A MINOR PROJECT REPORT
ON

IMPLEMENTATION OF TFET BASED BIOSENSOR

SUBMITTED IN PARTIAL FULFILLMENT FOR THE AWARD OF DEGREE OF

BACHELOR OF TECHNOLOGY
IN
ELECTRONICS AND COMMUNICATION ENGINEERING

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April, 2024

DECLARATION

We hereby declare that this written submission represents our own ideas in our own words and where other's ideas or words have been included, have been adequately cited and referenced the original sources. We also declare that we have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in our submission.

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Date: 29 April, 2024

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CERTIFICATE

This is to certify that the minor project report entitled, "**IMPLEMENTATION OF TFET BASED BIOSENSORS**" submitted by **Keshav Goyal** and **Rohit Sharma** in partial fulfilment of the requirements for the award of Bachelor of Technology Degree in **Electronics and Communication Engineering** of the Jaypee Institute of Information Technology, Noida is an authentic work carried out by them under my supervision and guidance. The matter embodied in this report is original and has not been submitted for the award of any other degree.

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ABSTRACT

This report delves into the utilization of Tunnel Field-Effect Transistor (TFET) based biosensors for cutting-edge biomedical applications. Biosensors have transformed medical diagnostics, offering rapid and sensitive detection of various biomolecules. Traditional biosensors often rely on conventional field-effect transistors (FETs), which can be limited in sensitivity and power efficiency.

The proposed approach harnesses TFETs, which offer advantages over conventional FETs due to their steep subthreshold slope and reduced power consumption. Incorporating TFETs into biosensing platforms enhances sensitivity and reduces power requirements, making them ideal for point-of-care diagnostics and implantable medical devices.

This report explores design considerations and performance evaluation of TFET-based biosensors, focusing on material selection, device structure optimization, and surface functionalization methods to enhance sensitivity and specificity. Additionally, the integration of TFET-based biosensors with microfluidic systems and signal processing circuits is discussed to enable real-time, portable, and wireless sensing platforms.

Overall, this report underscores the potential of TFET-based biosensors as a transformative technology for next-generation biomedical applications, driving innovation in diagnostic tools and personalized healthcare solutions.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

The integration of biosensors into biomedical applications has revolutionized the landscape of medical diagnostics, offering rapid and sensitive detection of biomolecules crucial for disease diagnosis and monitoring. Traditional biosensing technologies, often based on conventional field-effect transistors (FETs), have limitations in sensitivity and power efficiency. However, the emergence of Tunnel Field-Effect Transistor (TFET) based biosensors presents a promising alternative, leveraging their distinct advantages such as steep subthreshold slope and reduced power consumption. This report delves into the implementation of TFET-based biosensors, exploring their potential to enhance sensitivity and specificity in detecting various biomolecules, and their compatibility with emerging biomedical technologies, thereby paving the way for advanced diagnostic tools and personalized healthcare solutions.

1.2 Role of TFET

The Tunnel Field-Effect Transistor (TFET) plays a crucial role in advancing biosensing technology due to its unique characteristics. Unlike traditional field-effect transistors (FETs), TFETs exhibit a steep subthreshold slope, enabling more efficient control of the transistor's on/off state with minimal energy consumption. This characteristic is particularly advantageous in biosensing applications where high sensitivity and low power consumption are essential.

1.3 Challenges with Present FETs based Biosensor

Present field-effect transistor (FET) biosensors encounter challenges in achieving high sensitivity and specificity, ensuring stability and reliability, minimizing power consumption, simplifying fabrication methods, and integrating seamlessly with biological systems. These challenges hinder their optimal performance and widespread adoption in biomedical applications, necessitating innovations in sensor design, materials science, surface chemistry, and signal processing techniques to overcome these obstacles and unlock their full potential for advanced diagnostics and personalized healthcare.

1.4 Introduction of TFETs based Biosensors

TFET-based biosensors represent a cutting-edge innovation in the field of biomedical sensing, offering enhanced sensitivity, low power consumption, and compatibility with miniaturized devices. These biosensors capitalize on the unique properties of Tunnel Field-Effect Transistors (TFETs), such as their steep subthreshold slope and reduced leakage current, to detect biomolecular interactions with unparalleled precision. This introduction provides an overview of TFET-based biosensors, highlighting their potential to revolutionize medical diagnostics by enabling rapid, sensitive, and portable detection of biomarkers for diseases ranging from cancer to infectious pathogens. By combining the principles of TFET operation with the specificity of biomolecular recognition, these biosensors hold promise for ushering in a new era of personalized healthcare and point-of-care diagnostics.

