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DESIGN AND SIMULATION OF HETERO-JUNCTION TUNNEL FET FOR BIOSENSING APPLICATION

A Thesis Submitted
In Partial Fulfillment of the Requirements for the
Degree of

MASTER OF TECHNOLOGY
in
VLSI DESIGN & EMBEDDED SYSTEMS

by

SHASHI RANJAN UPADHYAY
(Roll No. 23/VLS/03)

Under the supervision of
Dr. Sumit Kale Dr. Anukul Pandey

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CANDIDATE'S DECLARATION

I, **SHASHI RANJAN UPADHYAY**, Roll No **23/VLS/03** students of M.Tech (Electronics & Communication Engineering),hereby certify that the work which is being presented in thesis entitled "**Design of Novel Hetero-Junction Tunnel FET Structure for Biosensing Application**" in partial fulfillment of the requirements for the award of the Degree of Master of Technology, submitted in the Department of **Electronics & Communication Engineering**, Delhi Technological University, is an authentic record of my own work carried out during the period from July-2024 to May-2025 under the supervision of **Dr. Sumit Kale** and **Dr. Anukul Pandey**.

The matter presented in the thesis has not been submitted for the award of any other degree of this or any other Institute.

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Certify that **SHASHI RANJAN UPADHYAY, Roll No: 23/VLS/03** has carried out their search work presented in this thesis entitled "**Design of Novel Hetero Junction Tunnel FET Structure for Biosensing Application**" for the award of **Master of Technology** from the Department of Electronics & Communication Engineering, Delhi Technological University, Delhi, under our supervision. The thesis embodies results of original work, and studies are carried out by the student himself and the contents of the thesis do not from the basis for the award of any other degree to the candidate or to anybody else from this or any other University.

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ABSTRACT

Tunnel Field Effect Transistors (TFETs) have emerged as promising alternatives for low-power applications, offering advantages like low power dissipation, reduced leakage current, and subthreshold swing below 60 mV/dec. TFETs operate on the principle of band-to-band tunneling (BTBT), and though they have lower Ion currents, structural modifications can improve performance. Various TFET architectures, including heterojunction and dual-gate designs, have been developed to enhance the Ion/Ioff current ratio and lower threshold voltage. Different TFET device reviews conclude that TFET biosensors based on P-N-P-N provide insight into electrical characteristics, although detailed sensitivity analyzes remain underexplored. TFET as biosensor give high sensitivity in impact ionization-based MOS transistor biosensors but did not address the effects of varying biomolecule concentrations TFET-based biosensors, leveraging their low power consumption and high sensitivity, outperform traditional FET-based biosensors, addressing limitations like short-channel effects and power dissipation. This review explores TFET structures, performance parameters, and their application in biosensing, highlighting sensitivity factors and design optimizations. we introduce a sensor based on a dielectric-modulated InAs Pocket Hetero Junction TFET (HJ-TFET), designed for power-efficient, label-free bio-molecule detection applications. The results demonstrate enhanced sensitivity to two distinct effects—dielectric constant and bio-molecule charge—compared to a FET-based biosensor. Key performance metrics, such as threshold voltage sensitivity, are also improved (ΔVth), I_{on}/I_{off} current sensitivity, and drain current sensitivity (S_{Id}) are calculated. We also present a comparative analysis demonstrating that this sensor is superior to others. The study examines neutral, positively charged, and negatively charged bio-molecules across various dielectric constants at the interface between the gate and channel.

PUBLICATIONS

SCI Journal

1. S. R. Upadhyay, S. Kale, and A. Pandey, “Dielectric Modulated InAs Pocket Heterojunction Tunnel FET for Biosensor Applications,” ECS Journal of Solid State Science and Technology, vol. 14, no. 4, p. 047006, Apr. 2025, doi: https://doi.org/10.1149/2162-8777/adc338.

Dedicated

To

My Family

Contents

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List of Symbols

ε	Permitivity,
ε_k	Dielectric Constant
N_{bio}	Concentration of biomolecules
I_d	Drain Current
$I_{\mathbf{ON/OFF}}$	ON-OFF Current Ratio
$V_{\mathbf{th}}$	Threshold Voltage
$S_{\mathbf{id}}$	Drain Current Sensitivity
$\Delta \frac{I_{\mathbf{ON}}}{I_{\mathbf{OFF}}}$	$I_{\text{ON}} - I_{\text{OFF}}$ Current Ratio Sensitivity
$\Delta V_{\mathbf{th}}$	Threshold Voltage Sensitivity

List of Abbreviations

FET	Field Effect Transistor
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
TFET	Tunnel Field Effect Transistor
HJ-TFET	Hetero Juntion Tunnel Field Effect Transistor
DM-TFET	Di-electrically Modulated Tunnel Field Effect Transistors
CMOS	Complementary Metal Oxide Semiconductor
SCE	Short Channel Effect
BTBT	Band to Band Tunneling
DNA	Deoxyribonucleic Acid
RNA	Ribonucleic Acid
InAS	Indium Arsenide
GaSb	Gallium Antimonide
HfO_2	Hafnium Dioxide
Al	Aluminium
Al_2O_3	Aluminium Oxide
CVD	Chemical Vapor Deposition
PECVD	Plasma-Enhanced Chemical Vapor Deposition
ALD	Atomic Layer Deposition
MBE	Molecular Beam Epitaxy
EBL	Electron Beam Lithography
RIE	Reactive Ion Etching

Chapter 1

INTRODUCTION

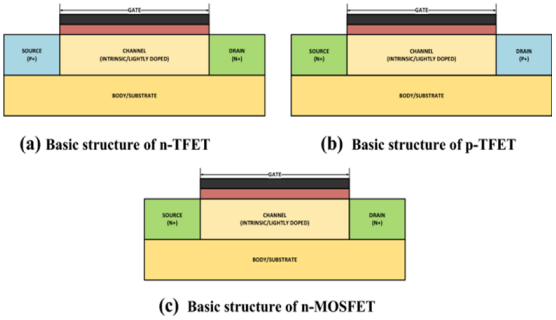
1.1 Fundamentals of TFET

In the current technological environment, lowering power consumption without compromising performance is essential, particularly given the proliferation of battery-powered gadgets like wearables and smartphones. The conductivity of a channel is modulated by an electric field supplied to the gate terminal of a FET Transistor, a type of transistor that regulates current flow. It is a voltage-controlled device as opposed to a current-controlled bipolar junction transistor. There are several other kinds of FETs, but the Metal-Oxide-Semiconductor FET (i.e MOSFET) is the most often used variety in digital circuits because of its very high input impedance, low power consumption, and fast switching rates. Basic FETs have reached a point where it is not feasible to lower the operating voltage any further without seeing a decline in performance [2].

Tunneling Field Effect Transistors (TFETs) are a class of transistors that leverage quantum-mechanical tunneling to switch electronic signals. Unlike traditional MOSFETs which rely on thermionic emission over a potential barrier, TFETs enable carriers to tunnel through a barrier, allowing for potentially lower power consumption and steeper subthreshold slopes. Because of its low power consumption and high performance, CMOS has been adopted in recent decades. But as technology develops and CMOS downscaling gets more complex, a new gadget called a TFET has emerged that can take the place of CMOS [3]. When compared to CMOS, TFET exhibits superior properties. By altering the TFET's physical properties, the electrical parameters can be enhanced. Transistors are becoming smaller in order to improve metal oxide semiconductor performance and circuit downsizing. Moore provided a law pertaining to transistor size. Due to Moore's law, CMOS downscaling is carried very extensively. Reducing power, delaying the circuit, and increasing the number of transistors in the smallest possible space are the primary goals of scaling. CMOS downscaling does, however, have certain negative impacts as well. Short channel effects (SCEs), which deteriorate transistor performance as channel length decreases, cause electron drift characteristics to limit in the channel, lower the threshold voltage, and increase leakage current. For these reasons, SCEs in a transistor are undesirable.

1.1.1 Structure

With reverse bias at the gate terminal, the tunnel FET structure resembles a basic P-i-N diode structure. The drain, gate, and source terminals of a tunnel FET are similar to those of a MOSFET. The gate is positioned over the channel, which is separated by a dielectric substance, and the channel is positioned between the drain and the source. The drain and source doping of TFETs is their greatest distinguishing characteristic [2]. The doping of the source and drain is different in TFETs than it is in regular MOSFETs.The drain and source are doped n-type and p-type, respectively, whilst the channel region is intrinsic or small doped. The dominant carrier in the channel beneath the gate determines the kind of TFET. It is an n-TFET if the channel's predominant carriers are electrons, and the inverse is true. The TFET is p-type if the predominate carriers are holes in the channel as shown in Fig 1.1



(a) Basic structure of n-TFET (b) Basic structure of p-TFET

(c) Basic structure of n-MOSFET

Figure 1.1: TFET Structure [1]

1.1.2 Working

A Tunnel Field-Effect Transistor (TFET) works like a gated P-i-N diode and operates under reverse bias. In the OFF state, there's a wide energy barrier between the source and the channel, so no tunneling occurs, and only a tiny leakage current flows. However, when the gate voltage goes above the threshold voltage, the barrier narrows, allowing significant tunneling, which marks the ON state [3].TFETs rely on two quantum mechanisms: band-to-band tunneling (BTBT) and quantum tunneling. In BTBT, charge carriers move from the valence band of the source to the conduction band of the channel, crossing the energy band gap as in Fig 1.2. For an n-type TFET in the OFF state, with almost zero gate voltage, the source's valence band sits lower than the channel's conduction band. The misalignment prevents tunneling, resulting in a very low drain current [4]. When a positive gate voltage increases above a certain level, it pulls the channel's conduction band down to align with the source's valence band. This alignment enables electrons to tunnel through the barrier and into the channel. A positive drain bias sweeps these electrons into the drain.

In a p-type TFET, the OFF state also occurs at zero gate voltage. Here, the channel's valence band is below the source's conduction band, preventing tunneling and keeping the drain current extremely low. When a sufficiently negative gate voltage is applied, the channel's valence band aligns with the source's conduction band. This

alignment allows holes to tunnel into the channel, and the negatively biased drain sweeps these holes away.

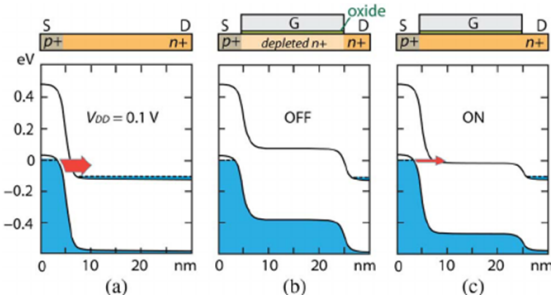


Figure 1.2: TFET basic working [1]

1.2 Overview of Biosensor

A biosensor is a device that generates electrical signals by detecting physicochemical reactions of biomolecules. The sensing mechanism of a targeted biomolecule typically involves three main stages: bioreceptor ,transduction and signal processing.

1.2.1 Basic Elements

Bioreceptor

The bioreceptor is the core biological element of a biosensor that specifically interacts with the target analyte. It recognizes and binds to the substance of interest with high specificity, much like a lock and key mechanism. Depending on the application, various types of bioreceptors can be used, Biomolecules are analyzed using various biological elements such as enzymes, antibodies, proteins, microorganisms, or even drugs. The interaction between the biomolecule and the detection element triggers a physicochemical reaction, producing by-products that serve as inputs for the transducer element. The choice of bioreceptor determines the selectivity and sensitivity of the biosensor.

Transducer

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The transducer plays a crucial role by converting the biological interaction between the bioreceptor and the analyte into a quantifiable signal, usually electrical. This conversion is essential for translating the biological response into a format that can be easily measured and analyzed.

Signal Processor and Display

The signal processor amplifies the weak signal, filters out noise, and converts it into a digital form if necessary. This processed signal is then displayed in a user-friendly

format, such as a numerical reading on a screen or a graph in a computer or mobile application. The electronics involved in this stage include amplifiers, analog-to-digital converters (ADCs), microcontrollers, and user interfaces. This component ensures that the biosensor provides meaningful and actionable information to the user, making it an integral part of the overall system.

1.2.2 Classification of Biosensors

Biosensors can be classified based on their detection mechanism or bioreceptor type, and transduction method. The detection mechanism is centered on biological elements, while the transduction method covers the conversion of the physicochemical reaction into electrical signals.

1.2.3 Based on Detection Mechanism/ Bioreceptor

Enzymatic Biosensors

In this, use enzymes as bioreceptors to catalyze a reaction with the analyte. These are highly specific and widely used, such as in glucose sensors using glucose oxidase.

Immunosensors (Antibody-based)

In this, use antibodies to detect specific antigens. Common in medical diagnostics, including pregnancy tests and disease detection.

DNA/RNA Biosensors (Genosensors)

In this, use nucleic acids are used to detect complementary DNA or RNA sequences through hybridization. Used in genetic testing and pathogen detection.

