Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
Vol. 47 No. 02 (2026)

A Comprehensive Study of Material-Optimized TFET Biosensors for Low-Power and Reliable Sensing Applications

Kishore Chandra Singh, Sudhansu Mohan Biswal,Prasanta Ku Khuntia,Biswajit Baral

Silicon University, Bhubaneswar, India

Abstract — For next-generation biomedical sensing applications, tunnel field-effect transistor (TFET)-based biosensors have drawn a lot of interest because of their steep subthreshold swing, low power consumption, steep subthreshold swing, and superior sensitivity compared with conventional MOSFET-based biosensors. This work presents a comprehensive study of material-optimized TFET biosensors aimed at achieving enhanced sensing performance, improved thermal stability, and reliable device operation for label-free biomolecule detection. The proposed biosensor employs dielectric modulation in the cavity region along with advanced material engineering techniques to strengthen electrostatic control and carrier tunnelling efficiency. Different biomolecules with varying dielectric constants are introduced into the sensing cavity to analyze their impact on important electrical characteristics such as drain current, threshold voltage, transconductance, and sensitivity factor. Furthermore, the influence of high-k gate dielectric materials, heterojunction engineering, and channel optimization on device performance is systematically investigated. Thermal stability analysis is performed over a wide temperature range to evaluate the robustness of the proposed structure under practical operating conditions. In addition, structural reliability is assessed by examining variations in cavity dimensions, oxide thickness, and channel parameters to ensure consistent sensing behavior.The simulation results demonstrate that the optimized TFET biosensor achieves enhanced sensitivity, improved ON-state current, reduced ambipolar conduction, and stable electrical characteristics with minimal temperature-induced degradation. The proposed architecture offers a promising platform for low-power, highly sensitive, and reliable biosensing applications in future biomedical and healthcare systems.

Keywords- TFET, short channel effects (SCE's), nanogap, sensitivity, and biosensor.

1 Introduction: -

The rapid growth of biomedical diagnostics and point-of-care healthcare systems has significantly increased the claim for extremely sensitive, low-power, and reliable biosensors capable of detecting biomolecules with high precision. Between various sensing technologies, FET-based biosensors have appeared as promising candidates because of their label-free detection capability, fast response time, compact size, and compatibility with CMOS fabrication processes [11-13]. These biosensors directly convert biological interactions into measurable electrical signals, assembly them very appropriate for real-time medical diagnostics and eco-friendly monitoring applications [17-26]. Conventional MOSFET-based biosensors, Despite being extensively studied, they suffer from a number of drawbacks, including high leakage current, significant subthreshold swing, and elevated power consumption at nanoscale dimensions [8–10], [14], and [15]. Due to their special band-to-band tunneling (BTBT) mechanism, which permits subthreshold swing values below the thermionic limit of 60 mV/decade and greatly reduces power dissipation, Tunnel Field-Effect Transistors (TFETs) have garnered significant research interest in order to overcome these difficulties [4]. TFETs are very appealing for next-generation low-power biosensing applications because of these features. Dielectric-modulated TFET biosensors have received a lot of interest lately for label-free biomolecule detection [1]–[3], [29]–[33]. These devices introduce nanocavity regions close to the

gate area. The immobilization of biomolecules within the cavity modifies the local dielectric environment, resulting in quantifiable changes in electrical properties like subthreshold swing, drain current, threshold voltage, and transconductance. The dielectric constant and charge properties of the biomolecules inside the cavity have a significant impact on the sensing performance. Because of its improved tunneling efficiency and greater gate control, TFET biosensors offer higher sensitivity than traditional FET biosensors, as several studies have shown [1]–[3]. An efficient method for enhancing TFET biosensor performance is material engineering. Device sensitivity and ON-state current are improved by including low-bandgap source materials, heterojunction designs, and high-k gate dielectric materials, which greatly increase tunneling probability and carrier transport efficiency. Advanced structures such as heterojunction TFETs, ferroelectric TFETs, and gate-engineered TFETs have shown remarkable improvements in biosensing performance and energy efficiency [5],[6]. Apart from sensitivity enhancement, thermal stability and structural reliability are critical considerations for practical biosensor implementation. Variations in operating temperature, cavity dimensions, oxide thickness, and fabrication imperfections can significantly influence device characteristics and sensing accuracy [8]– [10]. Therefore, comprehensive investigation of thermal effects and structural reliability is essential to ensure stable operation in real-world biomedical environments. Recent studies have also highlighted the importance of incorporating non-idealities and realistic operating conditions into TCAD-based biosensor simulations for accurate performance prediction [5], [8]. Motivated by these challenges, this work presents a comprehensive study of material-optimized TFET biosensors for low-power and reliable sensing applications. The proposed device investigates the influence of dielectric modulation, material engineering, thermal stability, and structural reliability on biosensor performance. Different biomolecules with varying dielectric constants are analysed to evaluate important sensing parameters including drain current sensitivity, threshold voltage variation, subthreshold swing, and transconductance. The study aims to provide an optimized TFET biosensor architecture suitable for future high-performance biomedical and healthcare sensing systems.