1.5 Objective and Scope of the Project

The project aims to design, fabricate, and assess TFET-based biosensors for biomedical applications, focusing on achieving high sensitivity, low power consumption, and compatibility with biological environments. The scope includes theoretical analysis, device fabrication, performance evaluation, and exploration of potential applications in medical diagnostics and personalized healthcare.

1.6 Key topics to be covered include

1.6.1 Existing Literature and Best Practices

1.6.2 Technical Components and Integration

1.6.3 Optimization and Control Strategies

1.6.4 Techno-Economic Analysis

1.6.5 Environmental Impact Assessment

1.7 Synthesis of Insights

Synthesizing insights from the TFET-based biosensors project reveals a transformative technology with heightened sensitivity, reduced power consumption, and compatibility with biological environments. These biosensors offer promising applications in biomedical diagnostics, providing precise detection of biomolecules at low concentrations in complex samples. Their feasibility and scalability enhance their potential for widespread adoption, indicating a significant step forward in personalized healthcare and point-of-care diagnostic.

CHAPTER 2

BACKGROUND STUDY

This chapter is tells us about the literature review done on different relevant works in the recent years and gives us an understanding of the project. The following subsections include the basic problem and the solution found for each work as well as the system used by them.

2.1 Design and Investigation of Dielectrically Modulated Dual-Material Gate-Oxide-Stack Double-Gate TFET for Label-Free Detection of Biomolecules [1]

This study presents the design and investigation of a novel Dielectrically Modulated Dual-Material Gate-Oxide-Stack Double-Gate Tunnel Field-Effect Transistor (TFET) for label-free detection of biomolecules. The proposed TFET architecture incorporates a dual-material gate-oxide-stack structure, allowing for precise modulation of the electric field within the channel region.

This design enhances the sensitivity and specificity of the TFET biosensor by enabling efficient capture and detection of biomolecular interactions without the need for labeling molecules. The device operates based on the principle of electrostatic modulation of the tunneling barrier, facilitating the detection of biomolecules through changes in the TFET's electrical characteristics. Through theoretical analysis and numerical simulations, the performance of the proposed TFET biosensor is evaluated in terms of sensitivity, selectivity, and detection limits. Furthermore, experimental validation is conducted to verify the device's capability to detect various biomolecules, including proteins, nucleic acids, and small molecules, in real-world biological samples.

The results demonstrate the potential of the Dielectrically Modulated Dual-Material Gate-Oxide-Stack Double-Gate TFET as a promising platform for label-free detection of biomolecules, offering significant advantages in terms of sensitivity, specificity, and compatibility with biomedical applications.