Microbial Biosensors

In this, use whole microorganisms are used to detect toxic compounds or environmental pollutants. Microbes respond to specific substances, producing a measurable signal.

1.2.4 Based on Transduction Method

Electrochemical biosensor

This will, in particular work by detecting changes in the sensor's electrical properties due to the interaction with target biomolecules [5]. These changes serve as measurable parameters for the sensor, with three main types: conductometric, potentiometric, and amperometric. These sensors are capable of detecting various biomolecules in the human body, such as proteins, glucose, DNA, hemoglobin, and more.

Thermal Biosensor

Measure temperature changes due to exothermic or endothermic reactions between the analyte and bioreceptor.

Optical Biosensor

Use light to detect the analyte. Changes in absorbance, fluorescence, or refractive index are measured.

For an effective and reliable biosensor, three key parameters must be considered: sensitivity, specificity, and ease of fabrication. Among all types, electrochemical and optical biosensors have gained significant attention due to their high specificity and low detection limits. In contrast, mass-based and calorimetric biosensors tend to be more complicated and have slower response times. Potentiometric electrochemical biosensors, especially after the introduction of FET-based designs, have become increasingly popular because of their high performance and low fabrication costs [6].

1.3 Research Motivation

Rapid advancement in biomedical diagnostics demands highly sensitive, label-free, and miniaturized biosensors capable of detecting low concentrations of biomolecules with high sensitivity. Field-effect transistor (FET)-based biosensors have emerged as promising candidates due to their compatibility with CMOS technology, scalability, and real-time detection capabilities. However, conventional FET biosensors face limitations such as poor sensitivity at low analyte concentrations, high power consumption, and the inability to operate effectively at low voltages, primarily due to the subthreshold swing (SS 60 mV/dec at room temperature).

TFETs, which exploit band-to-band tunneling (BTBT) as the primary conduction mechanism, offer a compelling solution to these challenges. TFETs exhibit a steep subthreshold slope (< 60 mV/dec), enabling ultra-low power operation and significantly enhanced sensitivity compared to traditional FETs. These characteristics make TFET-based biosensors particularly attractive for detecting biomolecules, which is critical for early disease diagnosis (e.g., cancer biomarkers, infectious pathogens, and neurodegenerative disorder indicators).

Despite their potential, the application of TFETs in biosensing is still in its emerging stage, with several challenges to address, including:

- **Optimization of Device Architecture for Maximum Sensitivity** : TFETs operate via quantum mechanical band-to-band tunneling (BTBT), making their performance highly dependent on materials and structure. Proper heterojunction engineering (e.g., Si/Ge or III-V compounds) ensures efficient tunneling through optimal band alignment. Gate dielectrics like HfO_2 must balance thinness for control with leakage prevention, while abrupt doping profiles—challenging to fabricate—are critical for sharp tunneling junctions. Nanowire or 2D-material designs may improve electrostatic control.

- **Surface Functionalization for Selective Biomolecule Binding**: For effective TFET biosensing, the surface must selectively capture target biomolecules (DNA, proteins) while rejecting interference. This demands careful immobilization of bio-receptors (antibodies, aptamers) without disrupting device operation, anti-fouling coatings (e.g., PEG) to minimize non-specific binding, and robust surface chemistries for stable performance in biological fluids like blood or saliva over extended periods.
- **Understanding Biomolecular Charge Effects on Tunneling Current**: Unlike conventional FET biosensors, TFETs exhibit extreme sensitivity to charge distribution near the tunneling junction. Charged biomolecules can dramatically alter local electric fields, though modeling these nanoscale effects remains challenging. In physiological fluids, charge screening (Debye length 1nm) limits detection range, while dynamic biomolecular interactions necessitate advanced signal processing to distinguish true signals from noise.

1.4 Research Gap

- **Lack of Comprehensive Sensitivity Analysis in TFET Biosensors**: Existing studies on P-N-P-N TFET biosensors focus on basic electrical characterization but lack detailed sensitivity optimization, including key metrics like detection limits, signal-to-noise ratio, and dynamic response under varying bio-analyte conditions.
- **Underexplored Biomolecule Concentration Effects**: Although impact ionization MOS biosensors show high sensitivity, their performance at different biomolecule concentrations remains uncharacterized, creating uncertainty in real-world applications where analyte levels vary significantly.
- **Incomplete Subthreshold Sensitivity Evaluation**: Prior FET biosensor studies in the subthreshold regime overlook critical parameters like threshold voltage shift and switching ratio, limiting understanding of ultimate sensitivity and detection capability in low-power operation.

1.5 Research Objective

- **Design and Optimization of a Heterojunction TFET Biosensor**: To develop a dielectric-modulated HJ-TFET biosensor with a heteropocket at the source-channel junction, enhancing tunneling efficiency and sensitivity by reducing the energy barrier, thereby improving drain current and Ion/Ioff ratio for low-power biomolecule detection.
- **Material and Structural Innovation for Enhanced Performance**: To employ InAs in the heterojunction design for bandgap reduction and improved tunneling, while optimizing the source shape for vertical tunneling, ensuring higher ON current and simplified fabrication compared to conventional P-N-P-N TFETs.

- **Comprehensive Electrical and Sensitivity Analysis**: To evaluate key performance metrics—energy band variation, surface potential, electric field distribution, and transfer characteristics—under varying dielectric constants, validating sensitivity improvements through simulation and proposing feasible fabrication methods

- **Investigation of Biomolecule Detection Sensitivity**:To systematically analyze the biosensor's response to varying biomolecule concentrations by evaluating threshold voltage shifts and current ratios, establishing detection limits for diverse analytes like proteins, DNA, and viruses.

1.6 Thesis Organization

The thesis entitled **'Design and Simulation of Hetero-Junction Tunnel FET for Biosensing Application'** comprises five chapters followed by conclusions, future scope, and Social Impact. The thesis is organized as follows:

Chapter 1: Introduction

This chapter introduces the foundation of the research, laying out the context and significance of biosensors in modern applications. It systematically presents the background, core elements of biosensors, research motivation, Gap and objectives. Furthermore, the structure of the thesis are outlined.

Chapter 2: Literature Review

This chapter provides a comprehensive examination of the extant literature pertinent to FET-based biosensors. It begins with an introduction to the field, followed by discussions on various detection techniques, biomolecule immobilization strategies, and the influence of biomolecular properties. Key performance parameters, the role of P-N-P-N structure, and the operation of TFETs are also addressed. In conclusion, the chapter synthesizes prior research to elucidate existing research gaps and substantiate the significance of the present study.

Chapter 3: TFET-Based Biosensor

This chapter explores the fundamentals of TFET biosensors, starting with the electrical properties of biomolecules that enable detection. It examines the working principles of TFET biosensors, focusing on their superior sensitivity and low-power operation through band-to-band tunneling and dielectric modulation effects. The discussion covers various device architectures, including nanowire, dielectrically modulated, junctionless, and charge plasma-based designs, highlighting their unique advantages and fabrication challenges. Finally, it establishes critical performance metrics for biosensor evaluation, such as sensitivity, selectivity, and power efficiency, setting the stage for advanced biosensor development.

Chapter 4: Exploration of Novel Hetero-junction TFET for Biosensing Application

This chapter presents a comprehensive study of hetero-junction TFET biosensors, detailing the device architecture and step-by-step fabrication process involving silicon growth, InAs doping, HfO_2 deposition, and nano-cavity formation. The investigation analyzes device performance with neutral, positive, and negative biomolecules, evaluating key electrical characteristics and sensitivity metrics. Results demonstrate superior detection capabilities compared to conventional biosensors, validated through systematic simulation studies. The discussion highlights the device's enhanced sensitivity and potential for advanced biosensing applications, supported by comparative analysis with state-of-the-art technologies.

Chapter 5: Conclusion, Future Scope & Social Impact This chapter summarizes the key findings and contributions of the research presented in the previous chapters, highlighting the significance of the work in advancing FET-based biosensors and semiconductor devices. It outlines potential future research directions, including the need for experimental validation, exploration of more advanced device structures, and investigation of real-world applications. The research presented in this thesis demonstrates the potential of HJ-TFET device for high-performance, label-free biosensing applications. It lays the foundation for future developments in this field.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

Biosensing technologies have gained immense importance in medical diagnostics, environmental monitoring, and food safety. As the demand for miniaturized, energy-efficient, and highly sensitive biosensors grows, researchers have increasingly turned to semiconductor devices. Among these, tunnel field effect transistors (TFETs) have emerged as promising candidates because of their unique ability to achieve a subthreshold swing (SS) below 60 mV / Dec, low power consumption, and scalability. These attributes, coupled with the potential for integrating TFETs into nanoscale systems, make them suitable for advanced biosensor applications. This chapter explores the fundamentals of TFETs, recent material advancements, and their application in biosensing while addressing current challenges and future directions in this emerging field [7].

2.2 TFET Devices Review for Biosensing Application

2.2.1 Detection Mechanisms

FET-based biosensors detect target biomolecules by converting biochemical interactions into quantifiable electrical signals. This process relies on the intrinsic properties of the biomolecules, particularly their dielectric constant and charge density:

- **Dielectric Constant**: Biomolecules with a high dielectric constant enhance capacitive coupling at the sensor interface, leading to improved detection sensitivity.
- **Charge density**: The distribution of charges on biomolecules influences the electrostatic environment within the nanogap, directly modulating the channel conductivity of the FET.

2.2.2 TFET Operating Principle

TFETs operate based on the principle of band-to-band tunneling (BTBT), a quantum mechanical phenomenon that allows carriers to tunnel through a narrow bandgap. Un-

like conventional MOSFETs, which rely on thermionic emission over a potential barrier, TFETs achieve switching by modulating tunneling current, enabling superior performance at lower operating voltages [5]. This steep subthreshold slope and reduced power dissipation are critical for biosensing applications, where energy efficiency and miniaturization are paramount. Furthermore, TFETs are highly sensitive to surface charges, making them ideal for detecting biomolecular interactions. For biosensing, TFETs must exhibit high sensitivity, stability in aqueous environments, and a large surface-to-volume ratio to maximize interactions with target analytes [8].

2.2.3 Materials Choice

The choice of materials is crucial in optimizing TFET performance for biosensors. Silicon-based TFETs, while offering compatibility with existing CMOS technology, suffer from moderate tunneling efficiency because of the wider bandgap of silicon. In contrast, III-V compound semiconductors such as InAs and GaSb provide higher tunneling currents and sensitivity owing to their smaller bandgaps. More recently, two-dimensional (2D) materials like graphene, MoS_2, and transition metal dichalcogenides (TMDs) have attracted attention for their ultra-thin channels and high surface-to-volume ratios, which enhance analyte interaction and sensitivity [9]. Beyond the semiconductor material, dielectric engineering is another critical aspect. High-k dielectrics such as HfO_2 and Al_2O_3 improve gate control and sensitivity while minimizing leakage currents in aqueous environments. For biosensing applications, surface functionalization is also essential. Functionalization techniques, including self-assembled monolayers (SAMs), covalent binding, and physical adsorption, enable the attachment of specific receptors such as antibodies, enzymes, or DNA probes, facilitating selective detection of target analytes.

2.2.4 Area of Significance

TFETs have demonstrated their potential in a variety of biosensing applications, leveraging their unique sensing mechanisms. These include changes in electrical response, where tunneling current is modulated by charge interactions between the analyte and TFET surface, and capacitive modulation, where variations in dielectric permittivity shift the threshold voltage. Examples of successful applications include DNA sensing, where TFETs functionalized with DNA probes detect complementary strands through tunneling current modulation, glucose monitoring via enzyme-functionalized TFETs, and pathogen detection through antibody-functionalized surfaces. These examples underscore the versatility of TFETs in detecting a wide range of biomolecules with high specificity and sensitivity [10].

2.2.5 Challenges with previous works

Despite these advances, TFET-based biosensors face several challenges. One primary limitation is their relatively low ON-state current compared to MOSFETs, which restricts their dynamic range. Additionally, the fabrication process for TFETs demands

precise control over material properties and functionalization techniques, posing scalability challenges. Furthermore, the stability of TFETs in biological environments remains a critical issue, as prolonged exposure to aqueous or reactive media can degrade device performance. Addressing these challenges requires continued efforts in material innovation, device architecture optimization, and surface chemistry.Looking ahead, integrating TFETs with hybrid architectures, such as combining them with nanomaterials like quantum dots or nanoparticles, offers a promising avenue for enhancing their sensitivity and functionality [11]. Their potential role in wearable devices and the Internet of Things (IoT) also highlights the importance of advancing TFETs for real-time, remote diagnostics.

