Analysis of High-Performance TFET-based Biosensors for Bioanalytes Detection

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***Abstract*—Identifying bioanalytes with biosensors is a critical field of research in technological advancement. FET-based biosensors are widely used due to their label-free detection capability, high sensitivity, and low power consumption. These sensors have fast response times, even at low concentrations, and their sensitivity is affected by device size. However, constraints include short-channel effects and excessive power dissipation caused by thermionic emission of charge carriers. To solve these disadvantages, researchers are shifting to TFET-based biosensors, which offer steep subthreshold swing (<60 mV/decade), low power consumption, and increased carrier transport efficiency. This review investigates the evolution and applications of TFET-based biosensors, focusing on qualitative and quantitative sensitivity assessments across various device topologies. It also examines methodologies that improve performance and sensitivity parameters, providing insights into future biosensor advancements.**

***Index Terms*—bioanalytes, sensitivity, TFET, subthreshold swing**

I. INTRODUCTION

TFET-based biosensors are major advances in biosensing, benefiting from the distinctive characteristics of Tunnel Field-Effect Transistors (TFETs) to improve sensitivity and efficiency. These biosensors are especially beneficial because of their label-free detecting capabilities, low power consumption, and great sensitivity, making them ideal for real-time healthcare monitoring and diagnostics [1-4].

Biosensors using TFETs offer increased sensitivity. Because of its significant subthreshold swing, TFETs can detect bioanalytes at low concentrations without labeling. TFETs are more energy-efficient than ordinary FETs because their topology decreases static power dissipation. By directly recognizing chemicals, TFET biosensors simplify detection and reduce labeling costs [5-8]. Design enhancements include modulating dielectric materials. Recent devices that use dielectric modulation techniques improve TFET sensitivity and performance by altering the electric field and capacitance in response to the presence of bioanalytes. Dual Cavity Dielectric Modulated Nanotube TFETs have significantly improved sensitivity and selectivity, outperforming standard biosensors [9-15].

TFET biosensors are being developed for real-time monitoring in healthcare applications such as point-of-care testing and wearable health monitoring devices, which will provide crucial data for tailored therapy. These biosensors can detect a wide range of biomarkers, including proteins, nucleic acids, and infections, which is important for the early detection and management of diseases [16-18]. While TFET-based biosensors offer several advantages, manufacturing complexity and low on-current remain significant impediments to widespread application in healthcare applications.

II. FUNDAMENTALS OF TFET

Tunnel field-effect transistors (TFETs) are a major breakthrough in semiconductor technology, especially for low-power applications. They outperform conventional MOSFETs in terms of subthreshold swing and energy efficiency, particularly using quantum tunneling. BTBT is the basis for TFET operation, enabling lower voltage operation and lower power consumption. TFETs are more efficient than MOSFETs because they can reach values below the 60 mV/decade SS [19-24].

Tunnel field-effect transistors (TFETs) advance semiconductor technology, particularly for low-power applications. They perform better than traditional MOSFETs in terms of energy efficiency and subthreshold swing, especially when using quantum tunneling. The foundation of TFET operation is band-to-band tunneling (BTBT), which permits lower voltage operation and lower power consumption. Because TFETs can achieve values below the SS of 60 mV/decade, they are more efficient than MOSFETs [25-27]. TFETs are ideal for ultra-low-power circuits and can be found in biomedical devices like pacemakers and neural interfaces. Their low quiescent currents and improved trans conductance are beneficial for high-frequency applications. Issues including poor ON-state current and ambipolar current conduction may complicate the development of TFETs. Moving TFETs from laboratory settings to real-world applications requires overcoming clinical and regulatory barriers. Despite the potential advantages of TFETs, significant barriers to their widespread use must be removed before they can be fully employed in a range of applications.