From the standpoint of the biosensor field, early and precise detection of dangerous or intriguing chemicals is crucial to preventing their lethal effects on the body or curing diseases at an early stage [16]–[28].Because biosensors are simple, quick, inexpensive, highly sensitive, and highly selective, they are contributing to advancements in next-generation medicines like personalized medicine and ultrasensitive point-of-care detection of disease markers, making research and development of biosensors the most studied field [21]–[28]. Although the tunneling field effect transistor's structure is nearly identical to that of a MOSFET, its crucial switching process differs. Instead of adjusting thermionic emission over a barrier as in conventional MOSFETs, the switching mechanism of TFETs is accomplished by modifying quantum tunnelling via a barrier.

2. Motivation and Objectives:

Enhanced Sensitivity: Staggered heterojunction dual-material TFET biosensors aim to achieve superior sensitivity in detecting biological analysts such as proteins, DNA, and viruses. By leveraging the unique properties of TFETs, including steep subthreshold slopes and low leakage currents, these biosensors can detect minute changes in analyst concentrations.

Low Power Consumption: TFETs inherently consume less power compared to traditional MOSFETs due to their tunneling-based operation. By incorporating staggered heterojunctions and dual-material configurations, these biosensors further reduce power consumption, making them suitable for portable and battery-operated applications, such as point-of-care diagnostics and wearable health monitors [5]–[7].

Improved Signal-to-Noise Ratio (SNR): The dual-material TFET design helps enhance the SNR of biosensors by minimizing noise and interference. Staggered heterojunctions contribute to better charge transport properties, reducing unwanted noise and improving the overall signal quality, thereby increasing the reliability of bio sensing measurements [5], [6].

Compatibility with Biological Environments: Staggered heterojunction dual-material TFET biosensors are engineered to operate effectively in biological environments, such as blood, saliva, or cellular samples. They are

designed to be biocompatible, ensuring minimal interference with biological processes and reducing the risk of false positives or false negatives in bio sensing applications.

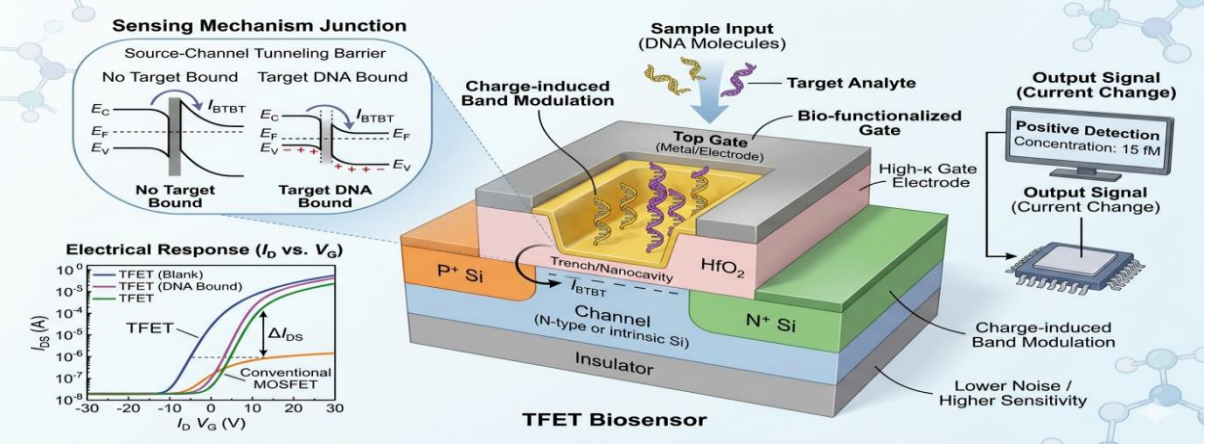

Fig 1. Diagrammatic representation of the procedures for detecting biomolecules by TFET Biosensor

3.Working of TFET as a biosensor

Since the bio-recognition/sample element for the targeted biomolecules must be prepared with extreme care and the sample must be modified when the targeted analyte changes, creating a label-based biosensor is an extremely challenging and time-consuming process.Neutrally charged biomolecules are not being detected, and the evaluation of quality changes in the physiochemical reaction of the target analyte is also difficult.

The most significant obstacle to TFET performance improvement in terms of sensitivity is ambipolar conductivity. Because no effort has been made to lower the ambipolar conductivity, the performance of the previously described dielectric modulated TFET biosensor is limited [1], [2], [29]–[33]. The targeted biomolecules' charge and dielectric constant were taken into account independently in the sensitivity analysis, although in reality, the charge is only present when the biomolecule has a dielectric constant. Rakhi Narang et al. suggested a DMTFET biosensor with a hetero gate structure in order to address these issues and improve performance [1][2]. An InAs-based TFET biosensor is a biosensor that detects biological substances using an Indium Arsenide (InAs) Tunnel Field-Effect Transistor (TFET). Similar to silicon-based TFETs, InAs-based TFETs employ InAs as the semiconductor material rather than silicon.An InAs-based TFET biosensor functions fundamentally similarly to a silicon-based TFET biosensor. A biological receptor that selectively attaches to a target molecule is used to functionalize the gadget. The local charge distribution surrounding the device is altered when the target molecule attaches to the receptor, which modifies the tunnelling current and modifies the electrical properties of the device.