2.3 Review Key Findings

After reviewing the different papers as stated in the previous paragraph, the main areas to work on are as follows:

- Conclusion of the review that TFET with the P-N-P-N structure is more efficient. Based on the inference, the focus is to design a novel structure that has less fabrication complexity.
- For lowering the band gap and to enhance better tunneling, InAs was used as a promising material to achieve this.
- Structural modification in the source shape also leads to a great improvement in ON current. That is because vertical tunneling occurs in the device.

This innovation achieves low power consumption alongside improved sensitivity and performance. Simulation results have been validated through calibrated graphs, and suggested fabrication methods provide a practical pathway for device realization. Key electrical parameters—such as energy band variation, surface potential, electric field distribution, and transfer characteristics—are analyzed for varying dielectric constants.

Chapter 3

TFET BASED BIOSENSOR

3.1 Overview of Biomolecules

Biomolecules are organic molecules that are essential for life. They form the structural components of cells and participate in biological processes such as metabolism, energy production, and genetic information transfer. Biomolecules (like proteins, DNA, carbohydrates, etc.) have charges because of the chemical groups they are made from. These groups can lose or gain electrons when placed in water (especially at a biological pH around 7), causing: loss of electron, positive charge (cation) and Gain of electron, Negative charge (anion).

Type	Examples	Charge Type
Carbohydrates	Glucose, Starch, Cellulose	Neutral/Polar
Proteins	Enzymes, Hemoglobin, Antibodies	Neutral
Lipids	Fats, Phospholipids, Steroids	Mostly Non-polar/Neutral
Nucleic Acids	DNA, RNA	Negatively Charged
Metabolites	Alkaloids, Flavonoids	Variable (polar or charged)

Table 3.1: Types of biomolecules with functions and charge type

Biomolecule Type	Dielectric Constant (ϵ_r)	Charge Type
Water (for reference)	~78.5 at 25°C	Polar
Carbohydrates	2 – 10	Neutral/Polar
Proteins	2 – 12	Zwitterionic (pH dependent)
Lipids	2 – 5	Mostly Neutral
Nucleic Acids	4 – 12	Negatively Charged (due to phosphate backbone)
DNA (hydrated)	10 – 20	Negatively Charged

Table 3.2: Dielectric properties and charge types of biomolecules

3.2 TFET based Biosensor

FET-based biosensors have garnered significant attention from researchers worldwide due to their exceptional characteristics, including label-free detection, small size, rapid response, and high reliability. These sensors also offer the advantage of on-chip integration with amplification circuitry, cost-effective mass production, high selectivity, and reusability. To detect targeted biomolecules, the oxide layer of the FET is functionalized with bio-receptors or recognition elements. Upon capturing the biomolecules, these receptors undergo a conjugation process that triggers electrochemical reactions. These reactions, in turn, induce a gating effect on the semiconductor device, altering its electrical properties and enabling the detection of biomolecules. Sensitivity is typically assessed using parameters such as current ratios (I_{on}/I_{off}), shifts in threshold voltage (VT), and variations in ON current (Ion) before and after biomolecule capture [12].

However, FET-based biosensors face some challenges. Scaling difficulties and short-channel effects (SEC) become prominent as devices are miniaturized. Additionally, a theoretical limit exists for the minimum achievable subthreshold swing (SS $>$ 60 mV/dec), which impacts the performance and sensitivity of the device [13]. Furthermore, thermionic emission of electrons in FETs results in higher power dissipation. To overcome these limitations, the focus has shifted toward TFET-based biosensors. TFETs offer superior performance, including low power consumption, steep subthreshold swing, and band-to-band tunneling of carriers. These advantages make TFETs ideal for biosensor applications, especially in terms of reducing power consumption and enhancing performance. Another key parameter for biosensors is response time, which is closely tied to subthreshold swing. Since TFETs can achieve a subthreshold swing (SS ¡ 60 mV/dec) that is lower than CFETs, they have become a promising area of research for the development of high-performance, low-power biosensors.

3.3 Working TFET based Biosensor

The structure of a TFET (Tunnel Field-Effect Transistor) resembles a p-i-n diode with an added gate. The barrier width of the TFET is kept thin to facilitate the tunneling of charge carriers. To enhance tunneling at the barrier junctions, the source and drain are heavily doped, with the source being more heavily doped than the drain. As a result, tunneling predominantly occurs at the source-channel junction. The current characteristics of the TFET describe its behavior under different biasing conditions, which is crucial for understanding its operation.

In a TFET-based biosensor, there are three main electrodes: the gate, drain, and source. The region between the source and drain, which is the channel, contains a biorecognition element. This element interacts with target biomolecules, sensing their presence and monitoring electrical activity. The biosensor directly converts biological information into a measurable electrical signal. The operation of the biosensor involves several steps: 1) A change in the concentration of charge at the channel surface, 2) This change in charge leads to a shift in the effective gate voltage (a gating effect), and 3) The increment in the drain current due to the reduction in the effective tunneling length

as a result of the gating effect [14].

As shown in Fig. 3.1, before biomolecules are captured, the energy states of the source and channel are not aligned. However, the figure demonstrates that the energy bands bend effectively, creating an opportunity for tunneling. This process highlights how the TFET-based biosensor utilizes tunneling to detect changes in biological conditions.

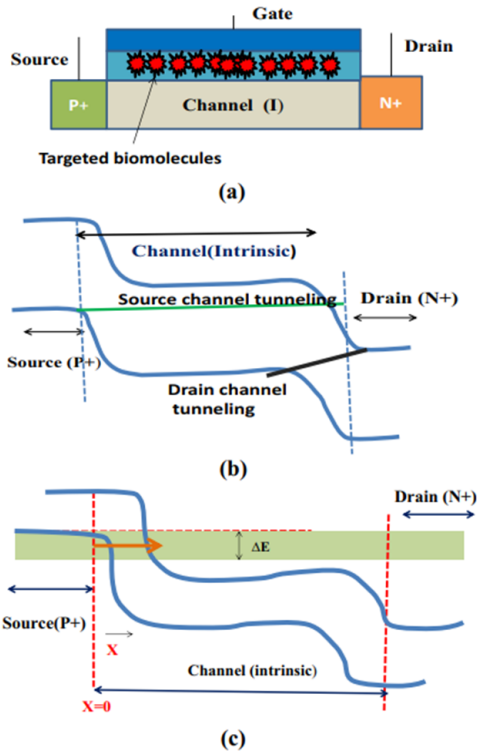


Figure 3.1: (a) structure of Tunnel-FET (b) OFF-state Energy band diagram (c) ON-state Energy band diagram [2]

3.4 Different Structure for TFET-based Biosensor

3.4.1 Silicon Nanowire-based TFET Biosensor

Nanowire structures are commonly used in TFET-based biosensors because their small dimensions offer excellent electrostatic gate control over the channel and enhance tunneling current. After studying the electrical properties of TFET devices, researchers began applying these characteristics to biosensor development. The biosensor structure typically consists of a single nanowire forming a p-i-n configuration, with varying doping profiles in the source (P+), channel (intrinsic, i), and drain (n+) regions, all immersed in an electrolytic solution as in Fig. 3.2. A gate is used to control the initial conditions. Over the intrinsic channel region, a thin oxide layer is placed, along with a receptor that captures target biomolecules. The detection mechanism is typically divided into two stages. The first stage occurs when the biomolecules are captured,

causing a development of surface potential due to the presence of ions in the electrolyte, leading to electrostatic screening. In the second stage, the tunneling current changes because of the surface potential created under the gate, a phenomenon known as the gating effect [15].

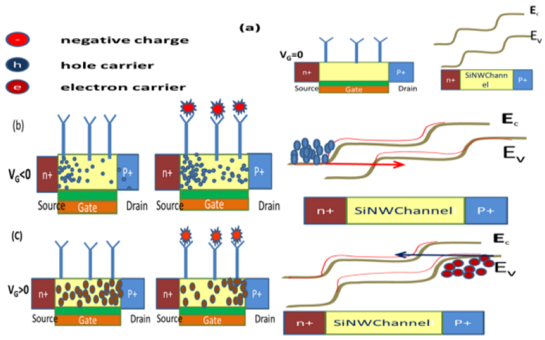


Figure 3.2: Operation of a Si-NW-TFET(a) OFF state, tunneling is not possible (b) when VG $<$ 0 the BTBT is possible at source-channel junction, (c) when VG $>$ 0 , which results in the ambipolar conduction
[2]

3.4.2 Dielectrically modulated TFET based Biosensor

Designing a label-based biosensor is a challenging and time-consuming process that requires meticulous attention to detail. The preparation of the bio-recognition or sample element for detecting specific biomolecules is critical, as the sensor must be able to adjust when the target analyte changes. Additionally, investigating the quality changes in the physicochemical reactions of the target analyte adds another layer of complexity [14]. This process becomes even more difficult when trying to detect neutrally charged biomolecules, as current methods often fail to accurately capture them. The overall effort demands precision and careful consideration to achieve reliable and responsive biosensing systems. The dielectric modulation technique enables label-free

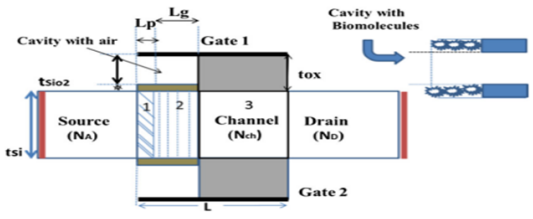


Figure 3.3: Structure of Dielectrically-modulated Tunnel-FET
[7]

detection of biomolecules, overcoming the limitations of traditional label-based detection methods. The first dielectric-modulated TFET biosensor uses the concept of dielectric-modulated FET for biosensing, where a cavity region is created within the oxide layer beneath the gate electrode. This cavity is designed to hold and immobilize

the targeted biomolecules. When the biomolecules settle in the cavity, their dielectric properties cause a change in the dielectric constant of the oxide. This change alters the effective coupling between the gate and the oxide, leading to the bending of the energy bands in the channel. This bending modifies the effective tunneling length, resulting in a change in the drain current [16].

To further enhance performance, a double-gate structure is sometimes employed, as it offers additional advantages. However, ambipolar conductivity remains a significant challenge for improving TFET sensitivity. In earlier designs, no efforts were made to reduce this ambipolar conduction, limiting the performance of dielectric-modulated TFET biosensors. Sensitivity analysis was often conducted by considering the charge and dielectric constant of biomolecules separately, but in reality, charge is only present when the biomolecule is also associated with its dielectric constant.

To address these challenges and enhance performance, Rakhi Narang et al. proposed a DMTFET biosensor with a hetero-gate structure in Fig. 3.3. This design improves gate modulation at the source-channel tunneling junction by using a high-K value at the source and a low-K value near the drain, effectively reducing ambipolar conduction. By suppressing this unwanted conductivity, the sensitivity of the sensor is improved, enabling more accurate detection of both charge and dielectric effects.

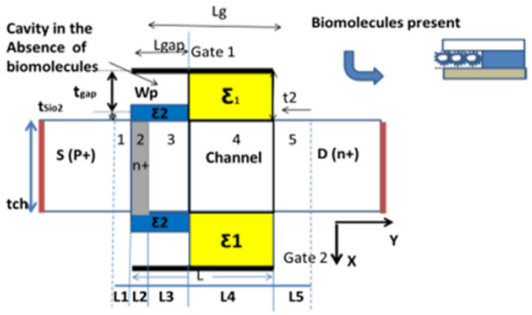


Figure 3.4: Struture of hetero-dielectric DMTFET [2]

The proposed device in Fig. 3.4 features a double-gated p-n-p-n architecture with two different dielectric values, K1 and K2, where K1 > K2. This design is aimed at suppressing ambipolar conductivity and enhancing the sensitivity of the device. A cavity region is introduced near the tunneling junction to immobilize targeted biomolecules. Additionally, the short gate structure of the TFET (SG-TFET) is reported to offer high sensitivity and a low subthreshold swing by reducing ambipolar conductivity. In the case of the FG-DMTFET, the intrinsic channel is fully gated, whereas in the SGDMTFET, the intrinsic channel is only half-gated. The non-gated region near the drain in the SG-DMTFET reduces the effective coupling between the gate and the channel, leading to an increase in the barrier width at the drain-channel junction [17]. This increase in the effective barrier width results in a reduction of the tunneling (ambipolar) current at the drain side. Conversely, the tunneling current at the source-channel junction increases due to the initial gate-to-channel coupling, thereby improving the device's sensitivity. A systematic arrangement of this architecture is shown in Fig. 3.5.