III. TFET BASED BIOSENSORS

Before Hu Liu [28] made the infusion and loading of bioanalytes the fabrication process with the help of a single vertical nanocavity in this biosensor. The biosensor's operation relies on line tunneling between the electron-hole bilayer, enhancing its sensitivity to bioanalytes. This section examines the impact of neutrally charged bioanalytes (i.e., Nbio = 0) on the direct current characteristics and sensitivity of the HBF-EHBTFET-based biosensor, including Biotin, Bacteriophage, Keratin, Staphylococcal nuclease, and Gelatin

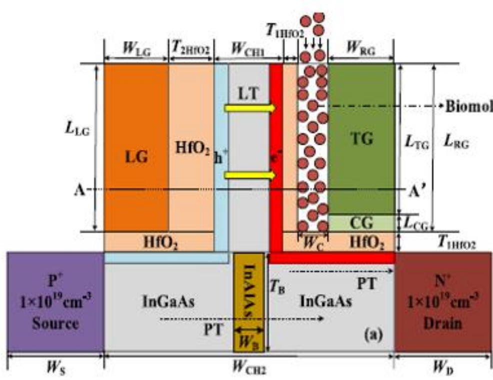

Fig.1 Structure of fin-type electron-hole bilayer TFET [28]

Figure 1 depicts the cross-sectional view of fin-type electron-hole bilayer TFET. As N_{bio} increases, the sensing performance of the HBF-EHBTFET-based biosensor worsens since the nanocavity is occupied by negatively charged bioanalytes, as shown by the reduction in S_{Vth}, S_{Ion}, and S_{SSavg}. For N_{bio} = 1 × 1012 C/cm², S_{Vth} for positively charged bioanalytes with k = 5 and 14 is 460 mV and 740 mV, increases of 54.6% and 12.6% from neutral bioanalytes with the same k value, respectively. The sensor exhibits heightened sensitivity to positively charged bioanalytes, with sensitivity increasing alongside the Nbio of these compounds, whereas it has a declining tendency for negatively charged bioanalytes. The research indicates that at a low operating voltage of 0.5 V, the S_{Vth}, S_{Ion}, and S_{SSavg} of the HBF-EHBTFET-based biosensor are 740 mV, 6.0 × 10³, and 0.92, respectively.

Priyanka [29] discusses design suggestions for a DG-TFET-based biosensor, highlighting its performance in non-ideal conditions for detecting various bioanalytes. The DG-TFET biosensor had better sensitivity than its MOS counterpart; however, it faced stability problems under temperature fluctuations and position changes. The thickness of the nanogap cavity (t_{cav}) was designed to accommodate bioanalytes with varying k-values and diameters. Figure 2 shows the structure of DG-TFET-BS having $t_{cav} = t_{ox}$ = 6 nm. Two values of that, 6 nm & 12 nm, were taken to fit 1 or 2 monolayers of bioanalytes, respectively. A deliberate air gap was maintained to accommodate the potential expansion of bioanalytes due to temperature fluctuations, thereby avoiding sensor structure damage. In charge of biomolecule interaction, the functionalization layer (FL) was modeled as a thick dielectric layer of 1.95 nm with a dielectric constant of 3.9 in the nanogap cavity.

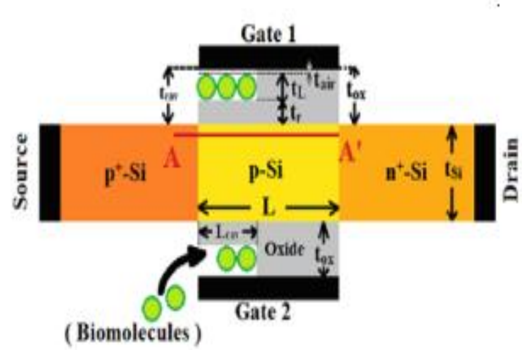

Fig. 2 Structure of DG-TFET-BS having tcav = tox = 6 nm [29]

Sharon Geege [30] investigated a novel biosensor using double gate single cavity InGaAs/GaAsSb HTFET for label-free bio-molecule detection. Figure 3 represents a schematic representation of DM-DG InGaAs/GaAsSb HTFET. Achieves high sensitivity (up to 1.63 × 106) for various bioanalytes, making it suitable for medical diagnostics. High sensitivity is marked by increased transconductance-to-current ratio (g_m/I_{ds}) increasing with increased biomolecule dielectric constants. Low subthreshold swing (SS) enables fast detection of immobilized biological molecules, enhancing the overall effectiveness of the biosensor. The gm/Ids ratio is enhanced with an elevation in the dielectric constant, facilitating superior gate control over the tunneling junction and attaining higher ratios at diminished drain currents. A higher dielectric constant shifts transfer characteristics towards lower gate voltages, increasing the maximum transconductance-to-current ratio and overall biosensor efficiency.