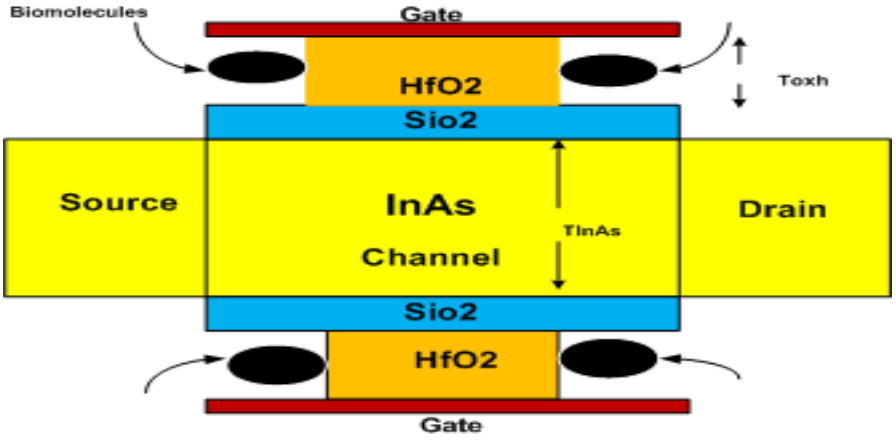

Fig 2: 2-Dimensional view of InAs based GSTFET as Biosensor

4.Device structure and simulation setup:

Technology Computer-Aided create (TCAD) simulations are used to create and analyze the suggested device structure. Heavily doped p-type material makes up the source region, and heavily doped n-type material makes up the drain region. To promote effective tunneling transport and reduce short-channel effects, an inherent silicon channel that has been gently doped is positioned between the source and drain terminals. High-k gate dielectric material is used in material engineering to increase the tunneling probability and sensing performance. HfO2 makes up the gate dielectric layer, which improves gate control, lowers leakage current, and increases capacitive coupling between the gate and the channel area [10]. A metal gate with an improved work function is used to produce the gate electrode in order to improve ON-state current characteristics and threshold voltage control. To effectively depict carrier transport and nanoscale device behavior, the simulation framework integrates a number of physical models. The quantum tunneling mechanism that drives TFET functioning can be captured by the non-local band-to-band tunneling (BTBT) model. To increase simulation accuracy under high doping circumstances, concentration-dependent mobility, Fermi–Dirac statistics, Shockley–Read–Hall (SRH) recombination, and bandgap narrowing models are also incorporated. When necessary, trap-assisted tunneling mechanisms and quantum confinement effects are also taken into account to depict realistic nanoscale functioning.

Table 1: Device Structural Parameters

Parameter	Value	Unit
Gate length	30	nm
Source and the drain length	20	nm
Length of the nanogap cavity regions Lgap	12	nm
T1 thickness of oxide thickness (SiO2)	1	nm
T2 (Thickness of the HfO2 layer)	11	nm
Doping level of the source (p+)	2×10^{19}	cm−3
Doping level of the drain (n+)	5×10^{19}	cm−3
Doping level of the channel (n−)	5×10^{16}	cm−3
Gate workfunction	4.61	eV
Underlap Length	0	nm

5.Result and Discussion:

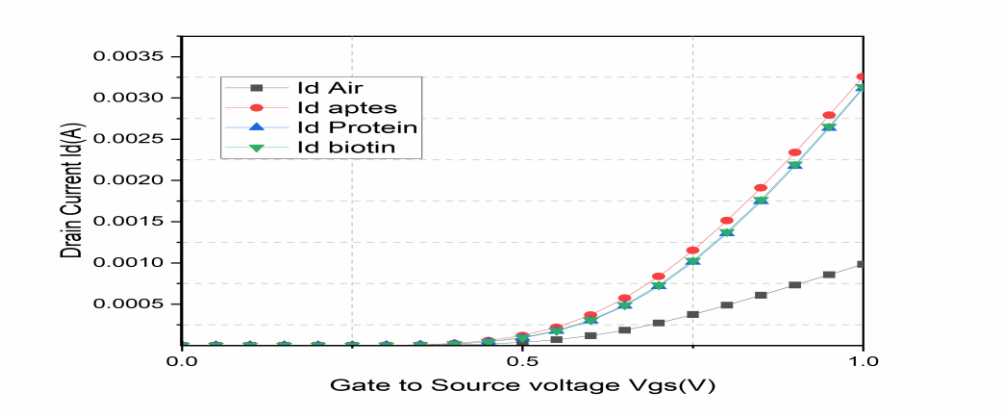

Fig 3 Drain Current vs. Gate Voltage Plot for Various Biomarkers

In a TFET-based biosensor, the graph displays the change of Drain Current (Id) with Gate-to-Source Voltage (Vgs) for various biomolecules (Air, APTES, Protein, and Biotin). The observed characteristics clearly show that when biomolecules with higher dielectric constants occupy the cavity region close to the source–channel junction, the drain current increases dramatically.Current conduction in a TFET biosensor mostly happens at the source–channel junction via the band-to-band tunneling (BTBT) mechanism. The local dielectric environment is altered by the presence of biomolecules inside the nanocavity, which alters the intensity of the electric field at the tunneling junction [1-3]. The gate control over the channel gets stronger as the dielectric constant rises, increasing the drain current and tunneling probability.Both the dielectric and the electric current alter when the biomolecule enters. The possibility of detecting biomolecules by sensing the change in current regulated by the presence of biomolecules is evident from the change in current. As a result, drain current rises as K increases.