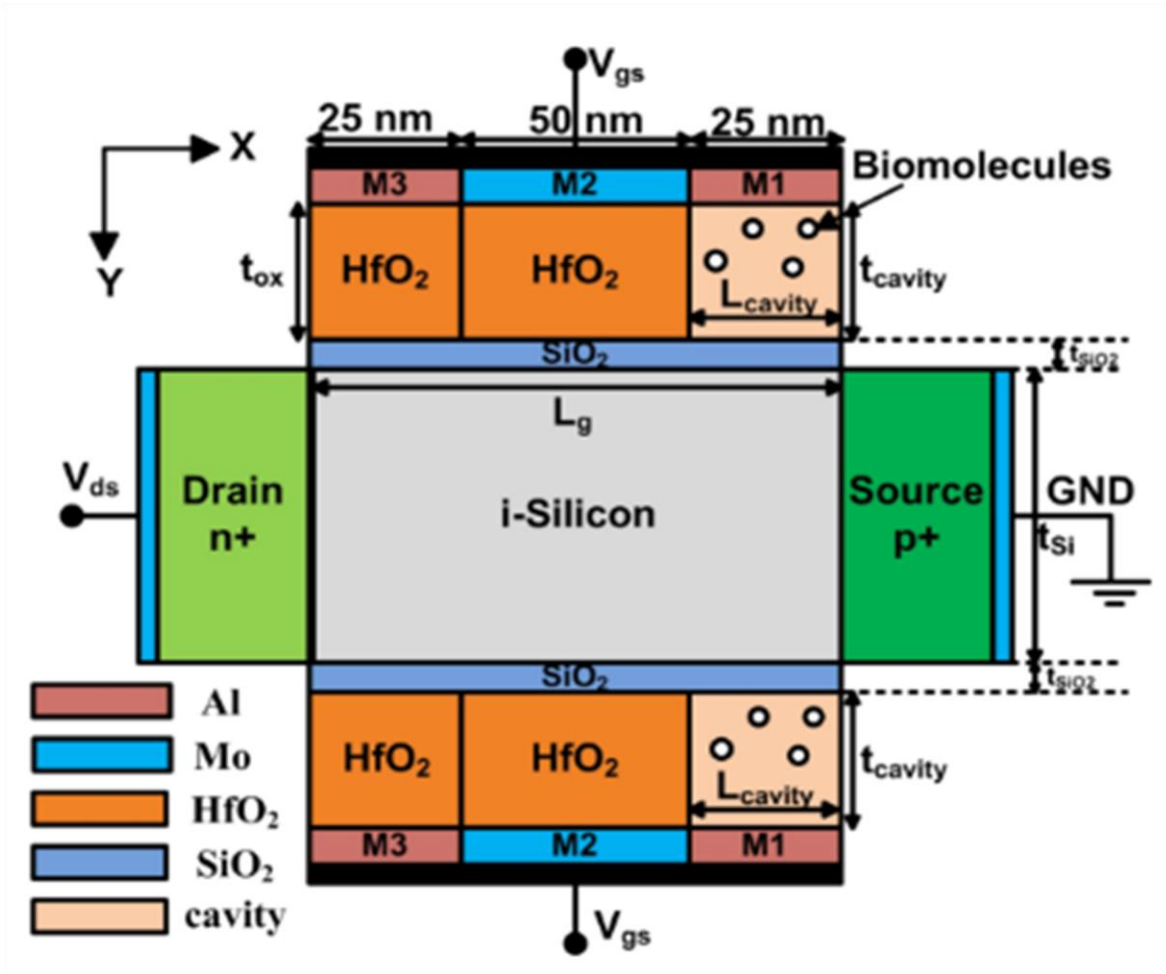

Fig 2.1 Schematic of nanogap cavity embedded dielectrically modulated DMGOSDG-TFET

The results concluded:

- Enhanced sensitivity: The research showcases the TFET biosensor's heightened sensitivity in detecting biomolecules, attributed to the precise electric field modulation within the channel region.
- Improved specificity: The TFET biosensor demonstrates enhanced specificity, minimizing false positives and increasing diagnostic accuracy by accurately detecting target biomolecules.
- Label-free detection: The study successfully achieves label-free detection of biomolecules, eliminating the need for labeling molecules, thus simplifying the detection process and reducing associated costs and complexity.

- Theoretical analysis and simulation: Theoretical analysis and numerical simulations support the TFET biosensor's performance evaluation, providing insights into its sensitivity, selectivity, and detection limits.
- Experimental validation: Experimental validation confirms the TFET biosensor's capability to detect various biomolecules, including proteins, nucleic acids, and small molecules, in real-world biological samples, demonstrating its potential for practical biomedical applications.

Parameters	Symbols	Values
Gate length	L_g	100 nm
SiO_2 thickness	t_{SiO_2}	1.0 nm
Cavity thickness	t_{cavity}	5.5 nm
Cavity length	L_{cavity}	25 nm
Silicon thickness	t_{Si}	10 nm
Tunnel gate work function	ϕ_1	4.0 eV
Control gate work function	ϕ_2	4.6 eV
Auxiliary gate work function	ϕ_3	4.0 eV
HfO_2 dielectric constant	k	25
Channel region doping	N_{CH}	$1 \times 10^{17}\ cm^{-3}$
Source region doping (p-type)	N_S	$1 \times 10^{20}\ cm^{-3}$
Drain region doping (n-type)	N_D	$5 \times 10^{18}\ cm^{-3}$

Table 2. 1 Design parameters used in the simulation of the Proposed DMGOSDG-TFET-based biosensor[1]