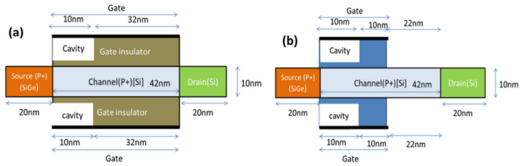


Figure 3.5: structure of complete-gate and partial-gate DM-Tunnel-FET [4]

3.4.3 Junctionless and Doping less TFET based Biosensor

The performance of Tunnel Field-Effect Transistors (TFETs) heavily relies on the abrupt doping at the source and channel junctions. However, achieving precise doping through physical means is challenging and expensive. The thermal annealing process, which is often employed to improve doping uniformity, is costly and does not guarantee uniform doping or thin junctions. Additionally, Random Dopant Fluctuations (RDF) pose significant issues for TFET-based biosensors, especially in the context of junctionless devices. To address these challenges, the Junctionless TFET (JL-TFET) has been introduced, offering a solution by eliminating the need for physical doping. In this context, B. V. Chandan et al. proposed a Junctionless-based Dielectric Modulated Electrically Doped TFET (JL-DM-EDTFET) biosensor, designed for the label-free detection of biomolecules, which effectively overcomes the limitations associated with traditional doping methods [18].

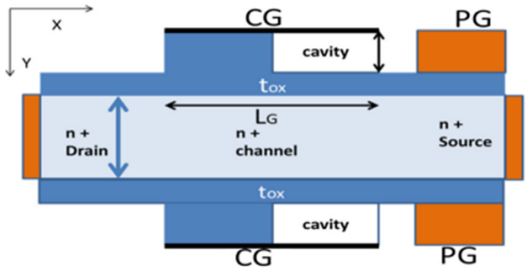


Figure 3.6: Structure of JL-DM-ED-Tunnel FET [19]

Fig. 3.6 shows the schematic arrangement of the JL-DM-ED-TFET. The design incorporates a control gate and a polarity gate with a suitable work function over the intrinsic silicon, which eliminates the need for physical doping and forms a p-i-n structure. A cavity is created under the control gate to immobilize biomolecules, enabling dielectric modulation. The absence of a junction further enhances the device's performance. Additionally, the structure is modified into a short gate dielectrically modulated electrically doped TFET (SGDM-EDTFET). When compared to a full gate dielectrically modulated and electrically doped TFET biosensor (FGDM-EDTFET), the SGDM-EDTFET biosensor demonstrates improved sensitivity [20].

3.4.4 Charge Plasma based TFET Biosensor

The device demonstrates excellent performance in selectively detecting biomolecules and exhibits high selectivity for specific volatile organic compounds. The cavity region beneath the gate extends towards the source region, enhancing the abruptness of the source-channel junction. This, combined with the charged plasma formation in the TFET biosensor, significantly boosts the device's performance by creating more abrupt junctions. However, challenges like random dopant fluctuations (RDF) and a high thermal annealing budget, due to physical doping, remain significant obstacles. To address these issues, researchers have proposed electrically doped TFETs as a potential solution. By merging the benefits of charge plasma and reduced doping, a novel architecture—charge plasma-based gate underlap DMTFET—has been developed, promising enhanced performance while minimizing doping-related complications as in Fig. 3.7.

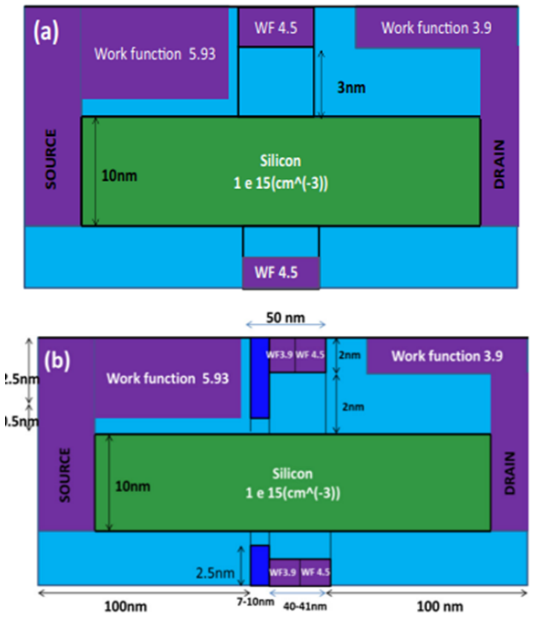


Figure 3.7: (a) structure of conventional undoped TFET (b) gate underlap charge plasma-based dielectrically-modulated Tunnel-FET
[21]

3.5 Performance parameter of TFET-based Biosensor

The sensitivity and selectivity are key factors in evaluating the performance of a biosensor. It has been observed that altering the physical structure and detection mechanism of the device can significantly enhance its performance. In the case of Tunnel Field-Effect Transistors (TFETs), sensitivity is measured by examining the changes in the electrical properties of the device before and after the biomolecule conjugation [20]. The sensitivity of TFETs is typically quantified using parameters such as the ratio of the on-current to off-current (I_{on}/I_{off}), threshold voltage shift, and subthreshold swing

(SS). Researchers have formulated the sensitivity of TFET-based biosensors by observing variations in these parameters. Specifically, the current response as a function of biomolecule conjugation improves the biosensor's sensitivity, as it produces a higher current even with a small potential induced by the biomolecules [7]. Moreover, the subthreshold swing and sensitivity plots suggest that TFETs exhibit an SS value lower than that of Carbon Nanotube Field-Effect Transistors (CFETs).

Chapter 4

Exploration of HETERO-JUNCTION TFET for Biosensing application

4.1 Introduction

We introduce a sensor based on a Dielectric-modulated InAs Pocket Hetero-Junction Tunnel Field-Effect Transistor (HJ-TFET), designed for power-efficient, label-free biomolecule detection applications. The proposed biosensor has a single cavity near the source side with an InAs pocket at the source side that will help in tunneling. Introducing Di-electrically Modulated Tunnel Field Effect Transistors (DMTFET) for bio-sensing, this work presents a novel approach, leveraging dielectric modulation for high sensitivity and specificity in detecting bio-molecules [7]. TFETs, bio-molecules that use quantum tunneling for charge carriers, enable low power consumption and improved performance. Nanoscale technology in biosensors offers high spatial resolution, crucial for detecting individual bio-molecules or studying molecular-level biological processes [8]. Modulating dielectric constants in DMTFET biosensors allows high precision in detecting specific biomolecules, optimizing sensitivity and specificity [22]. These advancements in Tunnel FET-based biosensors, particularly through dielectric modulation, offer significant opportunities for improving disease detection and diagnostics, transforming medical diagnostics with highly sensitive, low-power, efficient bio-sensing devices.

4.2 Device Architecture

The 2D architecture of Hetero-Junction TFET-based biosensors, along with their geometric descriptions, is illustrated in Fig. 4.1. Here, InAs is used as hetero pockets at the source-channel junction, significantly enhancing Band-to-Band Tunneling [23]. The device is constructed on a 20 nm thick SiO2 insulating layer, commonly called the BOX layer, with a total length of 100 nm. As shown in Fig. 2, the process of fabricating the device involves masking and lithography, followed by the deposition of source and drain regions [9]. For InAs deposition, the MBE(molecular Beam Epitaxy) process is used [19]. Using LPCVD and dry etching, a 40 nm thickness of hafnium oxide and an aluminum gate may be created [5], respectively. Subsequently, a 20 nm layer of HfO2 is removed from the source sides to create nanocavities. A metal electrode

over the source and drain is placed to increase the current driving of the device. The cavities, formed by etching the dielectric, expose a 1 nm thick silicon layer in the air, which facilitates the immobilization of biomolecules. Various dielectric materials have been incorporated into the nano-cavity on the source sides for systematic biosensing analysis.

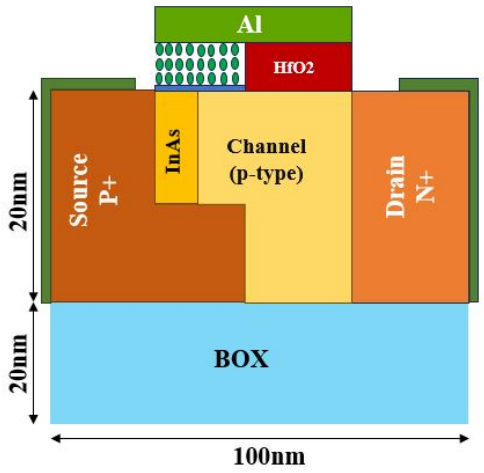
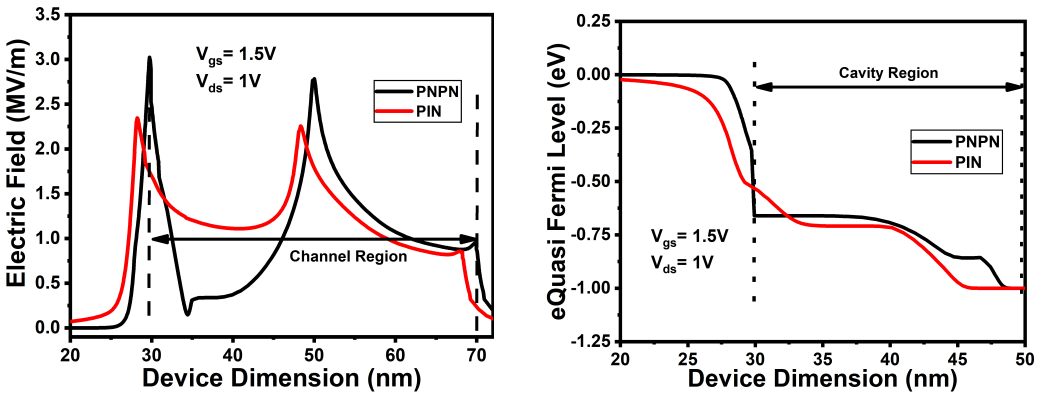


Figure 4.1: Cross-sectional view of the proposed device

The incorporation of a PNPN structure in TFETs has been shown to enhance the drain current by modifying the distribution of the electric field and the surface potential, facilitating increased band-to-band tunneling. This enhancement is primarily due to the introduction of a narrow, highly doped n-type pocket between the source and channel regions, which sharpens the energy band bending and increases the electric field at the source-channel junction. PNPN-based biosensor also has the advantages of high Ion, low leakage, steep SS [23].In Fig. 4.2(a),it is showing that the we are getting the high peak lateral electric field at the p-n interface then p-i interface. That high field supports the more charge to flow that will indirectly lead to more on current. And decrease in the vertical direction electric field, which lowers the interface traps' rate of generation and increases reliability. In Fig. 4.2(b), quasi fermi level for electron drastically decreases at the pocket layer that has n-type of doping. Its showing that the large concentration difference which lead to high tunnelling current. But for P-i-N type, not getting the sharp changes. Another for optimal length causes the N+ pocket to begin to partially empty and raises the concentration of charge between the channel and the source as it moves toward the drain side.

The extended source design in TFETs has proven to be a game-changer in addressing key performance limitations of conventional TFETs. One of its biggest advantages is the boost in the ON current (I_ON) by expanding the source region, the tunneling area increases, as InAs is a low band gap leading to stronger vertical band-to-band tunnelling and better current flow, as the tunneling width is very narrow and the position of the quasi-Fermi electron level at source causes the tunnelling current of 0.1 mA/μm in the proposed TFET structure as in Fig. 4.3(a).Another major issue in TFETs is ambipolar leakage, where unwanted charge carriers flow in the wrong direction, reducing efficiency. The extended source helps tackle this by modifying the energy band



(a) (b)

Figure 4.2: Characteristics for PNPN and P-i-N structure (a) Electric Field behavior, (b) eQuasi Fermi Level variation

profile, effectively suppressing leakage. Additionally, subthreshold swing (SS) performance improves with an extended source, meaning the transistor switches on and off more efficiently, consuming less power. In Fig. 4.3(b) show that the behavior of the potential energy across the channel at different height from the surface, its show that near the extended part of source the low potential and changing exponentially towards drain that will enable high tunneling. In Fig. 4.3(c) show that the behaviour of the electric field across the channel, its show that near the extended part of source getting the high electric field that will enable the high current density along the lateral direction.

Electrode Covering the open sides of the source and drain electrodes with an L-shaped in a TFET is an approach that significantly reduces trap charges and enhances the performance of biosensors. By extending the electrode in an L-shape around the source and drain, this structure helps improve charge transport, minimize recombination, and boost tunnelling efficiency, all of which are essential for high-precision biomolecule detection [24]. One of the major advantages of this design is that it suppresses interface trap charges, leading to a lower subthreshold slope and making the sensor highly sensitive to even the smallest charge variations. Additionally, the L-shaped electrode improves electrostatic control, reduces leakage currents, and enhances the transistor's switching behaviour, ensuring greater stability and reliability in biosensing applications.

4.3 Fabrication Process

The fabrication of the HJ-TFET (Heterojunction Tunnel Field-Effect Transistor) biosensor involves a series of precise steps to ensure optimal device performance.