The plots 4 represents the Transconductance (g_m) in mho (inverse ohms, or Siemens) against the Gate-to-Source Voltage (V_{GS}) in Volts for a field-effect device (typically a novel architecture like a dielectrically-modulated Nanosheet FET or Tunnel FET used in biosensing applications).The curves evaluate performance across three different dielectric constant values (K = 2.5, K = 12$, and K = 22).

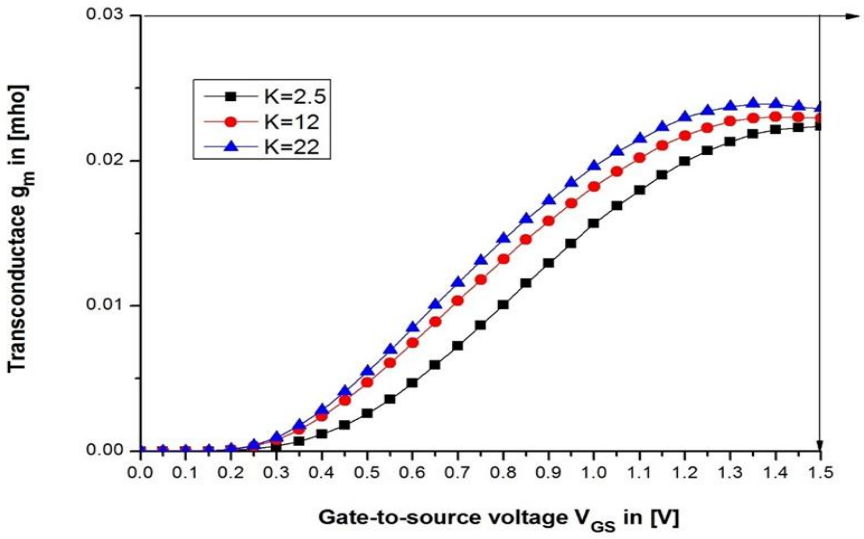

Fig 4 Plot of the transconductance gm for several biomolecules with respect to the gate to source voltage

In dielectrically modulated biosensors, the introduction of target biomolecules into a custom-etched nanocavity changes the effective dielectric constant (K) near the gate.A higher K increases the overall gate capacitance (Cox).Since transconductance is directly proportional to oxide capacitance higher K values amplify the channel transport modulation.The clear separation between the curves demonstrates that the device is highly capable of distinguishing biomolecules based on their dielectric signatures, translating to excellent sensor sensitivity.

Fig 5 shows Comparison of Transconductance Transconductance measures the amplification capability of the device, representing how effectively the gate voltage controls the drain current.Higher transconductance translates to better sensor sensitivity and a stronger electrical signal response. For both material types, the curves shift upward when target biomolecules fill the nanocavity compared to the baseline reference (Air). This occurs because target biomolecules have a higher dielectric constant (K) than air (K=1). The introduction of a higher-k substance increases the overall gate capacitance (Cox), amplifying the gate's electrostatic control over the channel carrier transport. the graph shows that Silicon-based curves (top cluster) reach a much higher maximum transconductance (around 0.0095 A/V) atVgs = 1 .0 V compared to the InAs-based curves (lower cluster, peaking around 0.004 A/V). The steep subthreshold swing and unique carrier saturation/confinement profiles of the optimized Si

heterojunction structure allow the gate bias to modulate its channel transport much more aggressively at higher operating voltages (Vgs > 0.5V) compared to the InAs configuration.

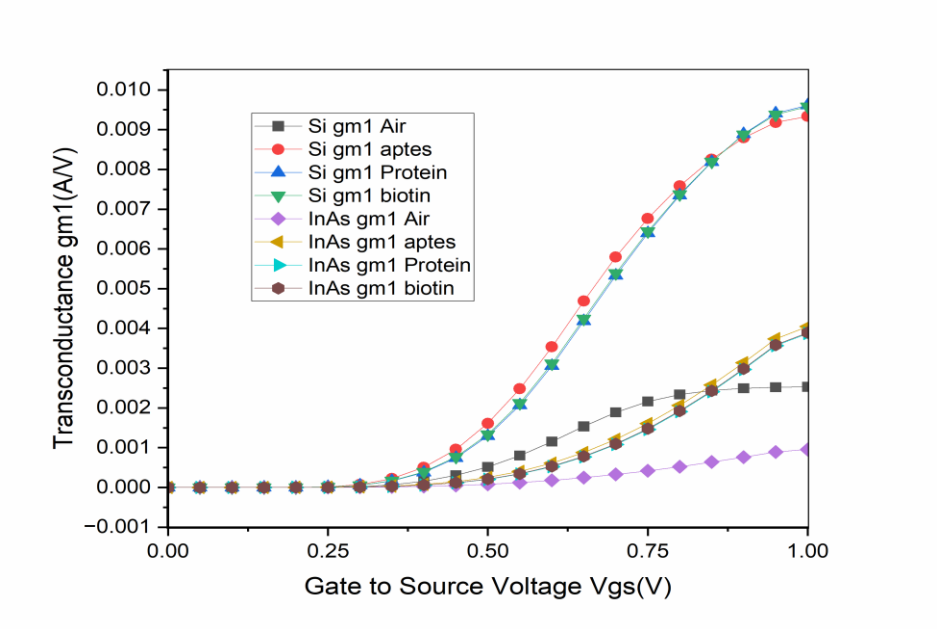

Fig 5 Plot of Comparison of Transconductance g_m w.r.t Gate to source voltage for InAs and Si based

