Study and Analysis of Dielectric Modulated–Double Gate-Tunnel Field Effect Transistor Structure for Biosensors Applications

Solomon Kebede Jorga

A Thesis Submitted to the Department of Electronic and Communication Engineering School of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Electronics and Communication Engineering (Communication Engineering)

Office of Graduate Studies
Adama Since and Technology University

June, 2022
Adama, Ethiopia

Study and Analysis of Dielectric Modulated–Double Gate-Tunnel Field Effect Transistor Structure for Biosensors Applications

Solomon Kebede Jorga
Main-Advisor: Dr. Avtar Singh.
Co-Advisor: Dr. Dereje Tekilu

A Thesis Submitted to
The Department of Electronics and Communication Engineering

School of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Electronics and Communication Engineering
(Communication Engineering)

June, 2022
Adama, Ethiopia

DECLARATION

I hereby declare that this Master Thesis entitled **"Study and Analysis of Dielectric Modulated–Double Gate-Tunnel Field Effect Transistor Structure for Biosensors Applications"** is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

_____	_____	_____
Name of the student	Signature	Date

RECOMMENDATION

We, the advisors of this thesis, hereby certify that we have read the revised version of the thesis entitled **"Study and Analysis of Dielectric Modulated–Double Gate-Tunnel Field Effect Transistor Structure for Biosensors Applications"** prepared under our guidance by Solomon Kebede Jorga submitted in partial fulfillment of the requirements for the degree of Mater's of Science in Electronics and Communication Engineering. Therefore, we recommend the submission of revised version of the thesis to the department following the applicable procedures.

Major Advisor	Signature	Date
Co-advisor	Signature	Date

APPROVAL PAGE

We, the advisors of the thesis entitled **"Study and Analysis of Dielectric Modulated–Double Gate-Tunnel Field Effect Transistor Structure for Biosensors Applications"** and developed by Solomon Kebede Jorga, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Major Advisor	Signature	Date
Co-advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by Solomon Kebede Jorga have read and evaluated the thesis entitled **"Study and Analysis of Dielectric Modulated–Double Gate-Tunnel Field Effect Transistor Structure for Biosensors Applications"** and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Electronics and Communication Engineering.

Chairperson	Signature	Date
Internal Examiner	Signature	Date
External Examiner	Signature	Date

Finally, approval and acceptance of the thesis is contingent upon submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC).

Department Head	Signature	Date
School Dean	Signature	Date
Office of Postgraduate Studies	Signature	Date

ACKNOWLEDGEMENT

I grateful to the God, without his blessing and forgiveness; this thesis would not have been possible.

I sincerely thank my advisor, Dr. Avtar Singh for his immense support and continuous guidance, invaluable suggestions and timely help throughout the duration of this work. His mentorship and help have a great impact on my life and made a very special time on my work.

I would like to thank my co-advisor Dr. Dereje Tekilu for his time and consideration in reading my thesis and for their help in defining and completing my thesis.

I acknowledge Dr. Avtar Singh, Dr. Dereje Tekilu for helping me out on getting started with the Silvaco software.

I would also thank my colleagues Solomon T. and Mhiratu T. for their help and for always lending a helpful hand.

I express my gratitude to the entire faculty and staff of Electrical Engineering Department, who cooperated a lot during my course of study at ASTU, Adama, Ethiopia.

Finally I take this opportunity to thank my friends and family for their love and support. I specially want to thank my mother Aberesh Gensa, and my parents for their encouragement, love and support.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYM

FET	Field Effect Transistor
DM-FET	Dialectical-Modulated Field Effect Transistor
DM-TFET	Dialectic-Modulated Tunnel Field Effect Transistor
DG-TFET	Structure of Double Gate-Tunnel Field Effect Transistor
TCAD	Technology computer-aided Design
MOSFET	Metal-oxide Semiconductor field-effect transistors
ISFET	Ion-sensitive field effect transistor
TFET	Tunnel Field Effect Transistor
NWFET	Nano-Wire Field Effect Transistor
IGFET	Insulated Gate Field Effect Transistor
CRP	C - reactive protein
SCE	Short Channel Effects
DG-BSC-TFET	Double Gate-Both Side Cavity-Tunnel Field Effect Transistor
DG-FBSC-TFET	Double Gate-Full Both Side Cavity-Tunnel Field Effect Transistor
DG-DSC-TFET	Double Gate-Drain Side Cavity Tunnel Field Effect Transistor
SMOSFET	Silicon Metal Oxide Semiconductor Field Effect Transistor
ICs	Integrated Circuit
CMOS	Complementary Metal Oxide Semiconductor
DNA	Deoxyribonucleic Acid
RNA	Ribonucleic Acid
ITRS	International Technology Roadmap for Semiconductor

ABSTRACT

Within several types of innovative bio-sensing technologies, label free dielectric modulated field-effect transistor (DM-FET) based biosensors view out because of their appealing properties, including such Ultra-sensitivity detection, mass-production capacity, and low cost of manufacture, and batch testing facility. Different types of DG-FET based biosensor including ion-sensitive-FET, silicon-nanowire-FET based biosensors had faced problems like short channel effect, low sensitivity and low response time. This work investigates the Dielectric Modulated Tunnel Field Effect Transistor structure for biosensor applications, and for simulation and performance characterization, ATLAS Technology computer-aided design (TCAD) simulator tool is used to simulate and characterize the biosensor. The electrostatics and electrical properties of tunnel field effect transistors are addressed in this work. Because this research area is not much explored. In particular, we focused on the sensitivity and ambi-polarity of tunnel field-effect sensors. Further we analyzed the effect of biosensor performance for sensing surface properties including Electric Field strength, Transfer Characteristics, I_{on}/I_{off} ratio, various other related parameters. The critical difficulties about device design and practical limits have been addressed. At the end, the simulation results shows that the ambipolar current sensitivity of the proposed structure have shown good results. Finally, the examined Double Gate-Full Both Side Cavity-Tunnel Field Effect Transistor (DG-FBSC-TFET)-structure for biosensor application has been identified as a promising contender for future biosensors for point-to-point care disease diagnoses.

Key words: - *Biosensor, FET, DM-FET, Sensitivity and Performance*

CHAPTER ONE

1. INTRODUCTION

1.1 Background of the Study

The lower voltage supply is required for the low electricity usage. The sub-threshold swing in MOSFETs (Metal Oxide Semiconductor Field Effect Transistors) cannot be minimized by 60mV/decade by lowering the supply voltage (Tamak & Mehra, 2017). Downscaling MOSFETs increases power consumption (static and dynamic power consumption are two main forms of power consumption), with static power becoming too high. As it is a p-i-n diode with tunnel current flowing in between the bands of source and channel, TFET (Tunnel Field Effect Transistors) is a promising alternative to MOSFET for low power consumption, high energy efficiency of loop, and comparatively tiny swing switch. As a result, such devices are very suitable for low energy applications with low leakage current and sub threshold swing. The only difference between a TFET and a MOSFET is the switching mechanism; TFETs are using a band-to-band tunneling method, whereas MOSFETs use thermionic emission.

In (Chong, Liu, Wang, & Chen, 2021), outstanding to the promising properties of great sensitivity, low delay time, scaled size, and low rate, silicon-based field effect transistor (FET) bio-sensors have recently attracted significant research interest. Thermal electron emission is a limitation of FET-based biosensors that have sub-threshold slope (SS) of higher than 60 mV/decade. The TFET overcomes the limits of band-to-band-tunneling (BTBT) transmission and minimize the short channel influence process (Li et al., 2021). As a result, TFET-based biosensors had emerged as a potential alternative to FET-based biosensors when it comes to sensitivity and response time. Dielectric modulation is by far the most common technique used during TFETs for molecule detection. A cavity is formed by etching a section of the gate dielectric material; as biomolecules are placed in the cavity, the cavity's dielectric constant changes, which are imitated within the drain current and transfer properties. Simultaneously, dielectric modulation helps in the detection of molecules that are also both charged and unbiased. A TFET with dielectric modulation (DMTFET)-based biosensor has just attracted the consideration of plentiful researchers. A p-n-p-n TFET by way of a biosensor for label-free biomolecule detection was also explored using device modeling. In the nonappearance of biomolecules, a TFET-based

biosensor exhibited low off-state current and increased sensitivity to both dielectric constant and charge, according to TFET-based findings.