4.3.1 P-Silicon Growth (Step a)

The process begins with the growth of p-type silicon (p-Si), which forms the base layer of the biosensor. This is typically done using methods like chemical vapor deposition

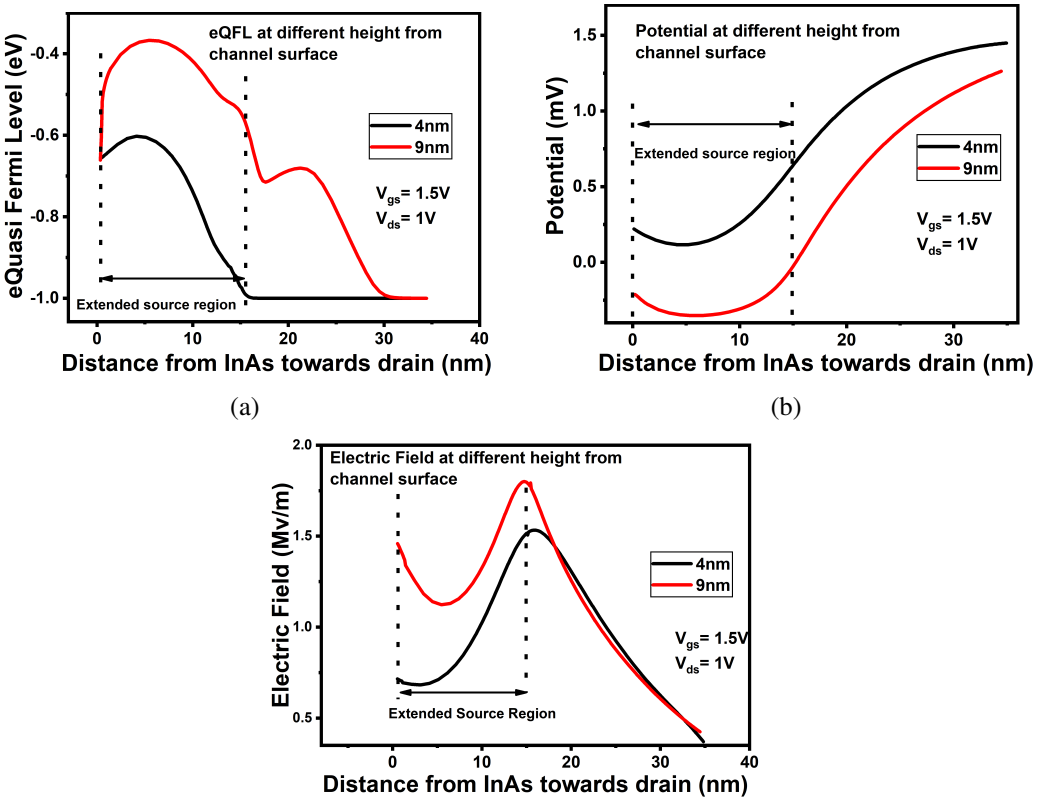


Figure 4.3: Characteristics for L-shape electrode (a) eQuasi Fermi Level variation, (b) Potential Energy variation , (c) Electric Field behavior

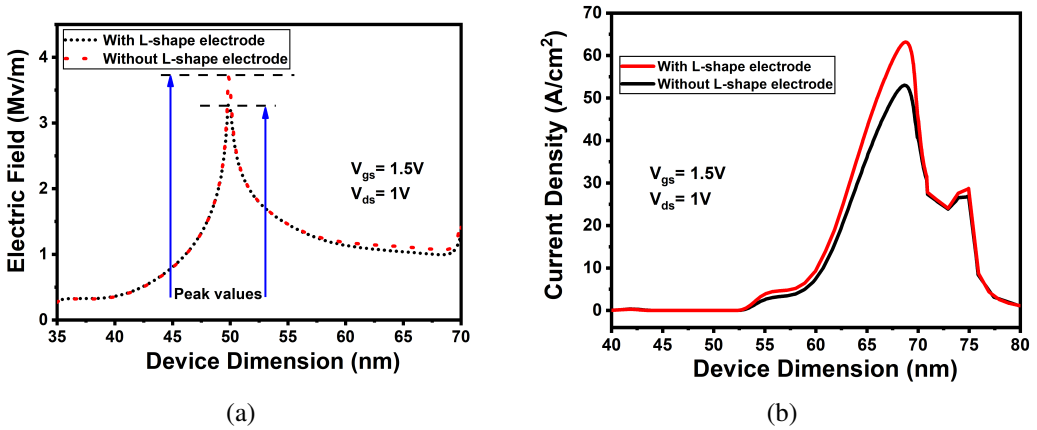


Figure 4.4: Characteristics for L-shape electrode (a) Electric Field behavior, (b) eQuasi Fermi Level variation

(CVD) or molecular beam epitaxy (MBE). The doping of silicon is carefully controlled to ensure that the p-Si layer has the desired electrical and structural properties. The quality of the p-Si layer is critical as it influences the tunneling behavior in the device.

Table 4.1: DEVICE DESIGN PARAMETERS

Parameters	Value
Doping concentration N^+ (cm^{-3}), N_D	1×10^{18}
Doping concentration P^+ (cm^{-3}), N_A	1×10^{20}
Source Length (nm), L_s	30
Extended Source Length (nm), L_{ex}	20
Source Thickness (nm), L_s	20
Drain Length (nm), L_d	30
Drain Thickness (nm), T_d	20
Gate Length (nm), L_g	40
Gate Thickness (nm), T_g	5
Pocket (InAs) Length (nm), L_p	5
Pocket (InAs) Thickness (nm), T_p	10
Length of Nano-cavity (nm), L_c	20
Thickness of Nano-cavity (nm), T_c	5
Gate-Oxide Thickness (nm), T_{ox}	6
Channel Length (nm), L_{ch}	40

4.3.2 Buried Oxide (BOX) Formation (Step b)

A buried oxide (BOX) layer is created over the p-Si substrate. This can be achieved through thermal oxidation or deposition techniques like plasma-enhanced chemical vapor deposition (PECVD). The BOX layer serves as an insulating barrier, preventing leakage currents between the substrate and the active device regions. Its uniformity and thickness are crucial for the performance and reliability of the biosensor.

4.3.3 Deposition of p+ Source and n+ Drain (Step c)

The source and drain regions are then formed by heavily doping specific areas of the silicon substrate with p+ and n+ impurities. This is typically achieved through ion implantation or diffusion processes, where dopants such as boron (for p+ regions) or phosphorus/arsenic (for n+ regions) are introduced at high concentrations. These regions act as the charge injection points for the device, enabling the tunneling effect.

4.3.4 InAs Doping Using MBE Process (Step d)

Indium Arsenide (InAs) doping is carried out using Molecular Beam Epitaxy (MBE), a highly controlled epitaxial growth technique. MBE involves the deposition of ultra-thin InAs layers on the p-Si substrate under vacuum conditions. The heterojunction formed between InAs and p-Si enhances tunneling efficiency and allows for better control over the electrical characteristics of the device. MBE ensures high-quality interfaces with minimal defects, which is crucial for biosensor sensitivity [6].

4.3.5 HfO_2 Deposition (Step e)

Hafnium dioxide (HfO_2) is deposited over the heterojunction structure using methods like atomic layer deposition (ALD) or sputtering. HfO_2, a high-k dielectric material, is chosen for its excellent insulating properties and ability to improve gate control while reducing leakage currents. The thickness and uniformity of this layer are critical, as they directly affect the biosensor's electrical performance and sensitivity to biomolecular interactions.

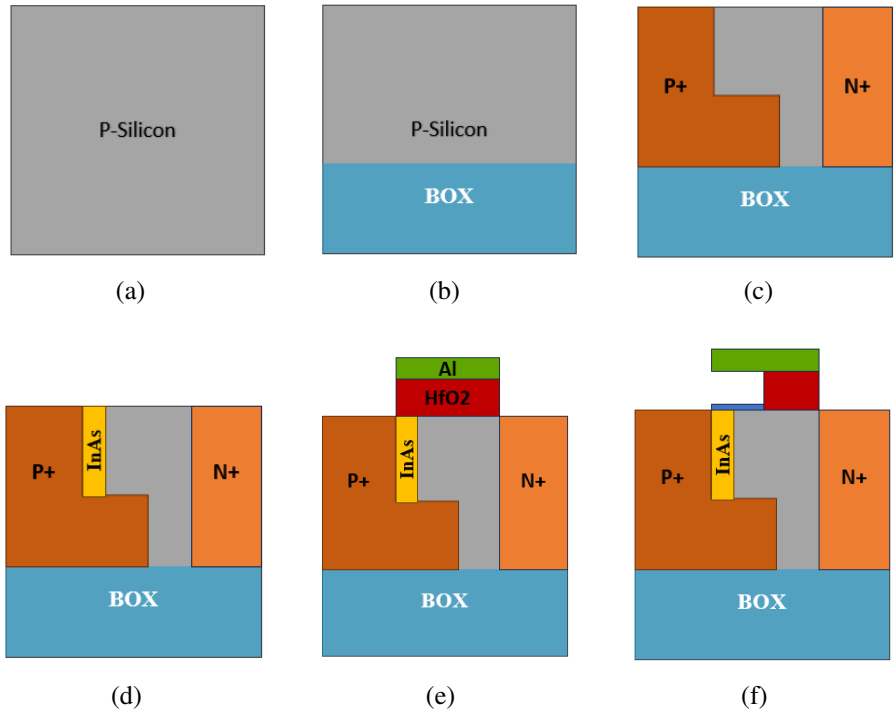


Figure 4.5: Steps for Fabricating the HJ-TFET Biosensor (a) P-Silicon growth, (b) BOX formation, (c) Deposition of p+ source and n+ Drain, (d) InAs doping using MBE process, (e) HfO_2 deposition, (f) Formation of nano-cavity and metalization

4.3.6 Formation of Nano-Cavity and Metallization (Step f)

A nano-cavity is etched into the structure to serve as the sensing region. This is typically done using advanced lithography and etching techniques, such as electron beam lithography (EBL) and reactive ion etching (RIE). The nano-cavity provides a confined space where biomolecules can interact with the sensor's active surface, enhancing sensitivity and specificity [25]. After nano-cavity formation, metallization is performed to create electrical contacts for the source, drain, and gate terminals. Thin metal layers, such as gold (Au) or aluminum (Al), are deposited and patterned using techniques like sputtering or evaporation followed by photolithography. These contacts ensure efficient electrical connectivity and stability for device operation.

4.4 Results and Discussion

The DC characteristics of a device, particularly in the context of biosensors based on TFETs or similar structures, refer to the relationship between the applied voltage and the resulting current under direct current (DC) conditions. These characteristics are crucial for understanding the performance and functionality of the device [16]. Here are the key aspects of the DC characteristics. The device's DC characteristics under the influence of various charged bio-molecules are discussed. The DC behavior is analyzed using key properties of the device, including the electric field distribution, energy-band diagram, and tunneling rate as well as Id vs Vgs characteristics. Along with this, the effect of gate-oxide thickness and source-drain doping concentration, and interface trap densities on the device's performance is evaluated.

4.4.1 Biomolecules used for this Device Simulation study

The TCAD simulation study presented in this section focuses on the di-electrically modulated HJ-TFET-based biosensor. The dielectric constants (ε_k) of proteins involved in DNA/RNA interactions exhibit significant variations depending on their structural and functional properties. Buried acids and bases within the staphylococcal nucleus typically exhibit dielectric constants in the range of 10–12. Charged amino acids show dielectric constants ranging from 11 to 25, while food proteins, such as gluten and zein, display dielectric constants between 5 and 7. These variations are critical for understanding protein-nucleic acid interactions, as they influence electrostatic forces, protein stability, and molecular folding.

