2×10^{11}	4×10^{13}
V_{th} (V)	0.46	0.32

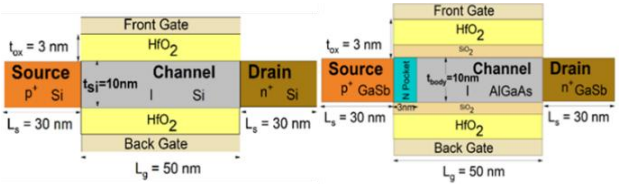

Fig. 3 – Device structure (a) Si based DGTFET, (b) with N-pocket DGTFET

This makes switching more reliable and less sensitive to noise. Also, the threshold voltage (V_{th}) the operating voltage is lower and the energy efficiency is better as it drops from 0.46 V to 0.32 V. All of these performance gains show how well material and structural engineering work in the modified DG-TFET. This allows it a great option for future ultra-low-power and high-performance nano-electronic applications.

3. RESULTS AND DISCUSSIONS

3.1 Drain Current vs Gate Voltage of Modified DG-TFET for Charged Biomolecules

Fig. 4 shows how the basic DGTFET and modified DGTFET with N-pocket structures transfer data differently in different biomolecular and dielectric environments at V_{ds} = 1 V. In the basic DGTFET (a-c), the drain current (I_d) changes depending on the dielectric constant (K) and the biomolecular charge density (N_{bio}). Fig. 4(a) elaborates that when the dielectric constant is higher, the drain current is higher for neutral biomolecules (N_{bio} = 0). This is because the gate-channel coupling is stronger, which improves electrostatic control. Fig. 4(b) shows that positively charged biomolecules greatly increase the tunnelling probability, which increases the ON-current. Figure 4(c), on the other hand, shows that negatively charged biomolecules slow down the tunnelling process, which makes the barrier wider and lowers

I_d. Figures 4 (d-f), on the other hand, show how well the modified DGTFET with *N*-pocket works. It has a clear improvement in drain current and subthreshold properties. The device has sharper switching and higher ON-current than the basic DGTFET when it is in neutral conditions (4d). The modified structure still has higher current and smoother transitions than the basic version for negative (4f) and for positively charged biomolecules (4e), the tunnelling efficiency is even better, which means more current amplification.

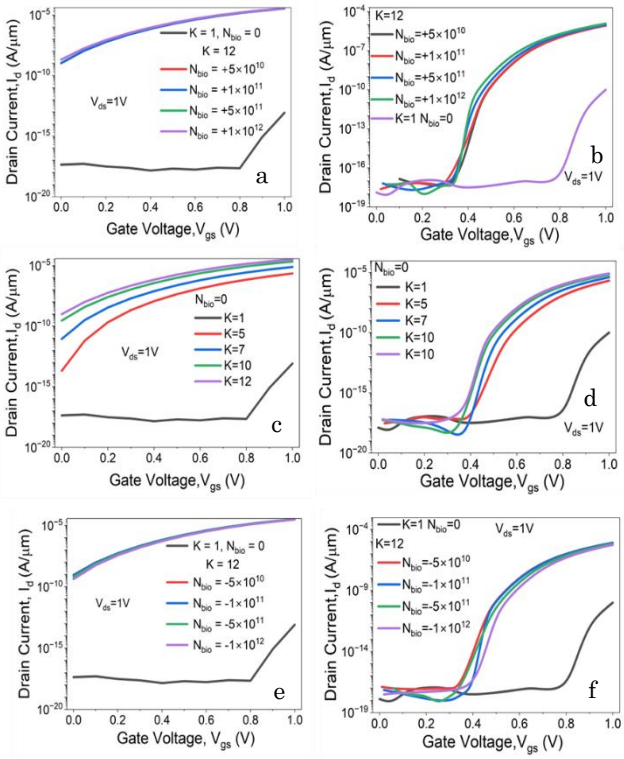

Fig. 4 – I_d-V_{gs} characteristics of Si- DGTFET (a) for positive biomolecules (b) for neutral biomolecules (c) negative biomolecules and modified DGTFET(d) for positive biomolecules (e) for neutral biomolecules (f) negative biomolecules

The *N*-pocket DGTFET shows better electrostatic coupling, a steeper subthreshold swing, and higher sensitivity overall. This suggests that it is better for high-performance and reliable biosensing uses. Figure 5 shows how the modified DGTFET biosensor reacts to changes in dielectric constants and biomolecular charge conditions. Fig. 5(a-c) show how the dielectric constant (*K*) of biomolecules affects the ON-current sensitivity (S_I). Fig. 5(a) shows that as *K* goes from 5 to 12, S_I goes up in a straight line. This means that the gate and channel are more strongly electrostatically coupled, which makes tunnelling more likely and improves the ON-current.