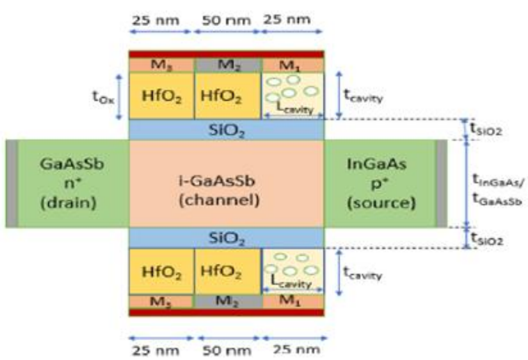

Fig. 3 Schematic representation of DM-DG InGaAs/GaAsSb HTFET [30]

Shazia Rashid [31] presented a novel DG-TFET based on III-V compound semiconductors for label-free biosensing. The structure involves an n+ doped pocket near the source-channel junction, enhancing performance by reducing tunneling width. The device traps bioanalytes in nano-gap cavities with different dielectric constants and charge densities. Simulation outcomes reflect significantly improved sensitivity measures, where I_{ON} sensitivity is 1.514×10^9, presenting 100-fold better capabilities than existing biosensors. The biosensor employs a wide bandgap channel material ($Al_{0.47}Ga_{0.53}As$) and low bandgap sources (GaSb), improving operational efficiency while reducing power consumption. Figure 4 depicts the device architecture of the ME-DG-TFET biosensor. Comparisons with traditional TFET biosensors underscore the enhanced performance of the proposed device, exhibiting advancements in selectivity and detection capabilities for neutral and charged bioanalytes. Nano-gap cavities (15 nm x 1.5 nm) are fabricated beneath the gates next to the source-channel junction to capture bioanalytes. The cavities enable the insertion of bioanalytes possessing varying dielectric constants and charge densities. When bioanalytes are introduced, the cavities detect alterations in the device's electrical properties.

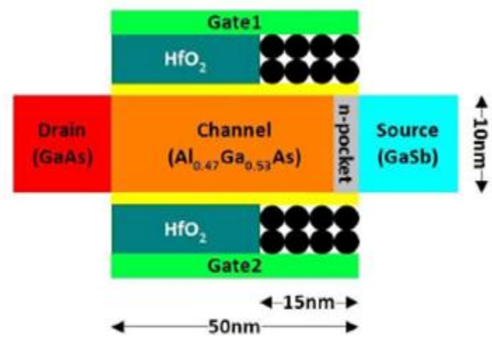

Fig. 4 Device architecture of ME-DG-TFET biosensor [31]

Deepika Singh [31] presented a simulation of a bulk-planar junctionless field-effect transistor (BP-JLFET) intended for biosensing. It detects neutral and charged proteins through a nanocavity below the gate dielectric. BP-JLFET possesses higher sensitivity compared to conventional dielectric-modulated FETs. The device has better noise behavior and a higher signal-to-noise ratio (SNR). Sensitivity evaluation shows that BP-JLFET is 10-20% more sensitive than existing biosensors in detecting bioanalytes like APTES and streptavidin. The SNR plays a crucial role as it indicates the biosensor's ability to detect specific bio-analytes with or without interference from unwanted bioanalytes. Higher SNR peak value of approximately 42 dB is obtained for BP-JLFET-based biosensor, compared to 25 dB and 35 dB for DM-FET and DM-TFET, respectively, meaning higher selectivity and lower noise disturbance. Improved SNR enhances the BP-JLFET's sensitivity and overall efficiency in biomolecule detection. Figure 5 shows 2-D cross-sectional view of BP-JLFET-based biosensor.. As a result, thicker gate oxides can deteriorate the performance of the biosensor by reducing its sensitivity towards target bioanalytes.