The DG-TFET landscapes two gates, one on the upper and one at the foot (named the front gate) and the extra at the bottom (called the rear gate) (called back gate). The electrostatic regulator out of entrance on the channel is enhanced because field outlines initiate at the back gate rather than in the channel. Due to the fact that two channels within which current can flow, the ON- frequency rises.

1.1.1 Introduction to MOSFET

In the semiconductor industry, the silicon metal oxide semiconductor field effect transistor (SMOSFET) was among the most essential and significant components. The MOSFET is already used in integrated circuits (ICs) as a basic operating device in switching operations for digital circuits and as an amplifier device for analog applications since its first practical use 50 years ago. With each new technology generation, device scaling had enabled IC chips to run faster with more functionality. These devices (MOSFETs) are widely used in analogue and digital circuit design. Between the current carrying channel and the gate terminal, there is a very small and thin layer of polysilicon that is coated by silicon dioxide, which acts as an insulator. An electric field is formed in the FET's oxide layer when voltage is applied to the source and gate in which creates an inverse channel in the conducting route termed the depletion area. In n-type semiconductors, electrons are the minority carrier, whereas holes are the majority carrier in p-type semiconductors (Mani et al., 2015). By altering the conductivity of the semiconductor region directly below the gate, the gate voltage controls the flow of electrical current from source to drain. The channel i.e. N-Channel MOSFET (Enhancement mode) is the name given to this area. For enhancement mode MOSFET, any value of $V_{DS:-}$

- When $V_{GS} < 0$, (accumulation), two back-to-back diodes make up the source-to-drain path. Irrespective of the direction of the drain voltage, one of these diodes is always reverse biased.
- When $V_{GS} < V_{th}$, (depletion), there is a shortage of electrons and holes making the channel very highly resistive implies that no drain current can flow.

In inversion case, $V_{GS} > V_T$ (continued): When $V_{DS} > 0$, the induced n-type region licenses current to flow among the source and drain. The induced channel like as a simple resistor. Thus, this drain current (I_d), depends linearly on the drain voltage V_d. This method of act is called the linear or “triode” region.

The "Gate" voltage gearshifts the amount of power from the "Source" to the "Drain."

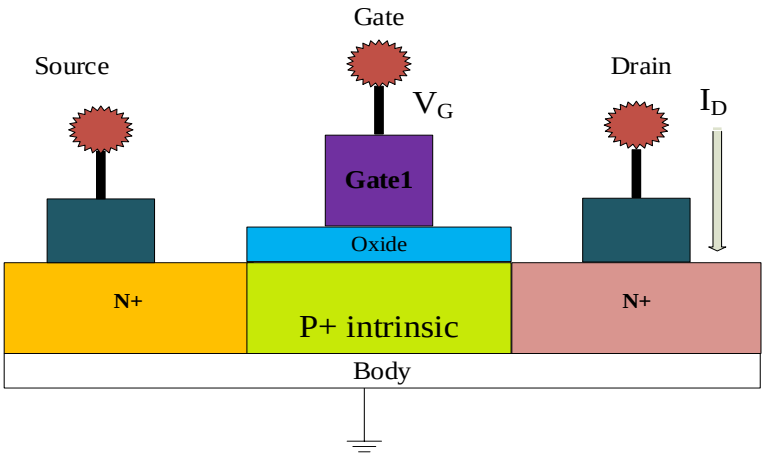


Figure 1.1 MOSFET Structure

Operation to MOSFET

In general, MOSFETs possess three modes of operation (Mendiratta & Tripathi, 2020). The first is the cut-off mode, when the applied gate voltage is lower than the threshold voltage. There is no flow of current or passing through the device because it is not operating. The second is when the current contrasts linearly with voltage because the drain to source voltage is less than the difference between the gate to source voltage and the threshold voltage. The third mode is saturation, which happens when the difference between the gate to source voltage and the threshold voltage is higher than the variance between the gate toward source voltage and the threshold voltage. The pinch-off voltage is a highly conducting mode in which the switch remains ON and the drain voltage is much greater than the gate voltage, resulting in half of the channel remaining in the off-state. Because it can be successfully fully integrated with ICs, CMOS technology is among the most popular widely applied in the semiconductor industry. Because the size of MOSFETs is shrinking, the amount of MOS transistors doubles every two years. When the MOSFET's size is reduced, the channel length is lowered, resulting in short channel effects and increased leakage current. To minimize the short channel effects, new projects and skills are being deployed. The performance of double gate MOSFETs as amplifiers was superior to single gate MOSFETs.

P - Channel MOSFET

The construction and working of a PMOS is same as NMOS. A lightly doped n-substrate is taken into which two heavily doped P^+ regions are diffused. These two P^+ regions act as source and drain. A thin layer of SiO_2 is grown over the surface.

When the gate terminal is given a negative potential at V_{GG} than the drain source voltage V_{DD}, then due to the P^+ regions present, the Hole current is increased through the diffused P channel and the PMOS works in Enhancement Mode. When the gate terminal is given a positive potential at V_{GG} than the drain source voltage V_{DD}, then due to the repulsion, the depletion occurs due to which the flow of current reduces. Thus PMOS works in Depletion Mode. Though the construction differs, the working is similar in both the type of MOSFETs. Hence with the change in voltage polarity both of the types can be used in both the modes.

1.1.2 Introduction to Biosensor

A biosensor is a device that mixes a biological component like that of enzyme or an antibody through an electrical constituent to produce a detectable signal. The microchip senses, records, and broadcasts signals relating to changes in the environment in the existence of chemical or genetic substances.

In (Syu et al., 2018), Biosensors come in a wide range of different shapes and sizes, and they can detect and quantify even minute amounts of diseases, dangerous chemicals, and pH levels. Figure 1.2 an analyte, bio-receptor, transducer, electronics, and display are all components of a conventional biosensor.

- **Analyte:** It's a material whose contents are actuality discovered or documented (e.g., glucose, ammonia, alcohol, and lactose).
- **Bioreceptor:** Bioreceptor (e.g., enzymes, cells, aptamers, deoxyribonucleic acid (DNA or RNA), and antibodies) are macromolecules (molecules) or biological elements that is possible identify the target substrate (i.e., analyte). Signal creation like in the case of light, heat, pH, charge change, plant or animal tissue, and microbial goods occurs during the interaction between bio-receptor and analyte.
- **Transducer:** A device that converts one kind of energy hooked on another. The transducer is an integral part of a biosensor. It converts a bio-recognition event into an electrical signal that represents a measure or directs the presence of a biological target. Signalization is the title for this energy change process. The number of analyte bio-receptor interactions causes transducers to generate optical or electrical signals. Transducers were classified as electrochemical, optoelectronic, thermal, electronic, transducers depending on their operating mechanism.

- **Electronics: -** The transduced information is estimated and willing for display. Electrical signal from transducer were enlarged and transformed to digital system. The display device counts the signals that have been processed.
- **Display:** The outcome is generated by user reading system, as an example computer or printer, such that user might read and understand the screen component's corresponding answer. The upshot could be an exact graphical or tabular number, figure, and based on the end demand.