Table 4.2: Various Biomolecules with corresponding Dielectric constants

Biomolecule	Dielectric Constant (K)	Charge at pH 7.0
Biotin	2.63	Slightly Negative
Gluten	5	Neutral
Zein	7	Neutral
Chlorobenzene	9	Neutral
Keratin	10	Neutral/Polar
Gelatin	12	Positive
Glutamic Acid	12	Negative

4.4.2 Device characteristics in the presence of Neutral Molecules

In Fig. 4.6 represents the transfer characteristics and other device parameters of HJ-TFET-based biosensor devices under the ascendancy of neutral bio-molecules. we are considering dielectric constants (ε_k) = 1,3,5,8,10,12 (where, ε_k=1 represents air) at vds and Vgs of 1V and 1.5V, respectively. Neutral bio-molecules do not contribute to the

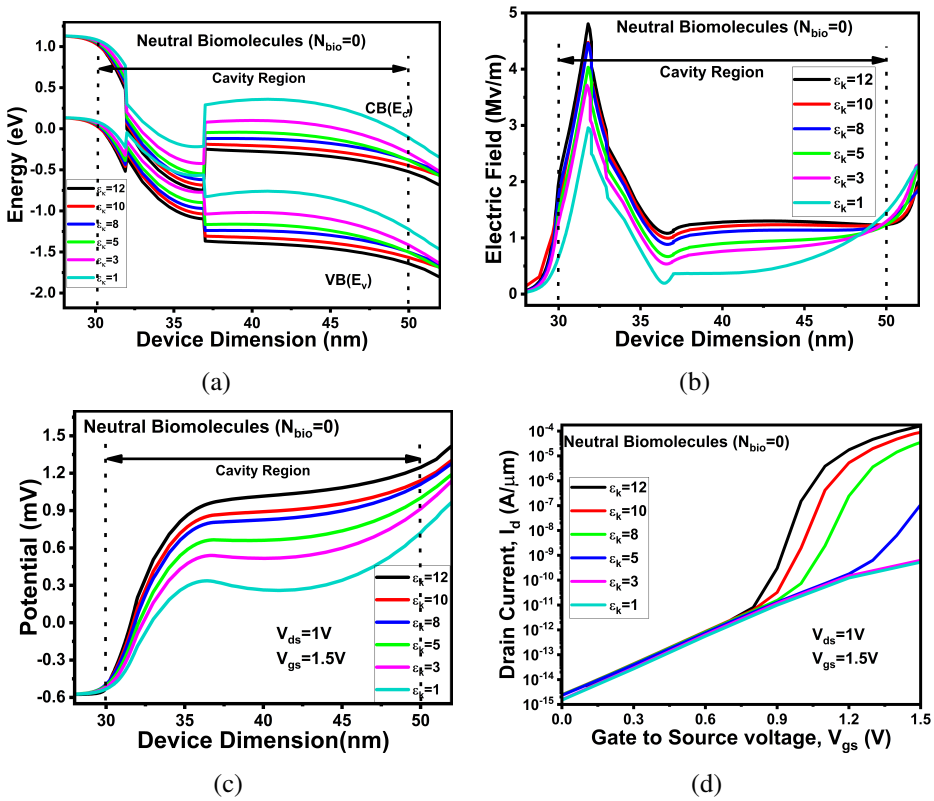


Figure 4.6: Device Characteristics for multiple values of permittivity ε_k=1,3,5,8,10,12 and $N_{\text{bio}} = 0(neutral)$ (a) Energy-Band Diagram (Conduction Band and Valence Band), (b) Electric Field behavior, (c) Potential variation, (d) transfer characteristics (I_d vs V_{gs})

electric field in the same way as charged bio-molecules. Since they lack a net charge, They do not directly affect the surface potential or the tunneling junction's electric field [17]. As a result, When neutral bio-molecules are present, the electric field does not alter significantly, which can limit the sensitivity of the biosensor compared to scenarios involving charged bio-molecules. The presence of neutral bio-molecules does not significantly alter the energy band structure of the semiconductor. Since neutral molecules do not affect the interface's charge distribution, the energy bands remain relatively flat, with minimal band bending. This lack of significant alteration can reduce tunneling efficiency, as the energy barrier for electron tunneling remains largely unaffected. Neutral bio-molecules do not contribute to the ion current because they do not introduce additional charge carriers into the system [18]. The potential distribution within the device is similarly unaffected by neutral biomolecules. Since there is no change in the charge density at the interface, the potential remains stable, and the depletion region width is not significantly modified [26]. This stability results in a lack of responsiveness when detecting neutral biomolecules, as there are no substantial changes in the potential to influence the current response.

The reduced sensitivity to neutral biomolecules highlights a limitation of the HJ-TFET-based biosensor in detecting such entities. Enhancements to the device design

may be necessary to improve responsiveness to neutral species, ensuring broader applicability in biosensing applications.

4.4.3 Device characteristics in the presence of Positive Molecules

Figure 4.7 presents the transfer characteristics. Simulations are conducted with varying dielectric constants (ε_k = 1, 3, 5, 8, 10, 12), where ε_k = 1 represents air, at V_{ds} = 1V and V_{gs} = 1.5V. A positive charge concentration of 5×10^{11}, cm^{-2} is considered for this analysis. When positively charged biomolecules are present, they increase the surface

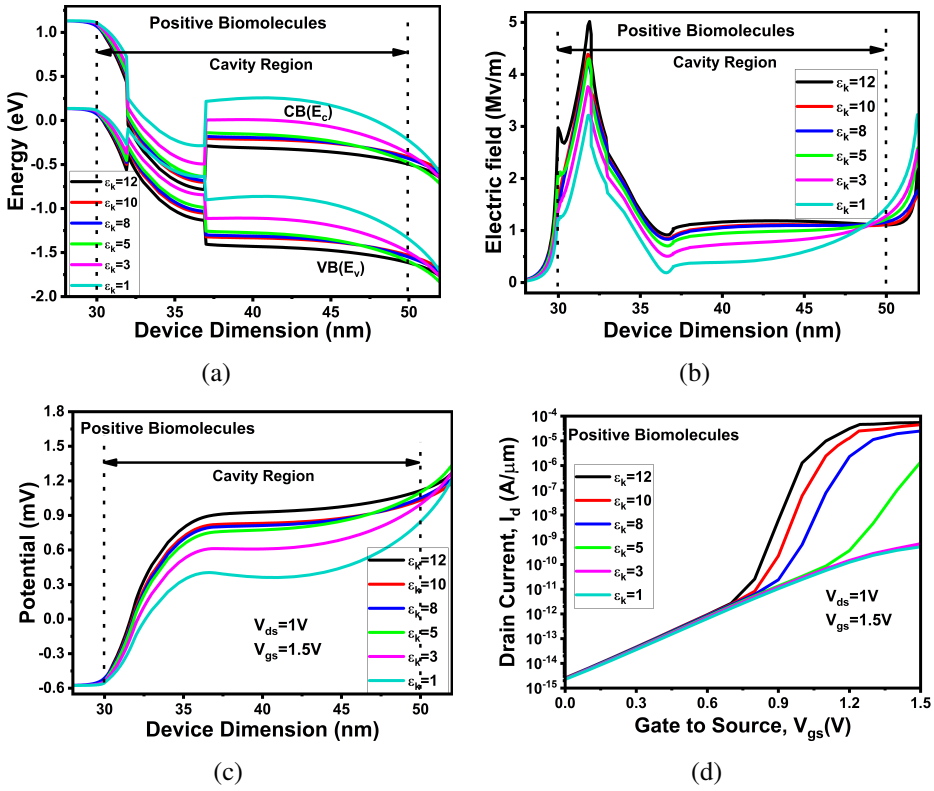


Figure 4.7: Device Characteristics for different values of permittivity ε_k=1,3,5,8,10,12 and $N_{\text{bio}} = 5 \times 10^{11} cm^{-2}(positive)$ (a) Energy Band Diagram, (b) Electric Field behavior, (c) Potential variation, (d) transfer characteristics (I_d vs V_{gs})

potential of the channel, enhancing the electric field near the tunneling junction. This stronger electric field facilitates electron tunneling from the valence band (VB) to the conduction band (CB), leading to a significant improvement in the biosensor's sensitivity. The presence of positively charged biomolecules induces an upward shift in the energy bands near the semiconductor surface, which directly impacts the tunneling current.

The charge density of these biomolecules influences the degree of energy band bending [27], thereby modifying the potential barrier that electrons must overcome to contribute to the current. As the concentration of positively charged biomolecules increases, the effective gate voltage rises, attracting more charge carriers into the chan-

nel. This enhances the device's overall conductivity, leading to a substantial increase in the ion current and improving the current response of the biosensor.

Additionally, the interaction of positively charged biomolecules affects the potential distribution within the device. The increased positive charge reduces the depletion region width, allowing more charge carriers to participate in conduction. These changes significantly influence the tunneling characteristics, enhancing the biosensor's performance and its ability to detect positively charged biomolecules [28].

4.4.4 Device Characteristics in the Presence of Negative molecules

Figure 4.8 presents the transfer characteristics. Simulations are conducted with varying dielectric constants (ε_k = 1, 3, 5, 8, 10, 12), where ε_k = 1 represents air, at V_{ds} = 1V and V_{gs} = 1.5V. A positive charge concentration of 5×10^{11}, cm^{-2} is considered for this analysis. Negatively charged biomolecules near the tunneling junction enhance the

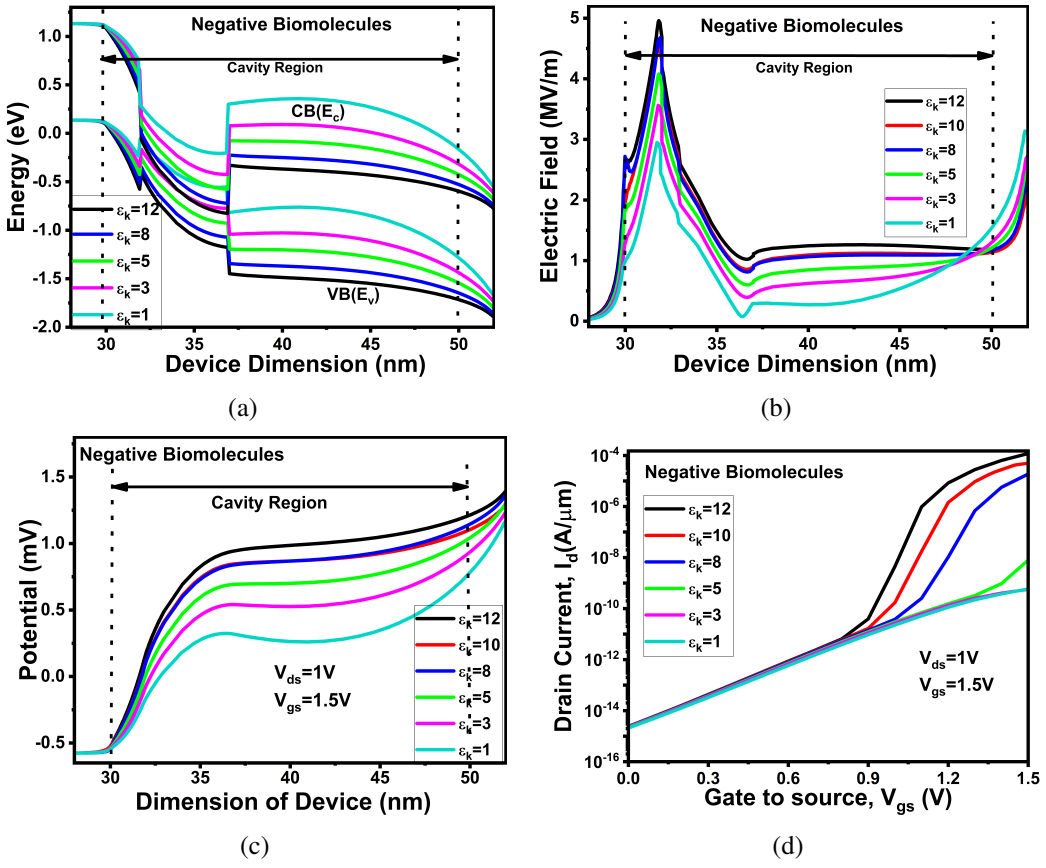


Figure 4.8: Device Characteristics for different values of permittivity ε_k=1,3,5,8,10,12 and $N_{\text{bio}} = -5 \times 10^{11} cm^{-2}(negative)$ (a) Energy Band Diagram(Conduction Band and Valence Band), (b) Electric Field behavior, (c) Potential variation, (d) transfer characteristics (I_d vs V_{gs})

electric field, increasing the tunneling of charge carriers from the valence band (VB) to the conduction band (CB). This results in improved sensitivity of the biosensor. The

energy band diagram reveals a downward shift in energy bands near the semiconductor surface due to negatively charged biomolecules.This shift increases the tunneling width and alters the potential barrier that electrons must overcome, thereby affecting the tunneling current [29]. As the concentration of negatively charged biomolecules rises, the effective gate voltage decreases, leading to a widening of the depletion region and a reduction in ion current. Additionally, the presence of impurities introduced by negative charges limits the number of charge carriers available for conduction, further impacting the device's performance.

The interaction of negatively charged biomolecules also modifies the potential distribution within the device. This interaction increases the potential drop across the channel and reduces the effective gate voltage, which directly influences the tunneling characteristics and overall current response of the biosensor. These findings highlight the critical role of negative biomolecules in determining the HJ-TFET biosensor's performance, offering insights into optimizing device sensitivity for specific biosensing applications.