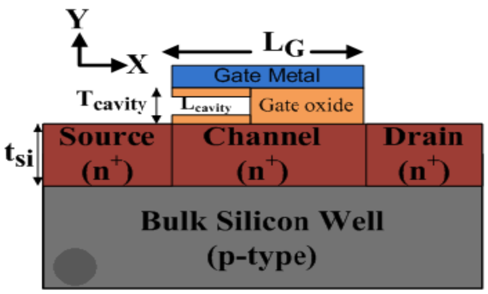

Fig.5 2-D structure of BP-JLFET-based biosensor [31]

Shraddha Singh [32] proposed a doping-free negative capacitance ferroelectric TFET for breast cancer cell line detection. The device incorporates twin metal gates and nanocavities to enhance sensitivity. Figure 6 illustrates the architecture of a two-dimensional schematic for immobilizing a DL-FE-TFET-based biosensor designed to detect breast cancer cell lines. Key performance metrics encompass elevated drain current sensitivity (2.88 × 109) and ION/IOFF ratio sensitivity (3.2 × 105). The characteristics of Si-doped HfO_2 evaluated for the proposed structural simulations include a coercive field (FC) of 2 MV/cm, remanent polarization (Pr) of 1 $\mu C/cm^2$, saturation polarization (Ps) of 20 $\mu C/cm^2$, and a dielectric constant of 31. The maximum drain current sensitivity for T47D breast cancer cell lines is 1.8 × 1010 at VGS = 0.4 V. The device is cost-effective, CMOS technology compatible, and suitable for breast cancer diagnosis.

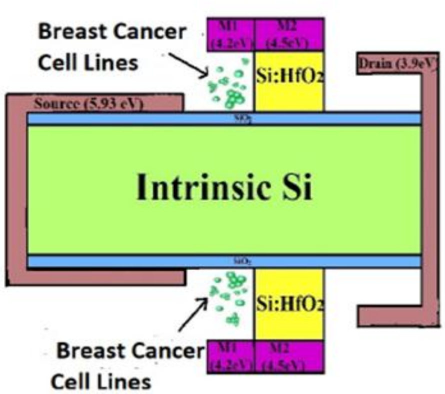

Fig.6 2-D structure of DL-FE-TFET [32]

Rathlavath Priyanka [33] evaluates n-channel TFET and Inversion Mode FET for label-free DNA detection. TFET presents higher sensitivity, 63% higher than IMFET at low gate bias. Variables for sensitivity include negative charge density, dielectric constant, and biomolecule orientation. The proposed TFET design enables flexible biomolecule positioning within a nanogap, enhancing detection performance. TFET's sensitivity is higher than IMFET in DNA biomolecule detection. TFET exhibits improvement in sensitivity by a factor between 1.61 times to 2.02 times over IMFET, depending on the negative charge density. Figure 7 shows a structure of biosensors n-channel IMFET: TFET possesses higher sensitivity at smaller gate biases, while IMFET requires higher gate voltages for effective detection. The electric field significantly affects the operation of n-channel TFET by creating a more significant electric field strength through its tunneling structure, thereby increasing drain current at smaller gate voltages. In contrast, the n-channel IMFET exhibits lower peak electric fields at the source-nanogap and nanogap-drain interfaces, lowering charge transport efficiency. This difference allows TFET to exhibit a more significant subthreshold swing and higher sensitivity for biomolecule detection than IMFET.

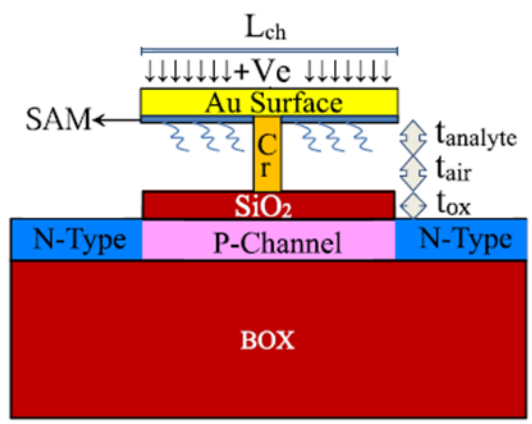

Fig.7 Schematic view of biosensors n-channel IMFET [33]