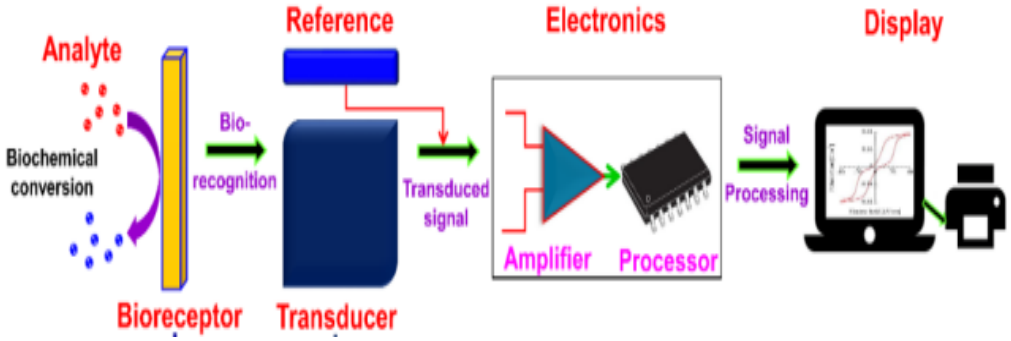


Figure 1.2 Schematic representation of a conventional biosensor with several types of components

Characteristics of Biosensors

Convinced static and dynamic constraints are obligatory to plan a highly effective and proficient biosensor system. The act of biosensors can be improved for commercial application based on the following requirements.

- **Selectivity:** it's a key feature to reflect when picking a bio-receptor for a biosensor. A bio-receptor can notice a particular mark analyte particle in a trial embraced of mixture spices and undesirable pollutants.
- **Sensitivity:** The smallest quantity of analyte which can be identified correctly in a few stages and at low doses (ng/mL) to confirm the presence of analyte remnants in the collection.
- **Linearity:** The accuracy of the experimental values is helped by linearity. The better the detection of substrate concentration, the higher the linearity (straight line).
- **Response time:** the time it takes for a person or system to respond to a particular stimulus or event.
- **Reproducibility:** Precision (consistent results when a sample is tested multiple times) and accuracy are two characteristics of consistency ability of a sensor to produce a mean value nearer to the definite value when the sample is measured

each time. Once the same sample is restrained multiple times, the biosensor's ability to produce identical findings is defined.

- **Stability:** One of the best behaviors of biosensor applications is stability where continuous controlling is required. The degree of sensitivity to environment changes inside and outside the biosensors equipment is referred to as stability.

1.1.3 Introduction to FET based Biosensors

As technology progresses, biosensors are becoming extremely important in human life, and their widespread use has inhibited researchers' efforts to develop alternative technique for identifying biomolecules. FET-based biosensors have attracted a portion of attention because of their excellent detection capabilities, low power consumption, low cost, label-free biomolecule detection, and CMOS compatible on-chip integration. In (Ahn et al., 2011) the label-free discovery of biological class is the main advantage of using field-effect-transistor (FET)-based biosensors, the intrinsic properties of the desired biomolecules, including such constant of dielectric and charge concentration, are used to detect them. The main operating idea of a DM-FET-based biosensor was to alter the electrostatic characteristics of the gate terminal by hybridizing target biomolecules and then measuring the changes in the electrical performance parameters. The sensitivity of these biosensors is critical, and greater sensitivity toward the target biological species indicates better performance (Moon et al., 2016). Recognized to its capacity to detect both charged and charge-neutral biological molecules, the dielectrically modulated FET (DM-FET) is regarded as the most promising versions of FET-based biosensors. A nanogap cavity was included in DM-FET structure, whichever in the gate metal or in the gate-insulator region, where the goal biomolecules can conjugate and modify the effective gate capacitance.

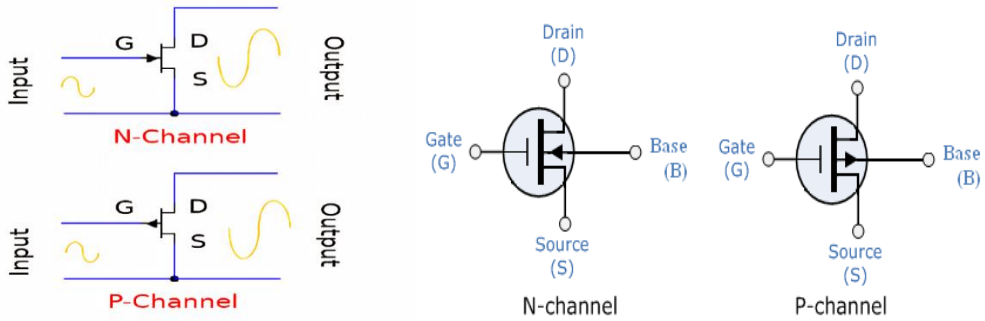


Figure1.3 Field Effect Transistor (Ahn et al. 2011).

Due to its capability to detect both charged as well as charge-neutral biological molecules, the dielectrically modulated FET (DM-FET) is reflected one of the most promising forms of FET-based biosensors (Sadighbayan et al., 2020). The dielectric constant (k) and charge density of biomolecules cause capacitance fluctuation (Chong, Liu, Wang, Chen, et al., 2021).

1.1.4 The Dielectric Modulated TFET (DM-TFET) as Biosensors

The advantages that field-effect transistor (FET)-based biosensors offer in order to be well-matched with typical CMOS technology, downsizing, expense mass production, and label-free sensing procedure had inspired a portion of research interest. The dielectric constant and charge of biomolecules in the nano-gap at the source end estimate the amount of gate modulation at the tunneling junction in DM-TFETs, and hence the current level rises as the k value goes up. Additionally, only a source-side nanogap cavity is studied because the effect of gate–drain underlap on the TFET's electrical characteristics is insignificant (Kanungo et al., 2015).

Due to their improved concert in terms of speed, power dissipation, and subthreshold swing, tunnel FETs (TFETs) are emerging as a potential substitute for multiple gate designed MOSFETs. Its band-to-band tunneling (BTBT) driven carrier transport of TFET was attributed with its enhanced performance. Consequently, the development of TFET-based sensors for label-free biosensing applications with higher sensitivity and lesser response time is drawing more and more attention in recent days. Attributed to its ability to detect both charged and charge-neutral biological molecules, the dielectrically modulated FET (DM-FET) is regarded unique of the most forms of FET-based biosensors. A nanogap cavity is included in the DMFET structure, either in the gate metal or in the gate-insulator region, in which the target biomolecules can conjugate and change the effective gate capacitance (Sadighbayan et al., 2020). The variation of capacitance depends on dielectric constant (k) and charge density (ρ) of the biomolecules.

1.2 Statement of the Problem

To be able to harvest high-speed integrated circuits with high-packing density, rapid innovations in semiconductor technology having pushed MOSFET dimensions down to the nanoscale regime. Short channel effects, from the other side, have such a significant impact on device performance in ultra-scaled designs (Ahangari, 2016). In contrast (Venkatesh et al., 2017), comparison to FET-based biosensors, a nanogap-embedded FET-based

biosensor was presented, with good sensitivity near dielectric strength and charge of biomolecules. Capability of dielectrically modulated-TFET to sense differences in dielectric strength and charge density of biomolecules had been demonstrated (Anand et al., 2019). In Dielectric Modulated Tunnel Field Effect Transistor based biosensor, design, analysis and study of the device biosensing parameters are very essential. Different types of DG-FET based biosensor including ion-sensitive-FET, silicon-nanowire-FET based biosensors had faced problems like short channel effect, low sensitivity, slower operation and high ambi-polar current sensitivity. However, the study and performance analysis of Dielectric Modulated Double Gate-Tunnel Field Effect Transistor based biosensor are not much explored. Hence, in this thesis work the performance of label-free Dielectric Modulated Double Gate-Tunnel Field Effect Transistor based biosensor was studied in order to improve the sensitivity performance of the biosensor and optimize the device architecture for better application. Finally, the concert of the biosensor device in relations of its energy band diagrams, electric field, surface potential, and ambipolar current by using different device level techniques. All the simulations and characterization have been done by using SILVACO TCAD (ATLAS tool or software).