4.4.5 Sensitivity Analysis

The TCAD simulation study presented in this section focuses on the di-electrically modulated HJ-TFET-based biosensor. The dielectric constants (ε_k) of proteins involved in DNA/RNA interactions exhibit significant variations depending on their structural and functional properties. Buried acids and bases within the staphylococcal nucleus typically exhibit dielectric constants in the range of 10–12. Charged amino acids show dielectric constants ranging from 11 to 25, while food proteins, such as gluten and zein, display dielectric constants between 5 and 7. These variations are critical for understanding protein-nucleic acid interactions, as they influence electrostatic forces, protein stability, and molecular folding.

$$\Delta\left(\frac{I_{ON/OFF}|\varepsilon_{k>1}}{I_{ON/OFF}|\varepsilon_{k=1}}\right) = \frac{I_{ON/OFF}|\varepsilon_{k>1} - I_{ON/OFF}|\varepsilon_{k=1}}{I_{ON/OFF}|\varepsilon_{k=1}} \tag{4.1}$$

$$\Delta V_{th|\varepsilon_k>1} = V_{th|\varepsilon_k>1} - V_{th|\varepsilon_k=1} \tag{4.2}$$

$$S_{I_d|\varepsilon_{k>1}} = \frac{I_d|\varepsilon_{k>1} - I_d|\varepsilon_{k=1}}{I_d|\varepsilon_{k=1}} \tag{4.3}$$

For Neutral Biomolecules

Fig 4.9 demonstrates the changes in the drain current sensitivity of the biosensor under varying dielectric constants of neutral bio-molecules. As shown in the results, an increase in the dielectric constant of neutral bio-molecules causes the effective gate voltage to drop. This leads to a reduction in the tunneling region, subsequently affecting the drain current response of the device. Additionally, the dielectric properties of these neutral bio-molecules influence the threshold voltage sensitivity (ΔV_{th}). Higher dielectric constants result in greater deviations in the threshold voltage, reflecting the biosensor's response to the presence of these molecules.

The observed shift in sensitivity can be attributed to the buildup of neutral bio-molecules altering the electric field at the tunneling junction, thereby modulating the electrostatic potential and tunneling conditions. These findings highlight that the presence and variations of neutral bio-molecules are integral to tuning the electric field distribution and improving the sensitivity of di-electrically modulated HJ-TFET biosensors.

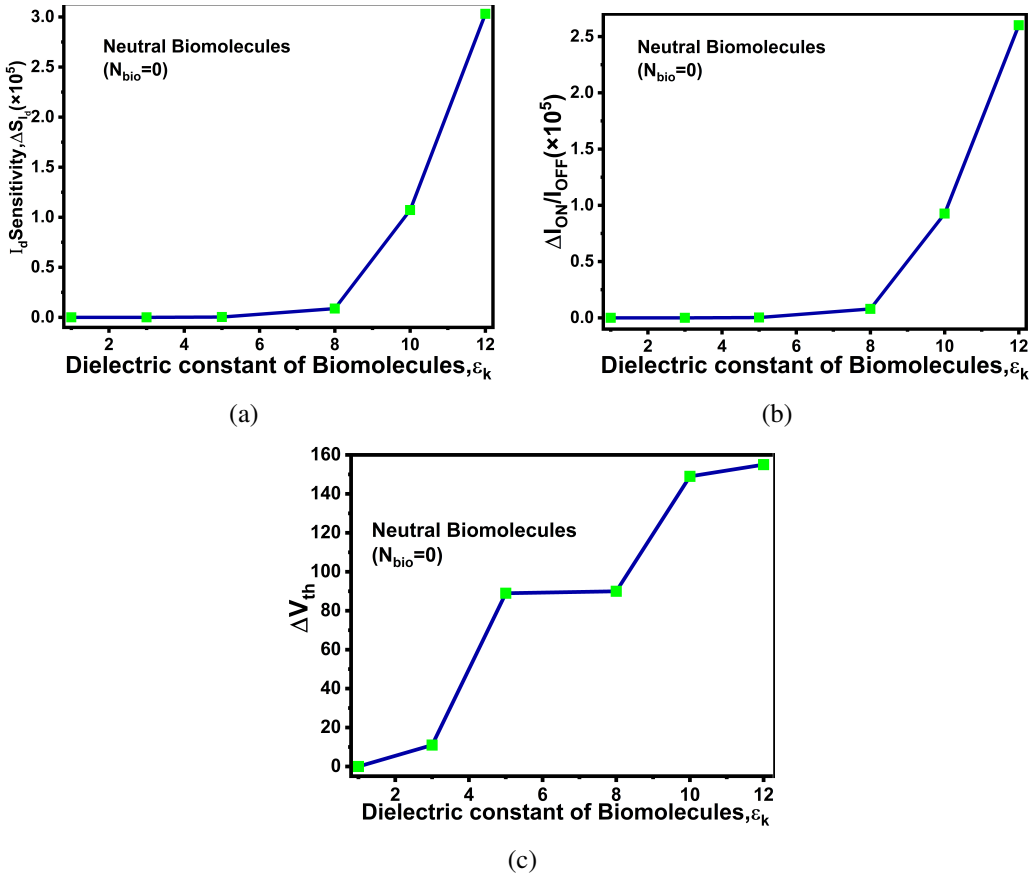


Figure 4.9: Sensitivity Variations (a) I_d Sensitivity $S_{(I_d)}$ vs bio-molecules(ε_k), (b) $\Delta_{I_{ON}/I_{off}}$ sensitivity vs bio-molecules(ε_k) , (c) Threshold Voltage sensitivity (ΔV_{th} vs bio-molecules(ε_k)

For Charged Biomolecules

The impact on sensitivity in the presence of charged bio-molecules when varying their concentration in dielectrically modulated HJ-TFET-based biosensors is significant, as shown in Fig. 4.10. The different bio-molecules concentration takes for analysis are 5×10^{11}, 1×10^{12} and 5×10^{12}. The dielectric constant for this analysis is taken to 12. As the positively charged bio-molecule concentration increases, the drain current in HJ-TFET biosensors increases. More effective electron transfer from the energy's valence band (VB) to the conduction band (CB) is made possible by the enhanced electric field at the tunneling junction.

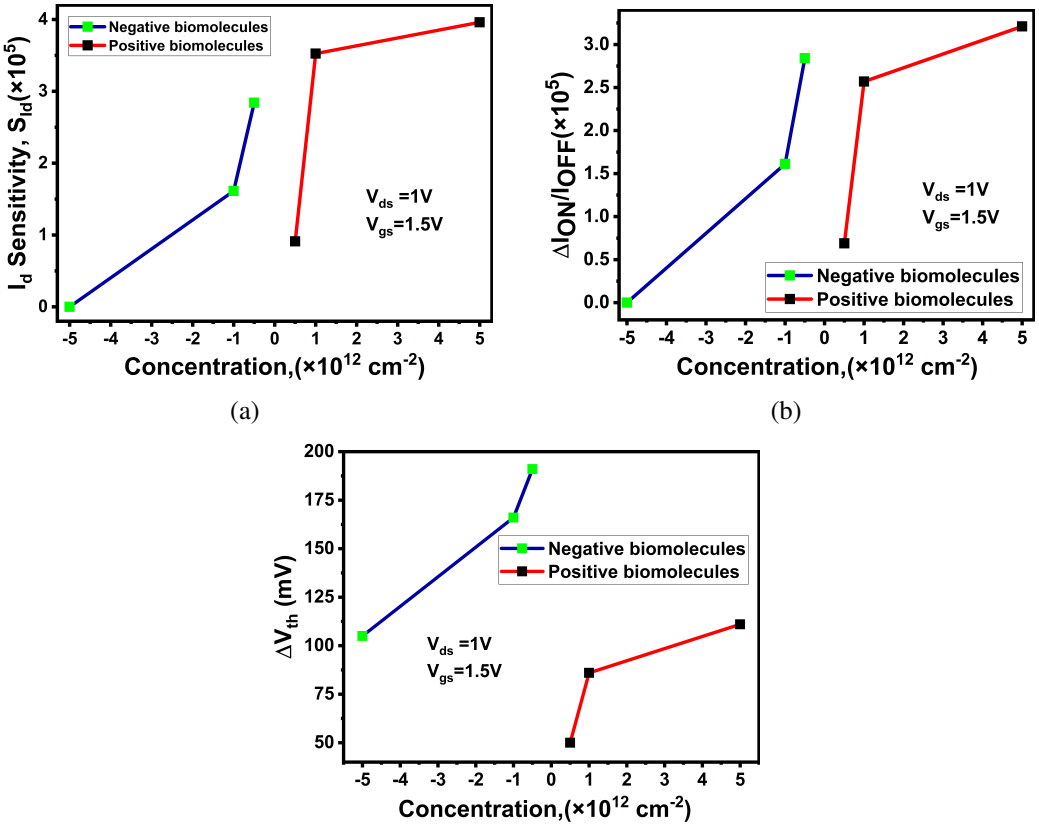


Figure 4.10: Sensitivity Variations (a) I_d Sensitivity $S_{(I_d)}$ vs bio-molecules(ε_k), (b) $\Delta_{I_{ON}/I_{off}}$ sensitivity vs bio-molecules(ε_k) , (c) Threshold Voltage sensitivity (ΔV_{th} vs bio-molecules(ε_k)

The enhancement of the depletion zone by an increase in positive charge results in increased tunneling at the junction and a consequent rise in drain current flow. The threshold voltage sensitivity (ΔV_{th}) also increases because the presence of charge bio-molecules modifies the electric field and the potential barrier at the channel, resulting in a greater change in the threshold voltage as the concentration increases. When the number of negatively charged bio-molecules rises, biosensors' drain current tends to fall. This happens because negatively charged bio-molecules decrease the efficiency of the gate voltage, increasing the tunneling width and decreasing the device's drain current together [30]. The negative charges can repel carriers in the channel, further diminishing the current. The concentration of negatively charged bio-molecules also affects the threshold voltage sensitivity (ΔV_{th}). Higher concentrations can lead to a more significant deviation in the threshold voltage, as the negative charges influence the electric field and potential barrier at the channel.

The ON-OFF current ratio sensitivity ($\Delta I_{ON}/I_{OFF}$) is also positively affected by the concentration of bio-molecules with a positive charge. As the concentration increases, the ON current rises significantly, leading to a higher $I_{ON} - I_{OFF}$ current ratio, This is a critical component in assessing the bio sensor's functionality.The dielectric

constant(ε_k) affects the biosensors' sensitivity of the surrounding medium. When the concentration of the negatively charged bio-molecules increases, the effective dielectric environment changes, This may affect the electric field near the device's tunneling junction. The effect of concentration on sensitivity is more pronounced at lower dielectric constants.

4.4.6 Sensitivity comparison with state-of-the-art Biosensor

Sensitivity serves as a crucial performance indicator for biosensors, representing the minimum concentration of a target analyte that the device can accurately detect. Recent advancements have significantly enhanced biosensor sensitivity, driven by innovations such as the integration of nanomaterials, electrochemical signal amplification, optical enhancement techniques, and advanced biorecognition strategies. To enable a comprehensive sensitivity comparison, three primary electrical parameters were considered: drain current, threshold voltage, and the Ion/Ioff current ratio. The study focused on various structural configurations of Tunnel Field-Effect Transistor (TFET)-based biosensors, including the Vertical TFET, Junction-less TFET, Source Structure Modified TFET, and the N-pocket Dropped TFET designs. The comparative analysis revealed that the Heterojunction TFET (HJ-TFET) architecture exhibited superior sensitivity across all evaluated parameters, outperforming the other TFET structures assessed. This highlights the HJ-TFET's potential as a highly effective platform for next-generation biosensing applications.

Table 4.3: Sensitivity Comparison of HJ-TFET based Biosensor with the State-of-the-art Biosensors

Bio-sensors	ΔS_{I_d}	$\Delta I_{ON}/I_{OFF}$	ΔV_{th}
SG-ESTFET [4]	60×10^2	60×23^3	80 mV
DG-ESTFET [4]	45×10^2	15×10^3	74 mV
Vertical-TFET [14]	40	10	54 mV
Lateral-TFET [14]	10	10^3	66 mV
DMG JL-TFET [31]	1.08×10^{-3}	-	-
DMG-GDS-HJL-TFET [20]	4.1×10^{-4}	-	-
SiGe TFET [32]	1.08×10^{-3}	-	0.004 mV
This Work	37×10^4	26×10^4	191 mV

Chapter 5

CONCLUSION, FUTURE SCOPE and SOCIAL IMPACT

5.1 Conclusion

This study proposes a hetero-junction Tunnel FET (HJ-TFET) based biosensor using a dielectric modulation approach, where nano-cavities are introduced at the source side to enhance performance and an InAs pocket has been created at the source junction to increase the tunneling current. first, we studied the variation in dielectric value which impacts the sensitivity we found that a dielectric increment leads to an increment in sensitivity. and then we varied the concentration of biomolecules and observed the sensitivity factor like voltage sensitivity at the threshold (ΔV_{th}), $I_{\text{ON}} - I_{\text{OFF}}$ current ratio sensitivity ($\Delta \frac{I_{\text{ON}}}{I_{\text{OFF}}}$), and drain current sensitivity (S_{Id}),and thoroughly analyzed to evaluate the biosensor's effectiveness. In addition to accounting for the influence of various dielectric constants, the analysis also examines the impact of diverse bio-molecules, including neutral, positively charged, and negatively charged molecules. It was found that positively charged bio-molecules significantly enhance the sensor's sensitivity in comparison to neutral and negatively charged bio-molecules, improving two major performance metrics. However, in practical applications, the sensor's sensitivity tends to decrease whenever the nano-cavity of device is not filled, leading to sub-optimal performance. In contrast, when the nano-cavity is filled, the biosensor achieves maximum sensitivity, with threshold voltage sensitivity,$I_{\text{ON}} - I_{\text{OFF}}$ current ratio sensitivity, and drain current sensitivity reaching values of $\mathbf{195mV}$, $\mathbf{26 \times 10^4}$, and $\mathbf{37 \times 10^4}$, respectively. In summary, the proposed HJ-TFET-based biosensor exhibits high sensitivity, especially in positively charged bio-molecules, and demonstrates significant potential for use in low-power, high-performance bio-sensing applications. The findings suggest that optimizing the nano-cavity filling is critical to achieving peak sensitivity, making this design highly promising for future biomedical sensing technologies.