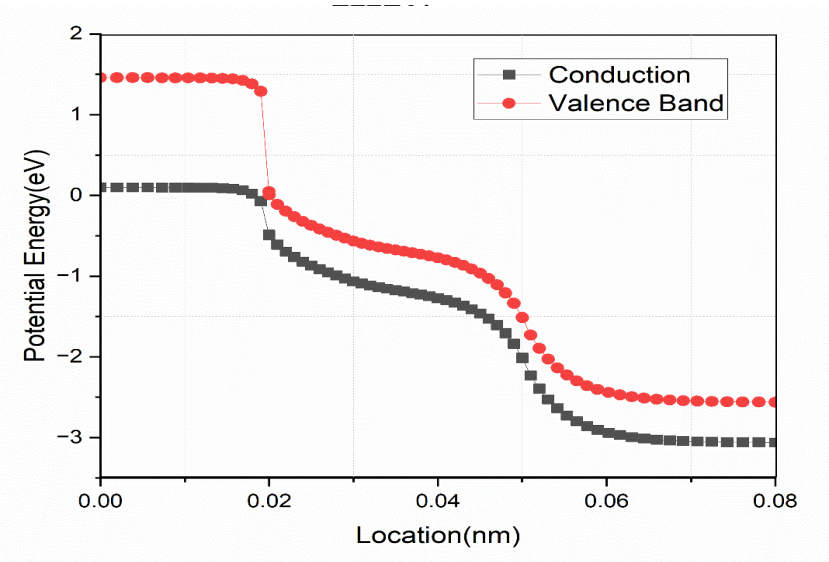

Fig 6 Plot of Energy band from source to channel for for TFET biosensor

Fig 6 represents the variation of Conduction Band Energy (Ec) and Valence Band Energy (Ev) along the channel length of a TFET-based biosensor. This energy band profile is one of the most important characteristics used to explain the operation of Tunnel Field Effect Transistors (TFETs), particularly the band-to-band tunneling (BTBT) phenomenon responsible for current conduction. From the graph, it can be observed that:Near the source region, the conduction band and valence band are separated by a finite energy gap. Around the source–channel junction, the energy bands bend sharply. The bending becomes significant near the tunneling junction, reducing the

tunneling barrier width[4]. At higher gate bias, the valence band of the source approaches the conduction band of the channel, enabling electrons to tunnel from the valence band to the conduction band. Toward the drain side, both bands shift downward due to the applied drain bias.

In TFET biosensors, biomolecules inserted into the cavity modify the dielectric environment near the source-channel junction. This changes the electric field distribution and alters the band bending profile.Biomolecules with higher dielectric constant enhance gate coupling. Enhanced gate coupling produces stronger band bending. Stronger band bending reduces tunneling barrier width. Reduced barrier width increases tunneling current sensitivity. Thus, the presented energy band diagram validates the sensing mechanism of the TFET biosensor.

Sensitivity Analysis:

Sensitivity analysis of a junction-less Tunnel Field-Effect Transistor (TFET) biosensor entails analyzing how the biosensor's performance is impacted by changes in several parameters. The sensitivity of a TFET biosensor is a crucial parameter since it establishes the sensor's capacity to identify minute

variations in the target biomolecules' presence. Sensitivity to drain current can be expressed as

$$I_d\ sensitivity = \frac{I_d(bio) - I_d(air)}{I_d(air)} \quad \ldots\ldots\ldots\ldots (1)$$

Similarly, threshold voltage sensitivity is determined using:

$$S_{V_{TH}} = \frac{V_{TH,air} - V_{TH,bio}}{V_{TH,air}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

As target biomolecules with progressively higher dielectric constants are added to the cavity—from protein (K = 2.5) to biotin (K = 2.63) to APTES (K = 3.57) Fig. 7 illustrates the drain current sensitivity of a Si-based TFET biosensor for a variety of biomolecules. Underlying Physical Mechanism: The local dielectric environment inside the nanocavity close to the source–channel junction is changed by the addition of these biomolecules. Higher dielectric constant biomolecules improve electrostatic control over the channel and gate capacitive coupling.

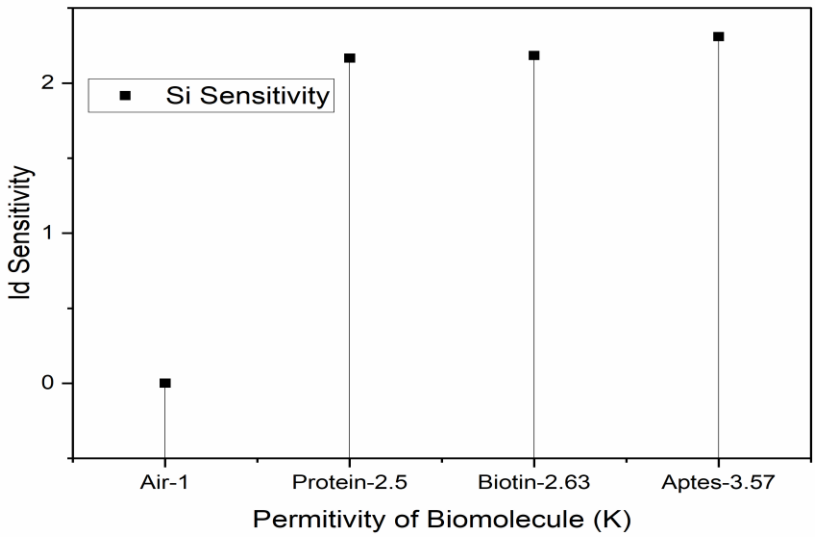

Fig 7: plot of drain current sensitivity of Si-based TFET Biosensor for various biomolecules

The quantum tunneling barrier width is greatly reduced due to the sharper energy band bending at the junction caused by this stronger gate coupling. The band-to-band tunneling (BTBT) probability is significantly increased by a thinner barrier, which results in a greater drain current and a stronger sensitivity response.