1.3 Objective of the Work

1.3.1. General Objectives

- Improve and optimize the performances of the Dielectric Modulated –Double Gate-Tunnel Field Effect Transistor structure for biosensors applications.

1.3.2. Specific Objective

The specific objectives of the proposed works are:-

- Design and simulate the low power Dielectric Modulated DG-Tunnel Field Effect Transistor Structure for biosensor applications
- Analyze the characterization of the biosensor device.
- Measure the biosensor's sensitivity and ambipolar current.
- Optimize biosensor for better sensitivity to immobilize more number of biomolecules by using different gate materials including HfO_2, Si_3N_4, SiO_2, and TiO_2.

1.4 Significance of the Study

The significant of this work is:-

- To be aware the device's capabilities.

- To design TFET based biosensor for different application such as, clinical applications
- To optimize the device performance by analyzing the parameter used to design the biosensor

1.5 Scope of the Work

In this work, we carefully explored I_D-V_G properties as well as sensitivity-related parameters for biosensor applications of the P-I-N channel of a Double Gate TFET with a gate length of 50nm. Device scope and length, material employed to construct device, oxide thickness and gate length, sub-threshold properties, and drain current I_D also were evaluated as sensitivity parameters. All of the components in this study are made and analyzed through the assistance of computer-aided design (CAD). All device characteristics are established as per the ITRS road map for gate lengths < 100nm.

1.6 Organization of the Works

The rest of the text is organized into six chapters, each with several sub-sections. The following is an overview of each chapter: CHAPTER-ONE Introduction, CHAPTER-TWO is a Literature review in which the performance analysis of different dielectric modulated TFET with proposed work. CHAPTER-THREE this part begins about methodology and materials used to complete the work. It also briefs about the different tools of the TCAD Software used in the current simulation work. CHAPTER-FOUR summarizes the result and discussion. CHAPTER-FIVE conclusion and recommendation.

CHAPTER TWO

2. LITERATURE REVIEWS

2.1 Concept and Definition of Terms

The consequence of a conversion in dielectric constant of area of the gate dielectric on the drain current and linked electric parameters was used for the concept of modulation (Anand et al., 2019). Due to their numerous advantages, several nano-gaps surrounded Field Effect Transistors (FET) grounded biosensors was researched by way of well-organized label free sensors, with the tunnel field effect transistor (TFET) based biosensors being one of them. Number of TFET geometries there had been planned as dielectric modulated biosensors, and their sensitivities had been analyzed in relation to device parameters (Venkatesh et al., 2017). The biosensor's sensitivity in the occurrence of biomolecules is measured against with a reference charge. In the instance of a dielectric-modulated biosensor, the reference value was calculated when the nanogap was free of biomolecules and thus occupied with air with a dielectric constant (k) of 1 and no charge at the oxide-semiconductor interface. The sensitivity of the drain current is expressed exactly as (Chong et al., 2020):

$$sensitivity = \frac{I_{D,k}}{I_{D,k=1}} = \frac{I_{ON}}{I_{OFF}} \; at \; different \; value \; of \; V_{GS} \; \text{--------} \; 2.1$$

Where $I_{D,\,k}$ and $I_{D,\,k=1}$ are the importance of drain currents when the cavity is marched with biomolecules and the cavity is unfilled. The values obtained must be measured at the identical gate voltage so as to get acceptable result of sensitivity. The most important characteristics of biosensor include selectivity, sensitivity, response time regeneration, and simplicity. Using different gate materials such as HfO2, Si3N4, SiO2, and TiO2 can improve the biosensor's sensitivity and immobilize a greater number of biomolecules. Due to excellent performance in terms of speed, power dissipation, and sub-threshold swing, TFETs are being considered as a potential replacement for numerous gate designed MOSFETs. Its band-to-band tunneling (BTBT) regulated carrier transport of TFET is credited with its excellent performance (Anand et al., 2019). For Point of Care applications, low-cost, low-power, quick, lightweight, ultrasensitive, and strong biosensors are highly suggested. The creation of a biosensor based on a silicon nanowire tunneling

field effect transistor (SiNW- TFET) compatible with adjacent metal oxide semiconductors has been proposed (Anand et al., 2019).

Rakhi Narang et al. 2015 developed an analytical model of P-N-P-N TFET for use as biosensor for label-free detection of biomolecules. The proposed model had been found to provide two crucial qualities that biomolecules exhibit. 1) Charge 2) dielectric constant. The sensitivity of TFET based biosensors was compared to that of traditional FET based biosensors using various parameters such as threshold shift, ON-current (I_{on}) level change, and ON-to-OFF current ratio (I_{on}/I_{off}). It was also determined that TFET-based sensors exhibit a wide range of current levels, and that the variation in ON current (I_{on}) can be used as a sensing parameters.

2.2 Dielectric Modulated Tunnel Field Effect Transistor based Biosensors

The need for FET-based biosensors had stimulated the improvement of TFET as dielectric modulation biosensors, which the dielectric constant, as well as charge of biomolecules in the Gate dielectric region, alter the drain current (Sang et al., 2015). Although several TFET architectures had been notionally explored on behalf of dielectric modulated label-free biomolecule detecting, no specific study on construction of TFET based dielectric modulated biosensor had been documented. TFET-based dielectric modulation sensors, had been researched by a number of experts (Mehrotra, 2016). Similarly Tunnel Field Effect Transistors have appeared as is among the most important devices for, because of its small energy consumption ability to survive the effect of scaling, reduced effective costs and simple process, Dielectric modulation is useful in biosensor (Reddy & Panda, 2021).

The FET biosensor had fascinated a lot of consideration in the medical field, diagnosis, and environmental safety protection in the current setup. The FET-based biosensor has been originate to be useful in healthcare industry, pollution monitoring, and biological pathogen treatment. As the tremendous scaling process continues, CMOS technology with conventional MOSFETs faces a number of challenges, including increased leakage current and a steeper sub-threshold slope (SS). In (Zhang et al., 2020), Tunnel field effect transistors that use BTB-tunneling technique were predicted to increase leakage current and SS limits. The goal of this article is to build a DG underlap-TFET structure for biosensors with low leakage current, subthreshold, and sensitivity. Asymmetry between source and drain, as well as step channel thickness, must be implemented using 2D Atlas device simulator software to further overcome the ambipolar current.

The sensitivity (I_{ON}/I_{OFF}) of 10^8 eV/dec. is obtained using the band-to-band tunneling model, which is a good result. The channel is p-n-n, and if it's a TFET, it has to be p-i-n, and the electrical parameters are just simulated in this study.

In contrast to a full-gate tunneling-field-effect-transistor construction of comparable dimensions, a short-gate tunneling-field-effect-transistor (SG-TFET) structure was explored for dielectrically controlled bio-sensing applications (Kanungo et al., 2015). Utilizing sophisticated device-level simulation tools, the detecting performance of mutually charged and charge-neutral biomolecules was investigated, and the consequences of the biomolecule dielectric strength and charge concentration were also considered using the band-to-band tunneling method. In this study, the DM-TFET of SG-TFET was compared towards the FG-TFET, and indeed the DG-TFET based biosensors reported a high drain current sensitivity of 10^7 at k=4.