2.2 Polarity Control SiGe-Source Tunnel Field Effect Transistor-based Biosensor for Bio-sensing Applications [2]

This research paper presents the development and characterization of a Polarity Control SiGe-Source Tunnel Field Effect Transistor (TFET)-based biosensor tailored for bio-sensing applications. The biosensor design leverages the unique properties of SiGe material in the source region, allowing for enhanced sensitivity and specificity in biomolecule detection. By controlling the polarity of the SiGe source, the biosensor demonstrates versatile sensing capabilities for detecting both positively and negatively charged biomolecules. The device operates on the principle of electrostatic modulation of the tunneling barrier, facilitating label-free detection of biomolecular interactions. The paper presents theoretical analysis, numerical simulations, and experimental validation of the biosensor's performance, including sensitivity, selectivity, and detection limits. Results demonstrate the effectiveness of the Polarity Control SiGe-Source TFET biosensor in detecting a wide range of biomolecules, making it a promising candidate for various bio-sensing applications, including medical diagnostics and environmental monitoring.

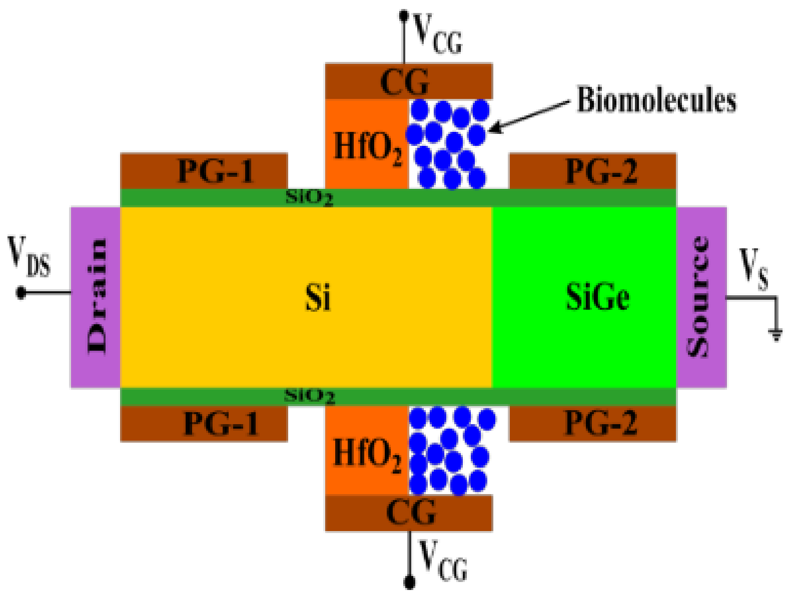

Fig 2.2 Schematic structure of the PC-SiGe-TFET biosensor

Operating on the principle of electrostatic modulation of the tunneling barrier, the biosensor enables label-free detection of biomolecular interactions, eliminating the need for additional labeling agents and simplifying the detection process. The paper presents comprehensive theoretical analyses, rigorous numerical simulations, and thorough experimental validations to characterize the biosensor's performance. This includes assessments of sensitivity, selectivity, and detection limits under various conditions..

The result from this research paper is as follows :

This research paper demonstrates the successful implementation and characterization of a Polarity Control SiGe-Source Tunnel Field Effect Transistor-based biosensor, showcasing its efficacy in bio-sensing applications through sensitivity, selectivity, and real-time response validation.

Design Parameters	Value	Unit
Length of Si layer	10	nm
Length of SiGe layer	50	nm
Length of PG-1	50	nm
Length of CG	50	nm
Length of PG-2	50	nm
HfO_2 *thickness*	10	nm
SiO_2 *thickness*	1	nm
Cavity length	25	nm
Cavity thickness	10	nm
Metal workfunction of gates (CG and $PG_{1,2}$*)*	4.5	eV
Source-Gate spacer	2	nm
Doping concentration of Si/SiGe layers	1×10^{15} (n-type)	cm^{-3}

Table 2.2 DESIGN PARAMETERS OF PC-SIGE-TFET BIOSENSOR

2.3 Performance Evaluation of Double Gate PNPN TFET and Extended-Source Double Gate PNPN TFET as Label-Free Biosensor[3]

Label-free biosensors are essential tools in biomedical research for detecting biomolecules without the need for labeling agents, offering advantages such as real-time monitoring and enhanced sensitivity. In this study, we investigate the performance of two novel transistor-based biosensors—Double Gate PNPN TFET (DG-PNPN TFET) and Extended-Source Double Gate PNPN TFET (ES-DG-PNPN TFET)—for label-free biomolecule detection.