This fig 8 plots and compares the Drain Current Sensitivity (Id Sensitivity) against the Permittivity of Biomolecules (K) for both a Silicon (Si)-based TFET and an Indium Arsenide (InAs)-based TFET biosensor. Key observations and physical explanations from this result include:Superior Sensitivity of InAs over Si: Across all tested target biomolecules—Protein (K = 2.5), Biotin (K = 2.63), and APTES (K = 3.57)—the InAs-based TFET biosensor (represented by the red dots) consistently exhibits a higher drain current sensitivity compared to the Si-based TFET biosensor (represented by the black squares). Impact of Low-Bandgap Material Engineering: This significant performance boost is due to material optimization. InAs is a low-bandgap semiconductor material compared to conventional silicon. Using a lower-bandgap material at the source-channel tunneling junction inherently reduces the energy barrier that electrons must cross.

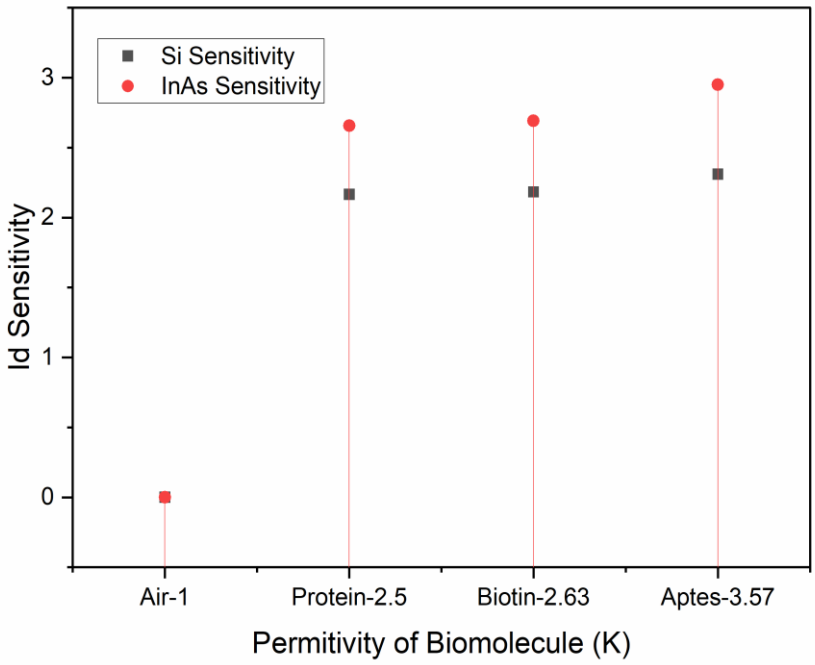

Fig 8 Plot of Comparing the drain current sensitivity of Silicon TFET and InAs based TFET for various biomolecules

The Vth sensitivity of silicon TFET and InAs-based TFET for different biomolecules is compared in Fig. 9. The sensitivity value is 0 when the cavity is empty or filled with air (k = 1). This is used to determine the shifts brought on by foreign analytes. Sensitivity Behavior at Lower Dielectric Constants (k = 2.5 and k = 3.57): The sensitivity remains positive or almost zero for biomolecules with relatively low dielectric constants, such as k = 2.5 (protein) and k = 3.57 (APTES), culminating at k = 2.5 with a value of roughly 0.03. This suggests that the initial weak gate capacitive coupling changes caused a little rise or change in the effective threshold voltage. At higher dielectric constants (k = 8 and k = 12), there is a shift to negative sensitivity. The threshold voltage sensitivity drastically decreases into negative values, reaching about 0.1, when biomolecules with noticeably higher dielectric constants (k = 8 and k = 12) are added. Physical Mechanism Underlying: A higher-k biomolecule added to the nanocavity of a TFET significantly increases the gate oxide capacitance (Cox). The gate's electrostatic control over the channel is greatly strengthened as a result.