In (Zhang et al., 2020), DG-TFET was projected to overcome the outflow current and subthreshold slope issues. Using the Silvaco Tcad 2D simulation, the performance of DG-TFET with step channel thickness (SC-TFET) was examined. The ambipolar tendency is expected to be comfortable because of the asymmetry between source and drain created with the stage channel thickness. When likened to the conventional DG-TFET, the SC-TFET offers a considerable reduction in ambipolar current. The mechanisms of SC-TFET were closely researched for the purpose of an improved understanding of the structure's physical properties. SG-TFET had an SS of 44.8 mV/dec, whereas typical DG-TFET had an SS of 50.6 mV/dec. To lower the series resistance, the source region is highly p-doped (10^{20} atoms/cm^{-3}) while the drain region is heavily n-doped (10^{20} atoms/cm^{-3}). The channel region is kindly n-doped (10^{17} atoms/cm^{-3}). Tunnel field effect transistors were the subject of contemporary research in device structure. It must be generated from p-type-channel source and n-type drain, but both channel and drain are strongly doped n-type in this work, thus this isn't recognized.

In (Ahangari, 2016), a new dielectric modulated dual material gate nanowire Junctionless MOSFET's potential as capable biosensor was already demonstrated. The impact of structural parameters on the sensitivity of the proposed device was carefully implemented using a 2D device simulator to design a low-power, highly responsive biosensor, and a nano-gap was inserted in the gate insulator section to immobilize the biomolecules. The gate capacitance was modified as biomolecules accumulated in the nanogap, resulting in a threshold voltage variation.

Streptavidin (k=2.1), 3-aminoppropyltriethoxysilane (APTES) (k=3.57), and protein (k=8) were biomolecules studied in this work. As a result, for the doping concentration, an optimum value of doping $3x10^{18}$ cm^{-3} up to $-5x10^{18}$ cm^{-3} was attained. By modifying the gate work function change over the cavity area and the remnant part of the channel, the biosensor's sensitivity could be improved for a varied collection of biomolecules, and were obtained $10^{8}cm^{-3}$. While in field of science, label-free biosensors, fabrication constraints and costs of nanoscale devices was a key concern. As a consequence, a dielectrically modulated electrically doped tunnel field-effect transistor (DM-ED-TFET) was proposed as biosensor for label-free detection to answer these difficulties (Venkatesh et al., 2017). For the detection of biomolecules, a cavity area embedded inside the gate dielectric was produced in the proposed work by etching a specified fraction of the gate dielectric coating towards the source adjacent. The detecting capabilities of DM-EDTFET were investigated in relations of dielectric constant and charge density of biomolecules, in addition device geometrical characteristics, under various bias situations. In terms of sensing properties, the suggested DM-EDTFET was matched to a MOSFET-based biosensor to determine relative sensitivity. Because of the obvious rise in dielectric constant of biomolecules, there was a large growth in drain current sensitivity, which reached 10^{9}.

In (Verma et al., 2017), biosensors constructed on field-effect transistors (FETs) are particularly general for label-free sensing and was also compatible with CMOS technology. High sub-threshold swing (SS > 60 mV/decade) and a long response time was two major problems for FET-based biosensors. Tunnel FET (TFET) based biosensors can eliminate this problem because TFET has an SS value lower than 60 mV/decade because of its band-to-band-tunneling (BTBT) mechanism. Based on this concept, a vertical dielectrically modulated tunnel field-effect transistor (V-DM-TFET) as a label-free biosensor was investigated and compared to a lateral dielectrically modulated tunnel field-effect transistor (L-DMTFET) just by means of underlap concept and gate work function engineering in this paper. Charged and charge neutral biomolecules are deposited in nano-gap cavities separately to test these devices' sensing capacity. After comparing the suggested structure towards the L-shaped DM-TFET for biosensor applications, the Vertical DM-TFET scored sensitivity of (10^{9}).

2.3 Performance Comparison DG-TFET with Respect to Sensitivity

The electrical properties of TFET or other MOS-based device reflect its performance (Singh et al., 2017). The drain current and threshold voltage are the most broadly applied parameters aimed at defining sensitivity. Sub-threshold swing (SS) might be used to express a sensitivity parameter; however, this drain current's calculation is dependent just on logarithmic scale orders across which it is recorded, because the drain current diverges with the dielectric constant of the immobilized biomolecules, this value or measurement may not be consistent. Generally, sensitivities are defined in terms of reference values. When the nano-gap is empty of biomolecules, it was supposed to be filled with air with a dielectric constant of 1 and no charges at the oxide-semiconductor interface, and was the reference value in the case of a dielectric-modulated biosensor.

$$S_{drain} = \frac{I_{bio} - I_{air}}{I_{air}} - - - - - - - - - - - 2.2$$

Where, S_{drain} is sensitivity of drain current, I_{bio} is current of the biomolecules and I_{air} is current of empty biomolecules. To acquire a reasonable sensitivity value, the standards must be monitored at the same gate voltage. The dielectric constant of the gate dielectric and the charge at the semiconductor-oxide interface determine the threshold voltage. Change in threshold voltage that occurs when biomolecules with varying dielectric constants were immobilized could be used as a sensitivity parameter.

$$\Delta V_{th} = \Delta V_{th(air)} - \Delta V_{th(bio)} - - - - - - - 2.3$$

Where, $\Delta V_{th}, \Delta V_{th(air)}$ and $\Delta V_{th(bio)}$ are threshold voltage, threshold voltage of air and threshold voltage of biomolecules respectively. Since biological analytes are difficult to detect due to their inherent characteristics, they require labels like enzymes or radioactive chemicals to be detected, which is a disadvantage because label-based detection is expensive and time-consuming. Label-free detection, on the other hand, depends on intrinsic physical properties like charge, size, dielectric permittivity, and others to identify the presence of biomolecules in a cheaper and faster method (Sang et al., 2015). Label-free biosensors are used in a variety of fields, including medicine, food processing, natural observation, security, and observation. Biosensor is an electronic apparatus that translates biological reactions into electrical signals. Its basic assembly of TFET is fairly similar by that of MOSFET, with the exception that the source and drain terminals are doped or fixed with opposite types, and also the doping utilized for the drain and source is the main distinguishing feature of TFET.

A P-I-N (p-type, intrinsic, n-type) junction is a common TFET device configuration in which the electrostatic potential of the intrinsic region is measured by a gate terminal and it operates under reverse bias.

Table 2.1 Comparison table of TFET based Biosensors (Singh et al., 2021)

S.No.	Device name	Performances	Limitations
1	Silicon Nanowire Tunnel Field Effect Transistor	small sub-threshold swing of 50mv/dec. that results in improved sensitivity compared to conventional FET device	Ambipolar conductivity
2	Dielectrically modulated Tunnel FET based Biosensor	Improved sensitivity for varying Dielectric Constant	The sensitivity study is performed using charge and dielectric independently but practically charge is present only when biomolecules are existing and that is one of the concern.
3	Short Gate and Full Gate TFET based Biosensor	Appropriate Biasing results in sensitivity perfection almost seven times that of full gate TFET based biosensor	On Current (I_{on}) was limited due to one directional tunneling
4	Junctionless dielectric modulated electrically doped TFET based Biosensor	Performance of device is increased due to absence of junction and improved issue of random dopant fluctuation	Device was free from SCE but still faces issue of ambipolar conductivity

CHAPTER THREE

3. MATERIAL AND METHODOLOGY USED

3.1. Methodology Used

To fulfill goals, we shall utilize a variety of methods, including reading reviews, data analysis, designing the DG-TFET based structure and finally study and analyzes the proposed work for better biosensor application. Using the Silvaco TCAD Atlas 2D program, a Double Gate-Tunnel Field Effect Transistor (DG-TFET) was investigated electrically (Singh et al., 2017). It gives electrostatic regulator over the channel via preventing the drain field line from interfering with the source-to-channel barrier and decreasing short channel effects.