Anirban Kolay [34] proposed a cost-effective, fast-testing biosensor for hepatocellular carcinoma (HCC) using source-extended tunnel field effect transistor (TFET) technology. It uses single- and double-gate architectures to detect changes in the dielectric properties of liver cell lines. The device possesses high sensitivity in distinguishing malignant cells from normal cells, showing optimal performance at 900 MHz. The cavity size plays an important role in GaAs channel device performance, with a source and drain side cavity of 15 nm exhibiting better performance in Δ ID and Δ (ION / IOFF) compared to other configurations under test. Devices with 10 nm and 20 nm cavity sizes exhibit high ΔID, but the 15 nm configuration increases sensitivity for both parameters. Figure 8 shows a schematic diagram of the Source extended device with DG TFET. The ideal cavity dimension improves the device's capacity to distinguish between healthy and cancerous liver cells. The fluctuations in drain current (ΔID) and the ratio ION/IOFF (Δ(ION - IOFF)) of GaAs channel SEDGTFET devices are contingent upon the gate work function, exhibiting a significant rise in ΔID at a work function of 4.6 eV, whilst the alteration in ION/IOFF is more pronounced at 4.2 eV. Devices with a gate work function of 5.3 eV provide enhanced sensitivity, although with diminished drain current. The ideal gate work function for differentiating malignant from non-cancerous liver cells is 4.2 eV, effectively reconciling both criteria.

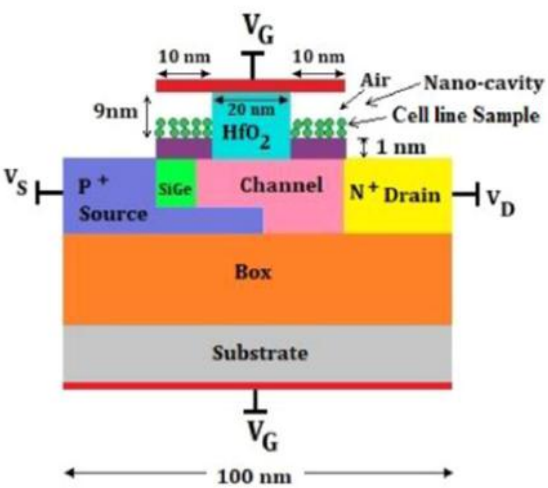

Fig. 8 Structure of Source extended device with DG TFET [34]

Sangeeta [35] reports on a new DT-DMTFET specifically this design takes advantage of diagonal BTBT mechanisms, which improve its sensitivity to bio-molecules without labeling. Comprehensive numerical simulations prove that the DT-DMTFET exhibits a current sensitivity of 3590, surpassing lateral tunneling (LT) DMTFETs at 2514 and vertical tunneling (VT) DMTFETs at 1550. Figure 9 shows a schematic representation of Diagonal tunneling DG-TFET. The best operating voltage range for sensitivity is determined at 4V and 0.4V gate and drain biases. The dielectric constant and biomolecule surface charge densities significantly impact the sensor's performance. The DT-DMTFET structure delivers improved sensitivity over a range of dielectric constants from 1.9 to 3.64. The study identifies critical structural parameters influencing the operation of the DT-DMTFET, such as cavity thickness, doping in the source pocket, and gate metal work function. These are critical for sensitivity optimization and enhanced transduction channels. Comparison table of electrical and sensitivity metrics of TFET-based biosensors

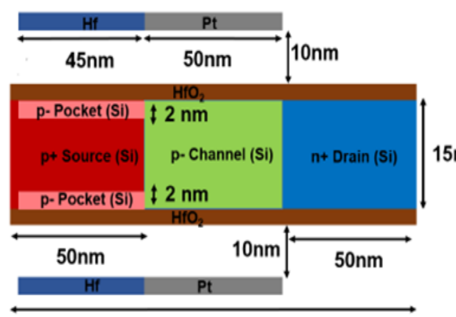

Fig. 9 Schematics representations of Diagonal tunneling DG-TFET [35]

Malihe Mahoodi [36] discusses a novel SiGe EFCS TFET proposed as a label-free biosensor for the identification of bioanalytes. The SiGe/Si heterostructure biosensor with enhanced BTBT provides better sensitivity and gate control performance than conventional TFET devices. Fig. 10 Schematic representation of SiGe EFCS TFET. Silvaco TCAD ATLAS investigates the impact of charged-neutral and charged bioanalytes on sensitivity, employing various bioanalytes like streptavidin, ferrocytochrome c, keratin, and gelatin with differing charge densities. The SiGe EFCS TFET biosensor attained a substantial drain current sensitivity of 1.69 × 105 for analyzing gelatin bioanalytes within a completely filled nanogap cavity at designated voltage levels. The research points out the configuration's high-sensitivity detection capability, addressing various structural features affecting performance. Figure 9 illustrates the Schematic representation of SiGe EFCS TFET.