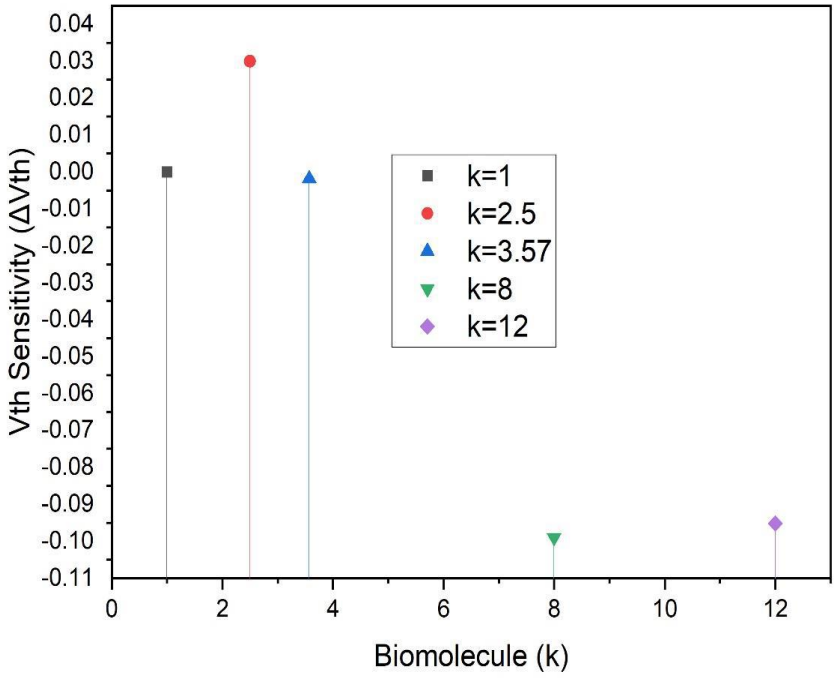

Fig 9 Plot of Comparing the Vth sensitivity of Silicon TFET and InAs based TFET for various biomolecules

6 Conclusion:

This work presents a material-optimized, dielectric-modulated TFET biosensor designed for low-power, label-free biomolecule detection. By incorporating advanced material engineering—specifically high-k gate dielectrics (HfO2) and alternative semiconductor channels—the architecture overcomes the leakage, high subthreshold swing, and power limitations of conventional MOSFET biosensors. Key findings from the investigation demonstrate introducing target biomolecules (such as APTES, Protein, and Biotin) into the nanogap cavity modifies the local dielectric environment. Biomolecules with higher dielectric constants (K) amplify gate capacitive coupling, resulting in sharper band bending, reduced tunneling barrier widths, and a significant increase in both drain current and transconductance Comparative analysis confirms that the Indium Arsenide (InAs)-based TFET biosensor achieves superior drain current and threshold voltage sensitivity across all analyzed biomarkers compared to the Silicon (Si)-based counterpart due to its enhanced carrier transport efficiency. The optimized structure successfully minimizes ambipolar conduction and short-channel effects while maintaining excellent thermal stability and structural reliability against fabrication tolerances.

7 References

[1] R. Narang, M. Saxena, and M. Gupta, "Comparative analysis of dielectric-modulated FET and TFET-based biosensor," *IEEE Transactions on Nanotechnology*, vol. 14, no. 3, pp. 427–435, May 2015.

[2] R. Narang, M. Saxena, and M. Gupta, "Dielectric modulated tunnel field-effect transistor—A biomolecule sensor," *IEEE Electron Device Letters*, vol. 33, no. 2, pp. 266–268, Feb. 2012.

[3] A. Chakraborty and D. Singha, "Sensitivity study of staggered heterojunction based SRG TFET sensor," in *Proc. IEEE Devices for Integrated Circuit (DevIC)*, 2017, pp. 1–4.

[4] A. M. Ionescu and H. Riel, "Tunnel field-effect transistors as energy-efficient electronic switches," *Nature*, vol. 479, pp. 329–337, Nov. 2011.

[5] I. C. Cherik and S. Mohammadi, "Impact of trap-related non-idealities on the performance of a novel TFET-based biosensor with dual doping-less tunneling junction," *Scientific Reports*, vol. 13, Art. no. 11495, 2023.

[6] H. Xie and H. Liu, "Performance assessment of a junctionless heterostructure tunnel FET biosensor using dual material gate," *Micromachines*, vol. 14, no. 4, Art. no. 805, 2023.

[7] A. Kumar and S. Kale, "A comparative analysis of cavity positions in charge plasma based tunnel FET for biosensor application," *IETE Journal of Research*, vol. 70, no. 3, pp. 2819–2832, 2023.

[8] R. K. Sharma, M. Gupta, and R. S. Gupta, "TCAD assessment of device design technologies for enhanced performance of nanoscale DG MOSFET," *IEEE Transactions on Electron Devices*, vol. 58, no. 9, pp. 2936–2943, Sep. 2011.

[9] N. Mohankumar, B. Syamal, and C. K. Sarkar, "Influence of channel and gate engineering on the analog and RF performance of DGMOSFETs," *IEEE Transactions on Electron Devices*, vol. 57, no. 4, pp. 820–826, Apr. 2010.

[10] S. K. Swain, A. Dutta, S. Adak, S. K. Pati, and C. K. Sarkar, "Influence of channel length and high-k oxide thickness on subthreshold analog/RF performance of graded channel and gate stack DG-MOSFETs," *Microelectronics Reliability*, vol. 61, pp. 24–29, Jun. 2016.

[11] P. Bergveld, "The development and application of FET-based biosensors," *Biosensors*, vol. 2, no. 1, pp. 15–33, 1986.

[12] G. Wenga, E. Jacques, A.-C. Salaun, *et al*., "Step-gate polysilicon nanowires field effect transistor compatible with CMOS technology for label-free DNA biosensor," *Biosensors and Bioelectronics*, vol. 40, no. 1, pp. 141–146, 2013.