3.1.1 Proposed DG-TFET based structures for biosensor applications

A. Device Specification

FET based Biosensors now are the emerging devices for the immobilization of the biomolecules and the major advantage that they are used in label free environment. In this work we are proposing three different device structure with different cavity area and immobilization methods.

- The first structure we used is the double gate both side cavity tunnel Field effect transistor (DG_BSC_TFET). In this structure we are using the cavity length of 50 nm in both, source and drain regions and the length of the channel is 50 nm. Metal is used as an electrode, which covers the cavity regions both sides and the gate region.
- Second structure is defined as the double gate with whole region above the source and drain side are covered with cavity (DG_FBSC_TFET). The metal electrodes are placed in vertical manner, i.e., as parallel to the Y-Axis. The surface to volume ratio is more in this structure because around total 200 nm are exposed for the immobilization of the biomolecules.
- The last and third structure we have used the double gate TFET with only the cavity at the drain side of 50 nm length and 10 nm of thickness. The gate electrode is covered the cavity as well as the drain region. In this work we are using (DG_DSC_TFET) as the nomenclature for this device structure.

Furthermost of the biosensors, however, are dependent on double-gate TFET, particularly where biomolecules are found are introduced from the both sides of the device structure. In this work the biological molecules are inserted from the top of the device as shown in below Fig 3.1. The proposed DG_BSC_TFET structure features a gate length of 50nm, a body thickness (t_{si}) of 9nm, a front and back device oxide thickness (t_{ox}) of 1nm, and a cavity length on both sides i.e., source side and drain side are 100nm. Because the output current is the tunneling current between the source and the drain as controlled by the gate voltage, the Sub-threshold slope (SS) value of a TFET is defined by a number of parameters in our proposed work, including gate oxide thickness (t_{ox}), SOI layer thickness, and the steepness of the source doping profile. The local BTBT models are used to calculate tunneling current from the source to drain with varying gate voltage (V_{GS}) (Anand et al., 2019).

The I_D–V_G graph of DG-TFET has been plotted and observed by using BTBT model which is simulated in the program. Our proposed DG-TFET based biosensor structure are designed by varying the typical device and electrical parameters shown in table 3.2 validated by recent literature (Chong et al., 2020). Throughout simulation, dissimilar dielectric constant (k) biomolecules (k=1, 3, 5, 7 and 9), and dissimilar densities of charged biomolecules are careful in simulation and discussion. Figure 3.1 illustrates the device design for the Dielectric Modulated Double Gate Tunnel FET (DM-DG-TFET) structure for biosensor application is employed in this thesis work. This investigation considers a double gate p-i-n TFET architecture. The DM-DG-TFET employed in this research work is shown in Figure 3.1(a, b, c) having three regions: p-type semiconductor by forming source and channel region, and n-type semiconductor forming drain region. Figure 3.1(a, b, c) shows 2D Structure of DG-BSC-TFET, DG-FBSC-TFE, DG-DSC-TFE are respectively with biomolecules immobilized and a cavity length of 100nm each, 200nm each and 50nm respectively, L_g = 50nm, t_{ox} = 1nm, t_{si} = 9nm, Doping on source , channel, and drain = $1x10^{20}cm^{-3}$, $1x10^{16}$ cm^{-3} and $5x10^{19}$ cm^{-3} respectively are the other parameters considered in this work.

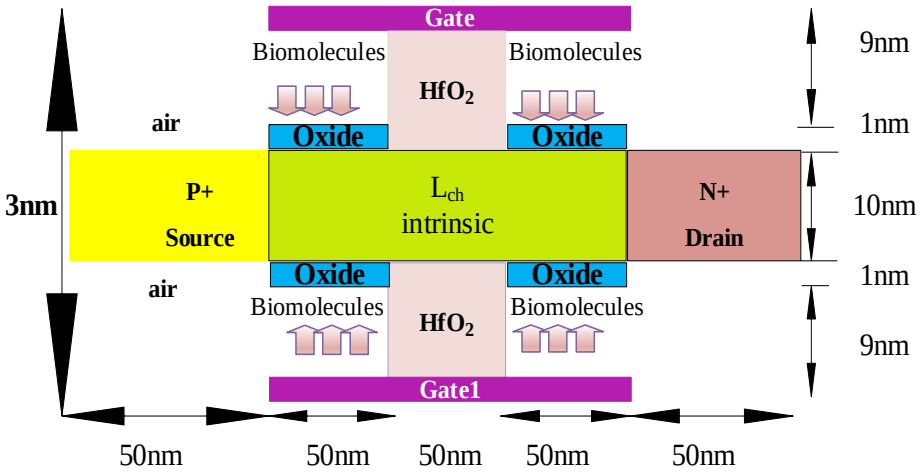


Figure 3.1(a) 2D Structure of DG-BSC-TFET

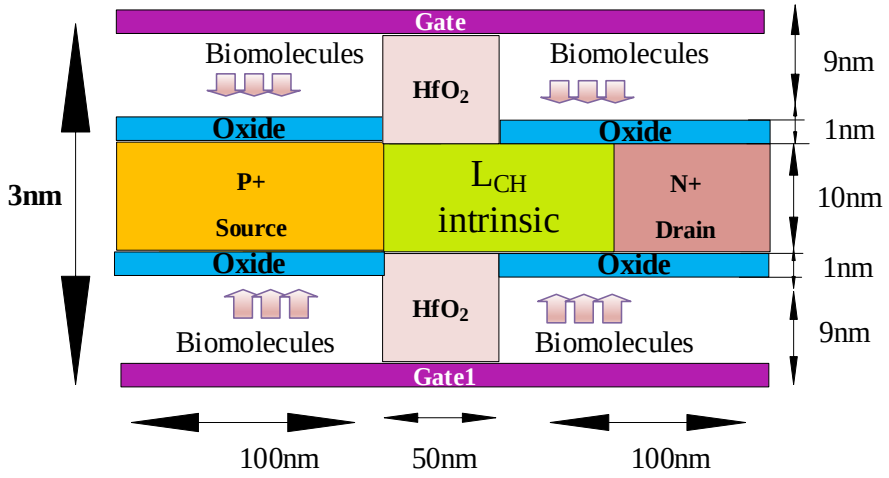


Figure 3.1 (b) 2D structure of DG-FBSC-TFET

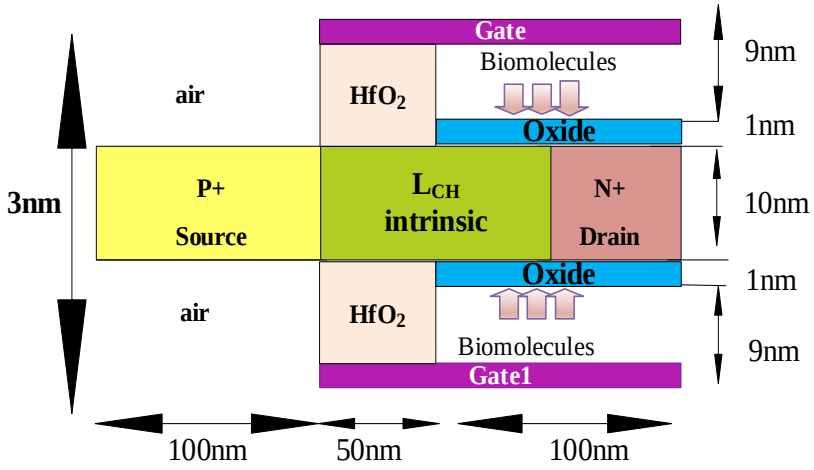


Figure 3.1 (c) 2D Structure of DG-DSC-TFET

The formation of built-in oxide in the Nano-gap cavity regions is considered to be accounted for with a 1nm thick SiO_2 layer. The target biomolecules are induced and fixed in the Nano-gap cavity areas, which serve as detecting sites. The simulations are showed using the SILVACO "ATLAS" commercial simulation program, which is frequently used to characterize the electrical properties of semiconductor devices. In the simulation, a non-local band-to-band tunneling (BTBT) model is used. Inserting dielectric constant material (for instance, streptavidin = 2.1, protein = 2.50, biotin = 2.63, and APTES = 3.57, K>1) into the nano-gap simulates the entry of biomolecules into the nano-gap cavity (assuming the cavities are entirely filled with biomolecules). To replicate the impact of biomolecule charge, a negative or positive fixed oxide charge (N_F) at the SiO_2 interface is used.