Fig. 5(c) shows how negatively charged biomolecules affect sensitivity parameters. As the amount of negative charge density goes up, S_I goes down. This happens because negative charges push carriers away, which makes the tunnelling barrier wider and lowers the ON-current. However, subthreshold swing still benefits from better gate modulation. Figure 5(b), on the other hand, show the response for positively charged biomolecules, which is the opposite of what we see in the first set of figures. As the positive charge density (5b) goes up, S_I goes up quickly. This shows that attractive electrostatic forces help carrier tunnelling and make sensitivity better. The results show that increasing the dielectric constant and the positive biomolecular charge improves the DGTFET's performance by lowering the threshold voltage, sharpening the sub-threshold swing, and greatly increasing the current sensitivity. This proves that it has great potential for ultra-sensitive and label-free biosensing applications.

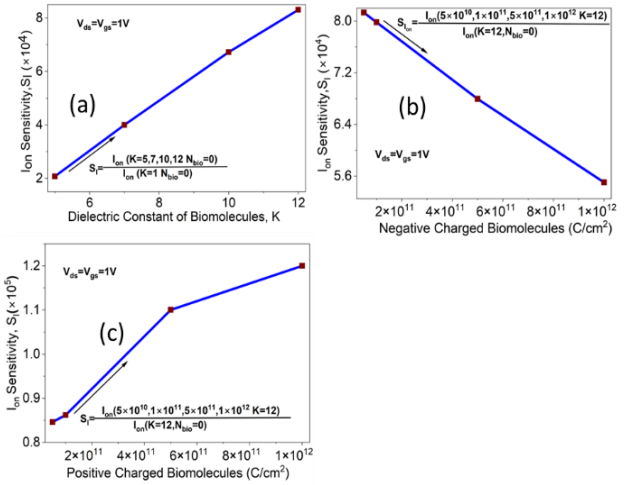

Fig. 5 – Sensitivity analysis of modified DGTFET (a) I_{on} sensitivity for neutral (b) I_{on} sensitivity for negative charged (c) I_{on} sensitivity for positive charged

Furthermore, the three panels compare two surface coverages as shown in Fig. 6, 50 % (black) and 100 % (red), at $V_{gs} = V_{ds} = 1$ V. They show current sensitivity (S_I) versus the biomolecule dielectric constant *K*. The left plot shows neutral biomolecules ($N_{bio} = 0$). S_I goes up almost linearly with *K*, and going from 50 % to 100 % coverage gives a consistent multiplicative gain. This shows that dielectric loading alone strengthens gate-channel coupling and BTBT.

The middle plot is for biomolecules with a negative charge ($N_{bio} = -1 \times 10^{12}$ C/cm^2). The absolute S_I is the lowest of the three cases, and it only goes up slightly with *K*. Full coverage still improves S_I, but only by a small amount, because the repulsive charge makes the tunnelling barrier wider, which cancels out the benefits of dielectric. The right plot is for biomolecules with a positive charge ($N_{bio} = +1 \times 10^{12}$ C/cm^2). S_I is highest and rises quickly with *K*. Going to 100 % coverage gives a huge improvement, as attractive charge narrows the tunnelling barrier and high-*K* further improves electrostatic control. In all cases, a higher *K* means a higher S_I, and a higher coverage means a higher S_I. However, the charge's polarity sets the baseline and slope (positive > neutral > negative). In terms of design, the sensor is most responsive to high-*K*, positively charged analytes. It is still sensitive enough for neutral targets, and it shows a suppressed but steady response for negative targets. This makes it possible to accurately measure *K* and surface coverage.