5.2 Future Scope

The findings of this thesis open several aspects for future research and practical advances in the field of biosensors:

- **Material Engineering**: Advanced heterojunctions built from 2D materials (e.g.,

MoS_2/WSe_2, InAs/GaSb, black phosphorus) can significantly improve the tunneling efficiency and biochemical interaction in TFETs.Steep subthreshold swing (< 60 mV/dec): Achieved by precise band alignment and engineered tunneling junctions.

- **Flexible and Wearable Biosensors**: TFETs are inherently well-suited for flexible electronics, making them highly promising for wearable biosensor applications. Their low-power operation significantly reduces energy consumption—an essential requirement for wearable and implantable medical devices. Furthermore, TFETs can be integrated with polymers and stretchable substrates, enabling their use in noninvasive, flexible formats such as skin patches, electronic tattoos, or sensors embedded in clothing. These devices facilitate real-time monitoring of vital biomarkers such as glucose, lactate, and cortisol. In many cases, they can operate without external power sources by leveraging energy harvesting techniques or near field communication (NFC), enhancing their practicality and wearability in everyday health monitoring.

- **Multi-analyte Detection**: TFET biosensor arrays enable the simultaneous detection of multiple biomarkers, which is a critical advancement for comprehensive health monitoring. Using arrays of functionalized TFETs, each designed to target a specific analyte, these systems can deliver multiplexed readouts that are particularly valuable for diagnosing complex diseases such as cancer or sepsis. The ability to detect multiple signals in parallel also facilitates the integration of machine learning models, which can interpret data from various sensors concurrently to generate multi-dimensional diagnostic insights. This approach not only improves diagnostic accuracy but also supports effective disease stratification, paving the way for earlier intervention and more personalized treatment planning.

- **CMOS-Compatible Biosensor Chips**: To transition from laboratory prototypes to mass-market diagnostic solutions, TFET biosensors must achieve compatibility with standard CMOS fabrication processes. CMOS compatibility ensures that TFET biosensors can be manufactured using existing semiconductor infrastructure, enabling high-volume production at reduced costs. This scalability is essential for widespread deployment, particularly in healthcare applications. Moreover, CMOS-based TFETs facilitate seamless integration with on-chip electronics, including signal processing units, memory, and wireless communication modules, paving the way for fully integrated system-on-chip (SoC) biosensors. Such integration not only enhances performance but also supports the development of compact and portable diagnostic devices. Additionally, the cost-effectiveness of CMOS-compatible fabrication makes it feasible to produce disposable, single-use biosensor chips, ideal for rapid diagnostics in field settings or at-home healthcare applications.

5.3 Social Impact

The outcomes of this thesis have the potential to generate a significant social impact across several key areas:

- **Pandemic Preparedness and Infectious Disease Control**: Highly sensitive TFET biosensors allow rapid, decentralized detection of viruses at low concentrations. Their disposability and scalability make them ideal for outbreak containment and mass screening in public health emergencies.
- **Personalized Health Data Empowerment**: Integrated with mobile apps, TFET biosensors give users real-time access to health data. Combined with AI, they support personalized medicine, early warnings, and preventive care, fostering proactive health management.
- **Accessible and Affordable Healthcare**: TFET biosensors enable low-cost, portable diagnostics ideal for rural and underserved areas. Their compatibility with CMOS technology supports mass production, reducing healthcare inequality by offering point-of-care testing without complex infrastructure.
- **Real-Time Chronic Disease Monitoring**: Wearable TFET biosensors provide continuous tracking of health markers like glucose or cortisol. This supports early intervention, reduces hospital visits, and empowers patients with data-driven self-care, improving chronic disease management.
- **Environmental and Food Safety**: TFET biosensors detect toxins, pathogens, or pollutants in air, water, and food. Their fast response and portability aid environmental monitoring and food quality assurance, enhancing public safety and regulatory compliance.
- **Workforce Health and Industrial Safety**: In factories or construction sites, TFET biosensors can monitor exposure to chemicals or signs of fatigue. If something's wrong, they can send instant alerts—helping prevent accidents and keeping workers safe and healthy on the job.

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Dielectric Modulated InAs Pocket Heterojunction Tunnel FET for Biosensor Applications

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This work proposes a dielectric-modulated InAs Pocket Heterojunction Tunnel FET (HJ-TFET) for high-performance biosensing applications. The device features a cavity on the source side and an InAs pocket on the source channel junction, significantly enhancing tunneling current and device sensitivity. The study examines the influence of biomolecule dielectric constants and charge densities on the electrostatics of the device. The results indicate that an increase in the dielectric constant improves the sensitivity, while neutral, positive, or negative biomolecule charges modulate the device response, demonstrating charge-dependent sensitivity variations. Comparative analysis reveals superior performance metrics: threshold voltage sensitivity doubles, drain current sensitivity increases 66 times, and ON-OFF current ratio sensitivity improves fourfold over existing FET-based biosensors. These findings underscore the potential of the InAs pocket HJ-TFET as a robust, high-sensitivity biosensor for detecting biomolecules.
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Nanosensor technology has become indispensable in a variety of sectors, including medicine, agriculture, defense, aerospace, and health monitoring, its relevance extending into everyday life. The COVID-19 pandemic underscored the critical need for advanced biosensors, particularly chip-based solutions,[1,2] highlighting their pivotal role in health monitoring and disease detection.[3]

Nanoscale biosensors offer exceptional spatial resolution, enabling the detection of individual biomolecules and facilitating molecular-level biological studies. The foundation for FET-based biosensors was laid in 1970 by P. Bergveld,[4] who pioneered the use of MOS transistors for ion activity detection. Since then, these biosensors have evolved significantly, celebrated for their high sensitivity, cost-effectiveness, lightweight design, and scalability for mass production. However, challenges such as short-channel effects (SCEs), high sub-threshold swing (SS), and prolonged response times remain unresolved.[5]

JFET-based biosensors face additional hurdles, requiring extensive doping, which introduces issues like random dopant fluctuations, device instability, and fabrication difficulties at the nanoscale. These limitations reduce their effectiveness for biosensing applications. Tunnel FET (TFET)-based biosensors provide a promising alternative, addressing these challenges through their compact design, CMOS-compatible fabrication processes, mass production feasibility, and label-free detection capabilities.[6]

TFETs excel in high-speed, low-power sensing due to their distinct charge transport mechanism, minimal leakage current, resistance to SCEs, and lower gate voltage requirements. These characteristics offer superior speed and sensitivity compared to traditional MOSFETs.[7,8] Furthermore, their suppressed SCEs and the ability to overcome the kT/q limit of conventional FETs enhance device performance, ensuring quicker response times and higher sensitivity for nanoscale biosensing applications.[9]

Recent research in biosensors has focused on two primary biomolecule detection mechanisms: gating effects and dielectric modulation, with dielectric modulation emerging as a promising approach. For example, Narang et al.[10] explored TFET biosensors based on P-N-P-N, providing insight into electrical characteristics, although detailed sensitivity analyses remain underexplored. Similarly, N. Kannan et al.[11] demonstrated high sensitivity in impact ionization-based MOS transistor biosensors but did not address the effects of varying biomolecule concentrations. Shoorideh et al.[12] highlighted the effectiveness of FET-based biosensors in the sub-threshold region, but did not investigate critical sensitivity parameters such as threshold voltage or switching ratio.[13]

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Advanced Tunnel FET designs, including heterostacked or vertical TFETs, have shown potential for improved performance metrics. However, these designs introduce significant manufacturing complexity, pose challenges for large-scale production and impact commercial viability.[14] Consistent device performance across large batches remains a key limitation.

To address these challenges, this work introduces a Dielectric-Modulated Heterojunction Tunnel FET (HJ-TFET) as a novel biosensor for high-sensitivity biomolecule detection. The device incorporates a hetero-pocket at the junction of source toward the channel, which enhances the quantum tunneling of the charge carriers. This innovation achieves low power consumption alongside improved sensitivity and performance. Simulation results have been validated through calibrated graphs, and suggested fabrication methods provide a practical pathway for device realization. For different dielectric constants, the device's essential electrical parameters—such as surface potential, energy band fluctuation, electric field distribution, and transfer characteristics—are examined. The dielectric modulation in the HJ-TFET biosensor enables precise biomolecule detection, optimizing sensitivity and specificity. The study also evaluates the biosensor response to charged and neutral biomolecules, with sensitivity parameters including drain current sensitivity (S_{Id}), threshold voltage shift (ΔV_{th}), and ON-OFF current ratio sensitivity ($\Delta \frac{I_{ON}}{I_{OFF}}$).

Device Architecture and Simulation Set-up

Device architecture.—The 2D architecture of the Heterojunction TFET-based biosensor, along with its geometric descriptions, is illustrated in Fig. 1. The device features InAs hetero pockets at the source-channel junction, which significantly enhance Band-to-Band Tunneling (BTBT).[15] The device is constructed on a 20 nm thick SiO_2 insulating layer, commonly referred to as the buried oxide layer having length of 100 nm.

In Fig. 2, the fabrication process shown includes a number of crucial steps. Masking and lithography are used to define the source and drain regions, followed by their deposition.[16] The InAs hetero pockets are deposited using the Molecular Beam Epitaxy (MBE) technique.[17] A 40 nm thick layer of hafnium oxide (HfO_2) is deposited using LPCVD, and the aluminum gate is created using dry etching.[18] Subsequently, a 20 nm layer of HfO_2 is selectively removed from the source side to form nano-cavities.

To enhance the device's current-driving capability, metal electrodes are placed over the source and drain. The nano-cavities, formed by etching the dielectric, expose a 1 nm thick silicon layer to the air, facilitating the immobilization of biomolecules.[19] Various dielectric materials are incorporated into the nano-cavities on the

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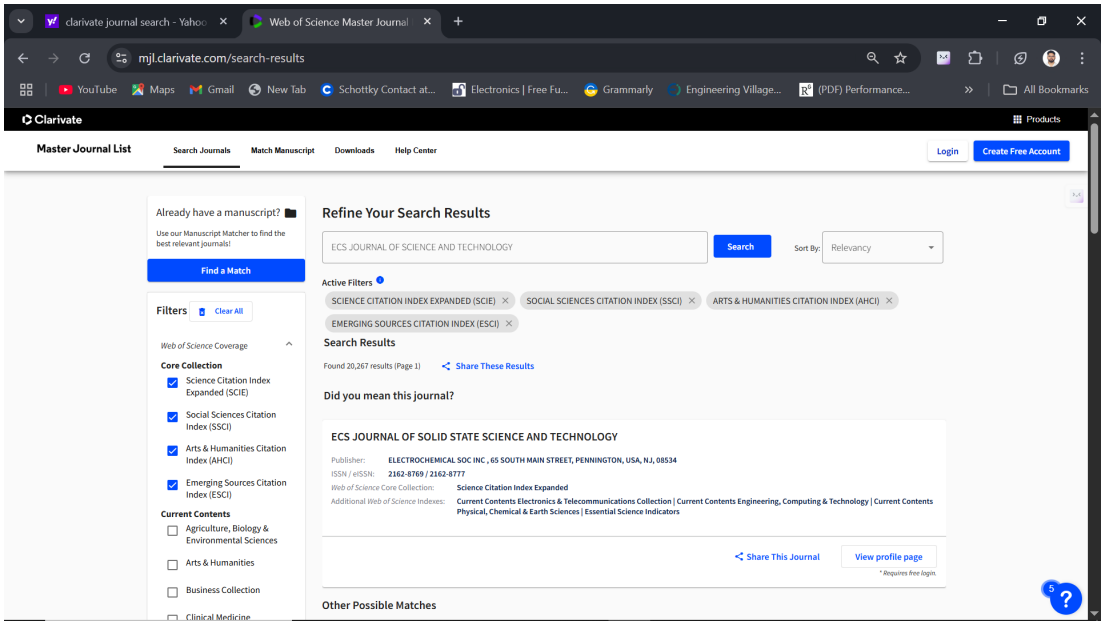

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