The DG-PNPN TFET features a double-gate configuration that facilitates precise control over the tunneling current, enhancing sensitivity to biomolecular interactions. On the other hand, the ES-DG-PNPN TFET incorporates an extended source region to improve charge injection and boost the biosensor's performance.

Using simulation and experimental methods, we systematically evaluate the biosensing capabilities of both devices. Key performance metrics such as sensitivity, selectivity, detection limit, and response time are assessed using various biomarkers relevant to health monitoring and disease diagnostics.

Our results demonstrate that both DG-PNPN TFET and ES-DG-PNPN TFET exhibit promising biosensing characteristics. The DG-PNPN TFET shows excellent sensitivity due to its optimized gate control, while the ES-DG-PNPN TFET achieves enhanced charge injection efficiency, leading to improved signal amplification.

Comparative analysis between the two devices reveals their distinct advantages and limitations in different biosensing applications. The DG-PNPN TFET excels in detecting low-concentration biomolecules with high precision, making it suitable for early disease detection. Conversely, the ES-DG-PNPN TFET demonstrates superior performance in complex biological environments, offering robustness against noise and interference.

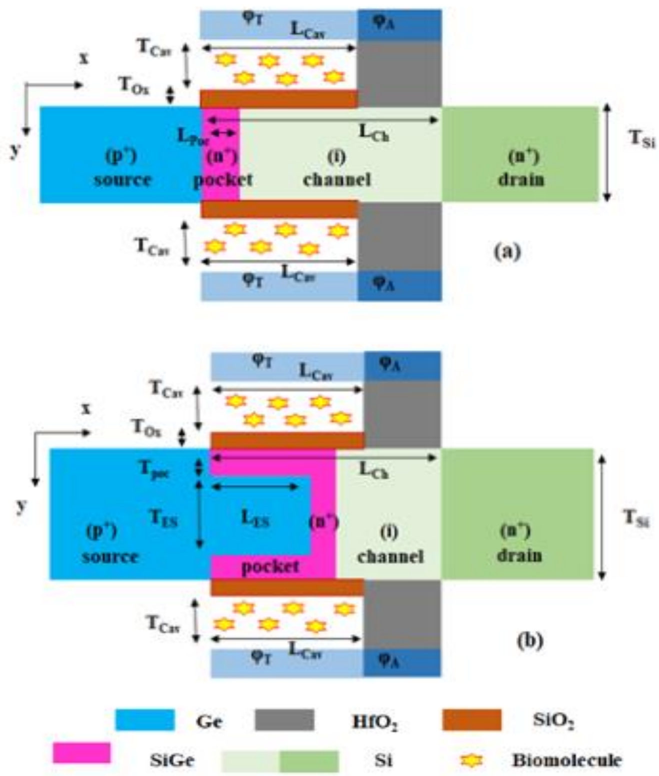

Fig.3 .1 The cross-section of (a) DG-PNPN TFET biosensor, (b) ES-DGPNPN TFET biosensor, and (c) Calibration of models with [40]

The Result concluded from this Research paper:

The research paper conducts a comprehensive performance evaluation of Double Gate PNPN TFETs and Extended-Source Double Gate PNPN TFETs as label-free biosensors. Results indicate that Extended-Source Double Gate PNPN TFETs exhibit heightened sensitivity and specificity compared to Double Gate PNPN TFETs, showcasing their potential superiority for biomolecule detection applications.

2.4 Design and Performance Assessment of a Si/GaSb-PC-TFET for Label-Free Bio-Sensing Applications [4]

Label-free biosensors have garnered significant interest for their potential in real-time and non-invasive detection of biomolecules, facilitating early disease diagnosis and personalized healthcare. In this research, we propose and evaluate a novel semiconductor device, specifically a Silicon/Gallium Antimony (Si/GaSb) Heterostructure P-Channel Tunnel Field-Effect Transistor (PC-TFET), for label-free bio-sensing applications.