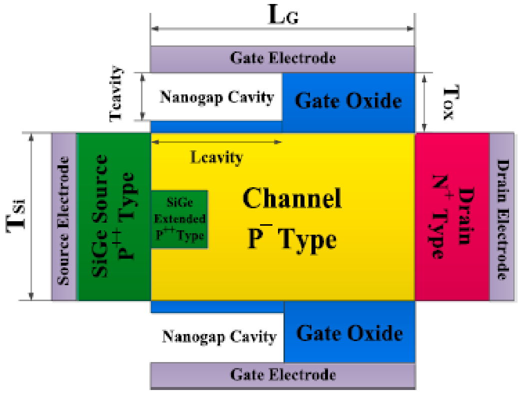

Fig.10 Schematic representation of SiGe-EFCS TFET

Navneet Kumar Singh [37] investigated the arc configuration of CP-GS-ArcTFET consisting of a source, channel, and drain regions forming an integrated center angle θ. Figure 11 shows the 2D structure of arc-shaped CP-GS-TFET. The drain and source regions are created as P+/N+ by the charge plasma process, using specified work functions for the electrodes. Gate stacking, using HfO_2 and SiO_2 layers, minimizes the subthreshold slope due to the reduced equivalent oxide thickness (EOT). Gate stacking improves drain characteristics by increasing gate capacitance compared to non-gate stacking architectures. Increasing central angles increases ON-current due to increased gate coverage while reducing OFF-current. The cut-off frequency (fT) is higher with smaller central angles due to lower gate-to-gate capacitance (Cgg). The device features a high ION/IOFF ratio and a low working voltage, rendering it suitable for low-power applications to detect the breast cancer biomarker c-erbB-2. The impact of bio-immobilization on device current, transconductance, and gate capacitance is analyzed at different c-erbB-2 concentrations, accompanied by a sensitivity analysis utilizing ON-current, OFF-current, and their ratio.

Amit Bhattacharyya [38] introduces an underlapped heterostructure electrolyte Bio-TFET for potential hydrogen (pH) sensing applications. A SiO2 layer with a thickness of 4 nm is established in the underlap region to improve the immobilization of bioanalysts. Figure 12 illustrates the schematic depiction of an n-type underlapped ionic Bio-HTFET. Physico-chemical properties like pH, ionic strength, surface chemical interactions, buffer compositions, and temperature control protein adsorption processes.

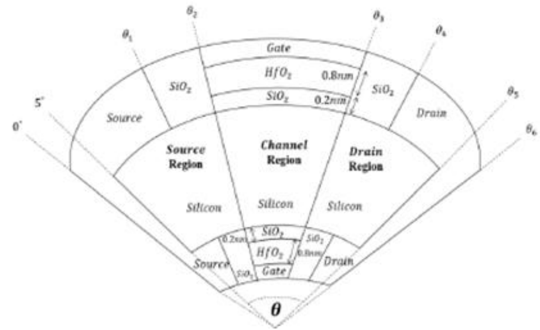

Fig.11 2D structure of arc-shaped CP-GS-TFET [37]