[13] W. Guan, X. Duan, and M. A. Reed, "Highly specific and sensitive nonenzymatic determination of uric acid in serum and urine by extended gate field effect transistor sensors," *Biosensors and Bioelectronics*, vol. 51, pp. 225–231, Jan. 2014.

[14] G. V. Reddy and M. J. Kumar, "A new dual-material double-gate (DMDG) nanoscale SOI MOSFET—Two-dimensional analytical modeling and simulation," *IEEE Transactions on Electron Devices*, vol. 52, no. 12, pp. 260–268, 2005.

[15] P. Razavi and A. A. Orouji, "Nanoscale triple material double gate (TM-DG) MOSFET for improving short channel effects," in *Advances in Electronics and Micro-electronics*, 2008, pp. 11–14.

[16] S. W. Oh, J. D. Moon, H. J. Lim, *et al*., "Calixarene derivative as a tool for highly sensitive detection and oriented immobilization of proteins in a microarray format through noncovalent molecular interaction," *FASEB Journal*, vol. 19, no. 10, pp. 1355–1357, 2005.

[17] T. G. Drummond, M. G. Hill, and J. K. Barton, "Electrochemical DNA sensors," *Nature Biotechnology*, vol. 21, no. 10, pp. 1192–1199, 2003.

[18] J. Fritz, M. K. Baller, H. P. Lang, *et al*., "Translating biomolecular recognition into nanomechanics," *Science*, vol. 288, no. 5464, pp. 316–318, 2000.

[19] X.-J. Huang, Y.-K. Choi, H.-S. Im, O. Yarimaga, E. Yoon, and H.-S. Kim, "Aspartate aminotransferase (AST/GOT) and alanine aminotransferase (ALT/GPT) detection techniques," *Sensors*, vol. 6, no. 7, pp. 756–782, 2006.

[20] Y. T. Yang, C. Callegari, X. L. Feng, K. L. Ekinci, and M. L. Roukes, "Zeptogram-scale nanomechanical mass sensing," *Nano Letters*, vol. 6, no. 4, pp. 583–586, 2006.

[21] Y. Cui, Q. Wei, H. Park, and C. M. Lieber, "Nanowire nanosensors for highly sensitive and selective detection of biological and chemical species," *Science*, vol. 293, no. 5533, pp. 1289–1292, 2001.

[22] K.-I. Chen, B.-R. Li, and Y.-T. Chen, "Silicon nanowire field-effect transistor-based biosensors for biomedical diagnosis and cellular recording investigation," *Nano Today*, vol. 6, no. 2, pp. 131–154, 2011.

[23] B. L. Allen, P. D. Kichambare, and A. Star, "Carbon nanotube field-effect-transistor-based biosensors," *Advanced Materials*, vol. 19, no. 11, pp. 1439–1451, 2007.

[24] W. C. W. Chan, D. J. Maxwell, X. Gao, R. E. Bailey, M. Han, and S. Nie, "Luminescent quantum dots for multiplexed biological detection and imaging," *Current Opinion in Biotechnology*, vol. 13, no. 1, pp. 40–46, 2002.

[25] M. Curreli, R. Zhang, F. N. Ishikawa, *et al*., "Real-time, label-free detection of biological entities using nanowire-based FETs," *IEEE Transactions on Nanotechnology*, vol. 7, no. 6, pp. 651–667, 2008.

[26] A. Syahir, K. Usui, K.-Y. Tomizaki, K. Kajikawa, and H. Mihara, "Label and label-free detection techniques for protein microarrays," *Microarrays*, vol. 4, pp. 228–244, 2015.

[27] Y. Ohno, K. Maehashi, and K. Matsumoto, "Label-free biosensors based on aptamer-modified graphene field-effect transistors," *Journal of the American Chemical Society*, vol. 132, pp. 18012–18013, 2010.

[28] D. Sarkar, W. Liu, X. Xie, A. C. Anselmo, S. Mitragotri, and K. Banerjee, "MoS_2 field-effect transistor for next-generation label-free biosensors," *ACS Nano*, vol. 8, no. 4, pp. 3992–4003, 2014.

[29] H. Im, X.-J. Huang, B. Gu, and Y.-K. Choi, "A dielectric-modulated field-effect transistor for biosensing," *Nature Nanotechnology*, vol. 2, no. 7, pp. 430–434, 2007.

[30] B. Gu, T. J. Park, J.-H. Ahn, X.-J. Huang, S. Y. Lee, and Y.-K. Choi, "Nanogap field-effect transistor biosensors for electrical detection of avian influenza," *Small*, vol. 5, no. 21, pp. 2407–2412, 2009.

[31] C.-H. Kim, C. Jung, H. G. Park, and Y.-K. Choi, "Novel dielectric modulated field-effect transistor for label-free DNA detection," *Biochip Journal*, vol. 2, no. 2, pp. 127–134, 2008.

[32] J.-M. Choi, J.-W. Han, S.-J. Choi, and Y.-K. Choi, "Analytical modeling of a nanogap-embedded FET for application as a biosensor," *IEEE Transactions on Electron Devices*, vol. 57, no. 12, pp. 3477–3484, Dec. 2010.

[33] N. Kannan and M. Jagadesh Kumar, "Dielectric-modulated impact-ionization MOS (DIMOS) transistor as a label-free biosensor," *IEEE Electron Device Letters*, vol. 34, no. 12, pp. 1575–1577, Dec. 2013.