When determining the sensitivity of such a sensor, a reference is usually assumed. As a result, the reference is considered in the case where the cavities are exposed to air, or simply when the cavities are not filled with biomolecules. As a result, a metric for the DM-TFET's voltage sensitivity, drain current sensitivity, and sub-threshold slope sensitivity is described as (Reddy & Panda, 2021).

$$\Delta V_{th} = \Delta V_{th(air)} - \Delta V_{th(bio)} \quad \text{---------3.1}$$

$$S_{drain} = \frac{I_{bio} - I_{air}}{I_{air}} \quad \text{----------3.2}$$

$$S_{ss} = \frac{SS_{bio} - SS_{air}}{SS_{air}} \quad \text{----------3.3}$$

Where $V_{th\ (air)}$ is the threshold voltage of the biosensor when the cavities are filled with air, and $V_{th\ (bio)}$ is the threshold voltage when the nano-gap are filled with biomolecules. Likewise, $I_{ds(air)}$ and SS_{air} are the on-state drain current and sub-threshold swing, correspondingly, of the biosensor when the nano-gap are occupied with air, and $I_{ds\ (bio)}$ and $SS_{\ bio}$ are the on-state drain current and sub-threshold swing, correspondingly, when the biomolecules are stuffed into the cavities. Over the investigation of the electrical features of the DG-TFET, the threshold voltage, on-state drain current and sub-threshold swing are extracted to analyze the sensitivity of the biosensor. The three proposed structures are made-up to be used with ATLAS software to examine and analyze the performance of DG-TFET based biosensors. The simulated parameters like sensitivity, ambipolar current, surface potential, charge concentration is covered and analyzed in result and discussion part for biosensor. Nano-gap is incorporated in the oxide layers where the biomolecules are confined in recently described dielectric modulated FET (DM -FET) biosensors.

Consequently, threshold voltage (V_{th}) and ON-current (I_{ON}) of the device vary dramatically depending on the dielectric strength and charge behavior in the biomolecules.

Table 3.1 Key parameters of this work compared to similar work

Parameters	DM-FGTFET with Si channel (Kanungo et al., 2017)	DM-DGTFET with Si channel (Ahangari, 2017)	DM-EDTFET with Si channel (Venkatesh et al., 2018)	DM-TFET with Si channel (Biosensor et al., 2019)	This Work
Source Length	20nm	30nm	50	20nm	100nm
Drain Length	20nm	20nm	50nm	20nm	50nm
Cavity Length	10nm	10nm	20nm	42nm	50,100 nm
Gate length	42nm	35nm	75nm	25nm	50nm
oxide thickness	----	10nm	0.8nm	6nm	1nm
P^+ source doping concentration	$5e19cm^{-3}$	$1x10^{18}$ cm^{-3}	$1x10^{15}cm^{-3}$	$5x10^{19}$ cm^{-3}	$1x10^{20}cm^{-3}$
N^+ drain doping concentration	$5e18cm^{-3}$	$1x10^{19}$ cm^{-3}	---------	$5x10^{18}$	$1x10^{18}cm^{-3}$
Intrinsic doping concentration	$1e12cm^{-3}$	-------	----------	$5x10^{19}$ cm^{-3}	$1x10^{19}cm^{-3}$
Dielectric Materials	SiO_2	TiO_2	SiO_2	HfO_2	HfO_2
Gate work-function (ϕ)	4.8eV	5eV	4.3eV	3.8eV	4.28eV
Gate voltage	1v	0.7v	1.5v	1.5v	0.2v
Supply voltage (V_D)	1v	1v	0.5v	0.7v	-1v

B. Simulation Framework

In this thesis work, the non-local band to band tunneling (BTBT) model is functional for tunneling. To be able to investigate the performance of DG-TFET biosensors a lot more plainly, this work utilizes TCAD tool to investigate sensitivity of TFET based sensors. The proposed DG-BSC-TFET, DG-FBSC-TFET, and DG-DSC-TFET with various high-k materials (HfO_2) are designed with TCAD device simulator called ATLAS Tool. The results are carefully analyzed. For accurate simulation, the relevant models are used. The nonlocal BTBT (Biosensor et al., 2017) model studies the electric field at all point in the tunneling pathway as a inconstant, that is to say the BTBT tunneling probability be contingent on the band bending at the tunneling connection.

The non-local tunneling model is more in line with the actual situation of TFET simulation. As a result, in this work, a nonlocal BTBT model is used. Tunneling is a quantum mechanical phenomenon that happens when electrons on the atomic scale have wave-like qualities. When an electron collides with an energy barrier, it can either be reflected or transmitted through. The tallness, width, and form of the barrier determine the likelihood of transmission through or tunneling. Tunneling takes place within the source-channel p^+-i-n^+ junction of n-channel TFETs. With an appropriate gate bias, electrons in the p+ source just below source Fermi level can tunnel through the energy gap into empty states above the Fermi level in the channel's conduction band. The tunneling current in the non-local band-to-band tunneling model is determined by the band edge profile along the whole path between the tunnelled locations. This means that the electric field evolves over time at each location along the tunneling path. As a result, tunneling is a non-local process.

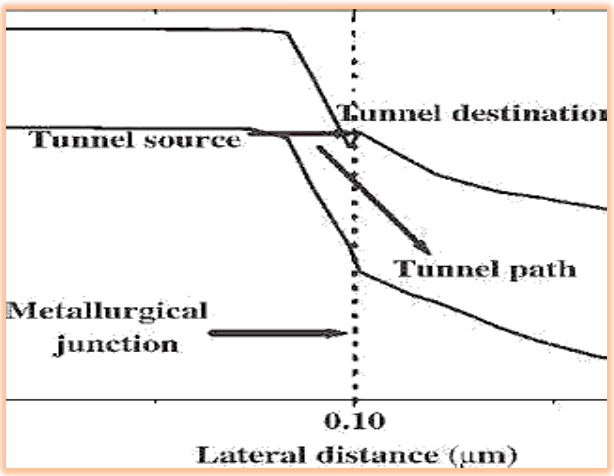


Figure 3.2: Prospective non-local band to band tunneling (BTBT) model (Kanungo et al., 2015)

The simulator's go atlas command is used to begin the simulation. Further, the double-gate tunnel field effect transistor biosensor must be configured for biosensor applications using appropriate ATLAS instructions such as mesh, region, electrode, doping, and so on.