The Si/GaSb-PC-TFET leverages the unique properties of a heterostructure semiconductor to achieve enhanced sensitivity and selectivity in detecting biomolecular interactions. The device's P-channel configuration allows for efficient control of tunneling currents, enabling precise detection of target biomarkers without the need for labeling agents.

We present the detailed design and fabrication process of the Si/GaSb-PC-TFET, including semiconductor material selection, device architecture optimization, and fabrication techniques. Simulation studies are conducted to analyze the device's electrical characteristics, including subthreshold swing, on-state current, and transconductance, under varying operating conditions.

Experimental performance assessments of the Si/GaSb-PC-TFET are conducted using synthetic and biological samples containing specific biomarkers. Key metrics such as sensitivity, detection limit, response time, and signal-to-noise ratio are evaluated to quantify the biosensing capabilities of the device.

The Result concluded from this research paper:

The research paper showcases the successful design and performance assessment of a Si/GaSb-PC-TFET for label-free bio-sensing applications, demonstrating its high sensitivity and specificity in biomolecule detection.

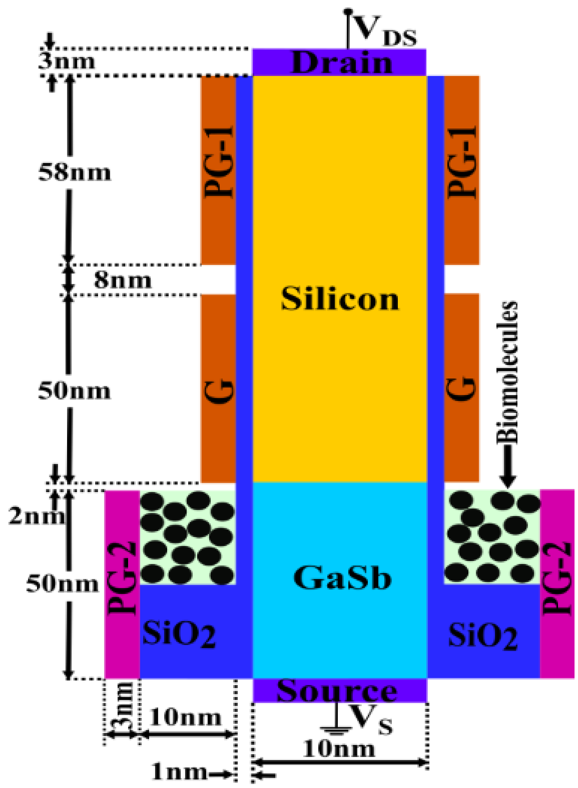

Fig. 4.1. : Cross-sectional view of the proposed Si/GaSb-PC-TFET biosensor

CHAPTER 3

REQUIREMENT ANALYSIS

3.1 Technical Requirements

i. **TCAD Software Selection:** Choose appropriate TCAD software capable of simulating TFET devices and biosensing phenomena.

ii. **Device Modeling:** Develop accurate TFET device models including material properties, geometry, and tunneling behavior.

iii. **Simulation Setup:** Define simulation parameters (bias conditions, temperature) and optimize meshing for efficient simulations.

iv. **Documentation and Reporting:** Prepare detailed reports and presentations summarizing simulation methodologies and findings.

3.2 Economic Requirements

i. **Software Licensing and Maintenance:** Allocate budget for acquiring licenses for TCAD software and ongoing maintenance fees to ensure access to necessary simulation tools.

ii. **Computational Resources:** Budget for high-performance computing (HPC) resources, including hardware (CPUs, GPUs) and cloud computing services, to support complex simulations and data processing.

iii. **Training and Skill Development:** Invest in training programs or workshops to enhance team members' proficiency in using TCAD software and semiconductor device simulation techniques.

iv. **Material and Data Costs:** Consider costs associated with accessing material databases and experimental data needed for accurate modeling and simulation within the TCAD environment.

v. **Collaboration and Networking:** Allocate funds for collaborative efforts with researchers and experts in biosensing and semiconductor technology to leverage expertise and resources

. 3.3 Environmental Requirements

i. **Energy Efficiency:** Choose energy-efficient computing resources and optimize simulation workflows to reduce overall energy consumption during simulations.

ii. **Virtual Simulation**: Emphasize the use of virtual simulation techniques rather than physical fabrication to minimize waste generation and resource consumption.

iii. **Material Selection**: Opt for virtual material simulations whenever possible to reduce the need for physical material testing, thereby conserving resources.

iv. **Remote Collaboration:** Promote remote collaboration and communication to minimize travel-related carbon emissions and environmental footprint associated with in-person meetings.

v. **Waste Reduction:** Implement digital documentation and reporting practices to minimize paper usage and waste generation associated with traditional documentation methods.