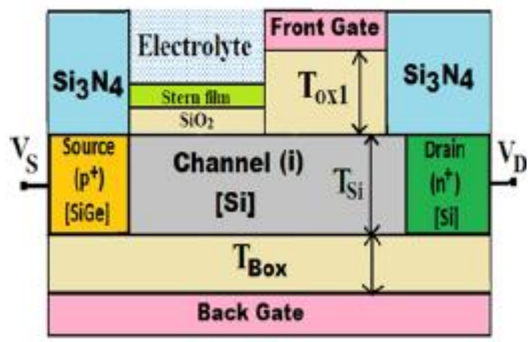

Fig. 12 Schematic representation of n-type underlapped ionic Bio-HTFET

With an increase in pH from 1 to 10, the intersection charge density (Dit) also increases accordingly. As a result, the width of the tunneling (TW) decreases, and the band-to-band tunneling probability (R) increases. As the dielectric constant of the oxide layer (k) increases, the oxide capacitance of the floating gate (Cox = kφox /Tox) increases; thus, the threshold voltage (VTH) reduces. The sensitivity Voltage (SV) is approximately 100 mV/pH, higher than the Nernstian limit. At the same time, the Sensitivity Current (SI) rises with pH because of a significant variation in drain current (IDS) related to two consecutive pH values. Sensitivity Voltage (SV) to achieve around 100 mV/pH, surpassing the Nernstian limit of 59 mV/pH. At the same time, Sensitivity Current (SI) improves by nearly an order of magnitude per pH variation. Table 1 shows the comparative analysis of various TFET-based biosensors and elaborates the key factors & their sensitivity metrics.

Table 1. Comparative analysis of various TFET-based biosensors

Ref. No.	Device name	Electrical metrics		Sensitivity Metrics	
		I_{ON} Sensitivity	V_{th} Sensitivity	Key factors	Ideal for
[28]	Fin-Type Electron-Hole Bilayer TFET	6.0×10^3	740 mV	Enhanced sensitivity attributable to line tunneling	Positively charged bioanalytes
[29]	DG-TFET-BS	4.351×10^8	-	TFET demonstrates exceptional sensitivity but exhibits challenges in stability	Fill-Factor effect on biosensor sensitivity
[30]	DM-DG InGaAs /GaAsSb HTFET	1.78×10^{11}	ΔV_{th} increases with biom-olecule charge density	Double-gate heterostructure TFET with high transconductance efficiency	Enhanced biomolecule detection in a dry environment
[31]	ME-DG-TFET	4.351×10^8	18–23 mV	100 times enhancement compared to prior biosensors	Label-free biosensing with ultra-high selectivity
[32]	BP-JLFET	$\sim10^6$	-	Bulk-planar configuration for enhanced responsiveness	Improved biomolecule detection
[33]	DL-FE-TFET	2.88×10^9	0.72	Enhanced electrical performance	Breast cancer cell detection
[34]	n-channel IMFET	high	-	63% superior to IMFET.	DNA biomolecule detection
[35]	Source extended device with Dual gate (DG) TFET	3590 (Diagonal) vs. 2514 (Lateral) vs. 1550 (Vertical)	-	Drain Current Variation at 900 MHz	Liver cancer cell line identification using dielectric constant variation
[36]	SiGe Extended Four Corner Source TFET	1.69×10^5	-	SiGe heterostructure improves sensing efficiency	High gate control, better charge-neutral biomolecule detection
[37]	Charge-Plasma Based ArcTFET	4.5×10^9	-	Charge plasma boosts signal amplification	Detecting C-erbB-2 protein
[38]	Hetero-TFET Based pH Sensor	-	100 mV/pH	Stable temperature biosensing	pH sensing applications with high stability

IV. CONCLUSION

After This review examined many TFET-based biosensors, emphasizing their enhanced sensitivity, selectivity, and reduced power consumption relative to MOSFET-based sensors. Fin-type TFET biosensors exhibited significant threshold voltage sensitivity (740 mV) and ION sensitivity (6.0×10^3), but III-V compound semiconductor TFETs attained an ION/IOFF ratio of 4.351×10^8, ensuring ultra-high selectivity. NC-FE TFETs exhibited remarkable drain current sensitivity (2.88×10^9), rendering them suitable for cancer diagnosis. Hetero-TFET pH sensors surpassed the Nernstian limit (100 mV/pH), guaranteeing enhanced stability. MoS_2 and SiGe-based TFETs enhanced charge carrier modulation, mitigating interface trap effects. Diagonal tunneling and charge-plasma-engineered tunnel field-effect transistors (TFETs) improved biomolecule transduction efficiency. Label-free double-gate HTFETs (InGaAs/GaAsSb) achieved a remarkable ION/IOFF ratio of 1.78 x 10^{11}, indicating their remarkable efficiency. Future developments must prioritize scalability, real-time integration, and stability improvements to facilitate practical applications.

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