CONCLUSION

This proposed GaSb-$Al_{0.47}Ga_{0.53}As$-GaAs-based ME-DGTFET biosensor solves the problems that regular TFET structures have by using heterostructure material

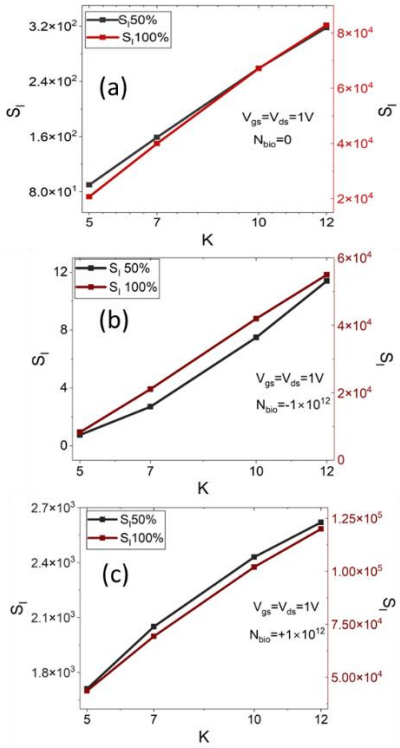

Fig. 6 – I_{on} sensitivity analysis for 50 % and 100 % fill factor for (a) neutral (b) negative (c) positive charged biomolecules

engineering, pocket doping, and dual-layer dielectric optimisation. These design strategies work together to make switching sharper, lower leakage, and higher ON-current, which makes the device as a whole more efficient. The simulation results show that the subthreshold swing has dropped to 9.2 mV/dec and the ratio between I_{on} and I_{off} has gone up by two orders of magnitude. This shows that the gate control is strong and the tunnelling characteristics are better. Sensitivity analysis shows that positive biomolecular charges and high dielectric constants greatly improve device response, while negative charges have the opposite but predictable effect. Moreover, heightened surface coverage amplifies current sensitivity, underscoring the significance of dielectric modulation in biosensing efficacy. These results show that the modified DGTFET can reliably find biomolecules with high accuracy and stability. This makes it a good choice for real-time, low-power, and label-free biosensing applications in healthcare, food safety, and environmental diagnostics. uence of dielectric and electrostatic modulation. The proposed ME-DGTFET has high Ion sensitivity, a low threshold voltage, and great selectivity. This shows that it has a lot of potential for next-generation biosensing platforms that use low power and high sensitivity.

ACKNOWLEDGEMENT

The Fund for Improvement of S&T Infrastructure (FIST), a program by the Indian government's Department of Science and Technology (DST) file no is (SR/FST/ET-1/2021/862), School of Electronics Engineering, Kalinga Institute of Industrial Technology, Deemed to be University, Bhubaneswar, Odisha, India.

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DGTFET: метод підвищеної чутливості для біосенсорики без міток

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У роботі проведений аналіз та дослідження матеріало-інженерного двозатворного тунельного польового транзистора (ME-DGTFET), розробленого для надчутливих біосенсорних застосувань без міток. Запропонована структура з двошаровою діелектричною гетероструктурою GaSb-AlGaAs-GaAs з n^+ кишеньками була реалізована для підвищення ефективності міжзонного тунелювання (BTBT) та електростатичного контролю. Silvaco-ATLAS було використано для проведення моделювання пристрою, яке враховувало нелокальні моделі BTBT, SRH, Оже та BGN. Модифікований DGT-FET має підпороговий розмах (SS) 9,2 мВ/дек, співвідношення I_{on}/I_{off} 4×10^{13} та порогову напругу (V_{th}) 0,32 В. Ці результати показують, що він має кращі характеристики за традиційні конструкції на основі кремнію. Аналіз чутливості з різними діелектричними константами (K = 5-12) та густинами біомолекулярного заряду (N^{bio} = ± 1×10^{12} С/см^2) показав, що вищі діелектричні константи та позитивно заряджені біомолекули значно покращують характеристики струму ввімкнення та підпорогових значень. Більше того, повне покриття поверхні (100 %) збільшує чутливість більш ніж удвічі порівняно з частковим покриттям (50 %). Тому запропонований ME-DGTFET може бути чудовим вибором для біосенсорних платформ наступного покоління, яким потрібні низька потужність та висока чутливість.

Ключові слова: ME-DGTFET, GaSb-AlGaAs-GaAs гетероструктура, Міжзонне тунелювання, Чутливість до діелектричної та електростатичної модуляції.