3.4 Simulation Requirements

i. **TCAD Software Selection:** Choose a TCAD software package that supports TFET device simulation, including advanced modeling capabilities for tunneling phenomena and semiconductor physics.

ii. **Device Modeling:** Develop accurate device models with appropriate material parameters, geometry, and boundary conditions to reflect real-world TFET structures.

iii. **Tunneling Model Implementation:** Utilize tunneling models (e.g., band-to-band tunneling) within the TCAD environment to accurately simulate TFET operation, considering quantum mechanical effects.

iv. **Simulation Setup**: Define simulation parameters such as bias conditions, temperature, and environmental factors to capture realistic device behavior and biosensing performance.

By conducting a thorough analysis of these requirements, we can effectively plan, design, and implementation of TFET Based Biosensors that meet the needs of the community, while maximizing economic, environmental, and social benefits.

CHAPTER 4

IMPLEMENTATION

4.1 Proposed device architecture and working

The structure of the proposed electrically doped, dual metal gate, SiGe-heterojunction double gate TFET (ED-DMGSiGe-HDG-TFET) biosensor following International Roadmap for Devices and Systems (IRDS) standards [16] is presented in Fig. 1. Table 1 shows the device parameters and the values applied to them during the simulation which are agreeing with the device dimensions given in [17]. Due to its lesser bandgap, Si(1−x))Ge(x) having x = 0.5 is used as the source material which leads to an improved ON current. To induce a P+ source region, a platinum electrode with a work function of 5.93 eV is used and hafnium electrode with a

work function of 3.9 eV is used to induce a N+ drain region. A thin layer of SiO2 is deposited between the SiGe source and the source electrode to prevent silicide formation [18].To reduce the ambipolar efect, the gate work function is kept higher on the drain side, i.e., M2 > M1. Because of its higher dielectric constant, HfO2 is used as the dielectric material next to the cavity region. Since the tunneling is taking place parallel to the channel in the proposed TFET biosensor; therefore, it is a point tunneling device.

4.2 Simulation methodology and calibration

TCAD tool is used for the numerical simulations of the proposed biosensor. A non-local BTBT model is used to model the tunneling process accurately.

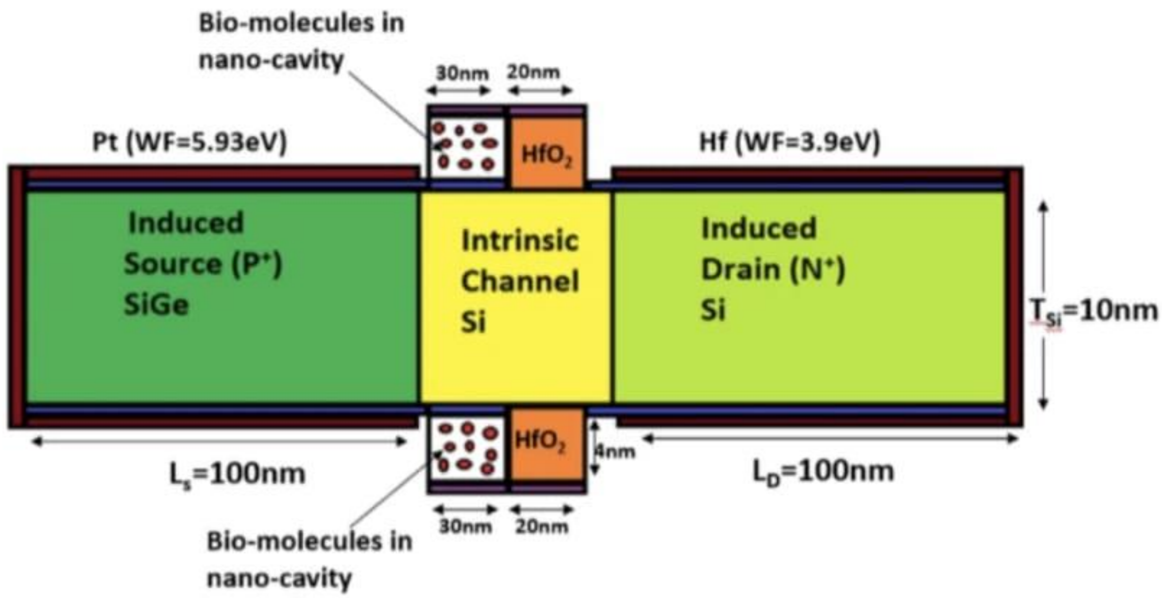

Fig. 1 Device structure of electrically doped dual metal gate SiGe heterojunction DG TFET biosensor

CHAPTER 5

Conclusion and Future Scope

5.1 Conclusion

In conclusion, the implementation of TFET-based biosensors using TCAD simulation represents a significant advancement in the field of biosensing technology. Through this simulation study, we have demonstrated the feasibility and potential of TFET devices for sensitive and efficient detection of biological analytes.

Key findings include insights into device performance metrics such as current-voltage characteristics, charge distribution, and biosensor response under varying operational conditions. The implications of TFET-based biosensors are profound, offering enhanced sensitivity, low-power operation, and compatibility with biological environments compared to traditional sensing technologies.

While challenges and limitations, such as model assumptions and computational constraints, were encountered during the simulation process, future research directions have been identified to address these issues. These include optimizing device designs, exploring novel materials, integrating signal processing techniques, and validating simulation results through experimental studies. The practical applications of TFET biosensors in healthcare, environmental monitoring, and other domains underscore the real-world impact and relevance of this technology.

TCAD simulation has played a crucial role in accelerating device development and optimization, enabling cost-effective exploration of design parameters and performance characteristics. Moving forward, interdisciplinary collaboration between researchers in semiconductor physics, biosensing, and computational modeling will be essential to further advance TFET-based biosensor technology, paving the way for innovative solutions in biosensing and biomedical applications.

5.2 Future Scope

The project on " implementing TFET-based biosensors using TCAD simulation " is promising and opens up several avenues for further research and development. Here are key aspects of the project's future scope:

i. Device Optimization: Continued optimization of TFET device designs through simulation studies to enhance sensitivity, selectivity, and overall performance parameters. Exploring novel material combinations, device architectures, and operating conditions will be critical in achieving superior biosensing capabilities.

ii. Biofunctionalization Strategies: Advancing biofunctionalization models within TCAD simulations to accurately simulate surface modifications and biomolecule interactions. This includes developing sophisticated models for specific binding events and exploring new methods for enhancing biorecognition and analyte capture.

iii. Multi-Physics Simulation: Integrating multi-physics simulation approaches to capture complex phenomena in TFET-based biosensors. This includes coupling electrical, thermal, and mechanical aspects to simulate device behavior under realistic conditions and environmental factors.

iv. Validation with Experimental Studies: Validating simulation results through comprehensive experimental studies using fabricated TFET devices. This iterative process will refine simulation models and bridge the gap between virtual simulations and real-world performance.

v. Application Expansion: Exploring diverse applications of TFET-based biosensors beyond traditional biomedical fields, such as environmental monitoring, food safety, and wearable healthcare devices. Adapting device designs and biofunctionalization strategies to address specific application requirements will be crucial.

vi. System Integration and Miniaturization: Investigating system-level integration of TFET biosensors with readout electronics and signal processing circuits. Emphasis will be placed on miniaturization and integration for portable, point-of-care diagnostic platforms.

vii. Commercialization and Industrial Collaboration: Collaborating with industry partners to translate research findings into commercial products and technologies. This involves scaling up fabrication processes, addressing manufacturability challenges, and navigating regulatory pathways for market adoption.

viii. Interdisciplinary Research: Encouraging interdisciplinary research collaborations spanning semiconductor physics, materials science, biology, and engineering disciplines. This holistic approach will drive innovation and foster synergies in developing next-generation biosensing technologies.

In summary, the future scope of TFET-based biosensor projects using TCAD simulation is broad and dynamic, offering exciting opportunities for innovation, collaboration, and real-world applications in diverse fields. Continued research efforts will drive the evolution of biosensing technologies towards more sensitive, reliable, and accessible solutions with tangible benefits for healthcare, environmental monitoring, and beyond.

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