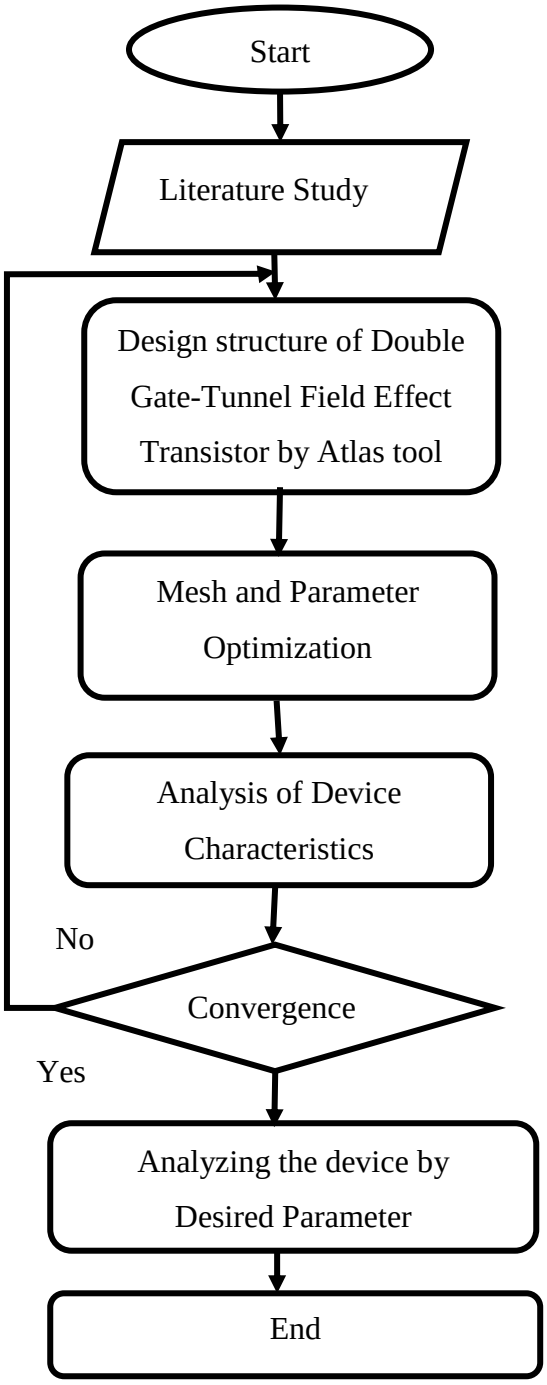


Figure 3.3 Flow chart of this work

This flow chart is the base line to this work and through this step will design and study and analysis the performance of DG-TFET for biosensor application.

Under DG-TFET we study and analyze the proposed work i.e. DG-BSC-TFET, DG-FBSC-TFET, and DG-DSC-TFET based biosensor. The project design flow must require the following points:

- The design flow start with a given set of specification or requirement
- At the end, when the desired specifications are not met, the project has to be modified and re-checked until it meets the required specifications.
- Finally verification have been done by ATLAS tool software.

3.1.2 Double Gate Tunnel Field Effect Transistor (DG-TFET)

The construction in the DG-TFET is made up of two gates, one at the top called Front Gate and the other at the bottom called Back Gate. Since field lines terminate at the back gate rather than in the channel, electrostatic control of the gate on the channel was improved (Tahi et al., 2018). Because there are two channels via which current might travel, the ON-current rises. Computer-aided design was used to simulate the performance of the proposed DG-TFET biosensor (ATLAS TOOL). A suitable model is applied in the program to correctly simulate the device parameters. The grade of band bending and the border profile have a considerable influence on the amplitude of the tunneling current. The TFET simulation's actual situation is more consistent with the nonlocal tunneling concept.

3.1.3 Design and Simulation Parameters for Both Three Proposed TFET Based Biosensors

The parameters used to create the structure in the SILVACO TCAD ATLAS TOOL Software are listed in Table 3.2 below.

Table 3.2. The system implementation parameters.

Parameter Name	Symbol	Value	Unit
Source doping	s_d	$1e^{20}$	cm^{-3}
Channel doping	c_d	$1e^{18}$	
Drain doping	d_d	$1e^{19}$	
Source length	s_l	100	nm
Channel length	c_l	100	
Oxide thickness	t_{ox}	10	
Drain length	d_l	50	
Gate length	g_l	50	

3.1.4 Parameters used to simulate a Biosensor Based on DG-TFET

The following simulation parameters are important in this work after constructing the DG-TFET structure for biosensor applications:

- ON-current (I_{ON}) to OFF-current (I_{OFF}) ratio
- Ambipolar current understanding
- Sub-threshold slope (SS) sensitivity

A). Threshold Voltage

The threshold voltage is the smallest potential difference that can be useful among the transistor's gate and source to form a channel. The tangent to the point where the voltage just shoots up exponentially is it the threshold voltage. The threshold voltage varies depending on the diode's material. The threshold voltage for silicon is around 0.7V, while for germanium it is around 0.3V.

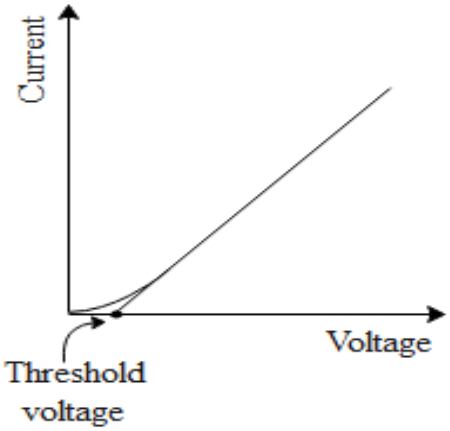


Figure 3.4 Graphical representation of V_{th}

Note: The current increases just slightly before reaching the threshold voltage. This is because the depletion layer is in charge of managing the charge's mobility. Since each semiconductor's depletion layer width is distinct, each semiconductor's threshold voltage is also different.

B). OFF-State Current

The MOSFET is in off whenever the gate voltage is much less than the threshold voltage. Nevertheless, there is a current that flows between the drain and source in the OFF-state because to minority charge carriers. Sub-threshold current is the name for this type of current.

C). ON-State Current

Once the voltage of the gate is extra than the threshold voltage of the MOSFET, the MOSFET is said to be in ON-state. The flow of current in this state is known as ON current denoted by I_{on}. The movement of electrons takes place from source to drain.

D). Sub-threshold Slope (SS)

The degree of gate voltage essential to increase or decrease the sub-threshold drain current by a issue of ten is known as the sub-threshold swing of a FET and is commonly given in millivolts per decade (mV/dec). The equation 3.4 for The expression for sub-threshold slop is (Zhang et al., 2020),:

$$SS = \frac{nkT}{q} \ln 10 \quad ----- \quad 3.4$$

The performance of the gate voltage in modifying the semiconductor surface potential is described by the factor n. To decrease the heating influence in short channel devices, a suitable sub-threshold slope (60 mV/decade) is required.

3.2. Material Used for Designing the System

Microsoft Word Professional 2016, Vision 2016, visio2019, Origin software and the Silvaco TCAD ATLAS tool software version 5.19.20 (for simulation purposes) are used in this work, and there will be no hardware requirement due to various issues such as budget constraints, the lack of a Very-Large-Scale Integration device working environment or lab.

3.2.1 Software used in this Work

The ATLAS tool or software provides an effective solution for simulating semiconductor device structure.

A). Introduction to Silvaco

Silvaco (Silicon Valley Corporation) allows you to use physics-based simulation to project and forecast the performance of semiconductor devices. This tool can be used to model a semiconductor device before it is fabricated. This is actual supportive in many investigation and expansion projects. Silvaco, a leading company in the TCAD (Technology Computer Aided Design) products, has comprised new physical models which use well-organized mathematical methods and algorithms, new meshing techniques, optimized linear solvers, etc., which benefits in getting the simulation outcomes very close to the real-world results. TCAD products are used whichever for:

- Process simulations which use tools like ATHENA.

- Device Simulations which use the Atlas Framework. Atlas has several simulators like S-Pisces, Luminous, Mixed Mode, TFT, Laser, Blaze etc.
- Virtual Wafer Fab to automate and emulate physical wafer manufacturing.

TCAD (Technology Computer Aided Design)

- It is used to explore new design or concepts and learn semiconductor physics.
- Reduce development cost: Reduce development time and cost semiconductor technology. In industry tcad simulation can reduce the cost of the development cycle by 30%
- Visualization of physical processes
- Virtual experimentation: - Experiment with the cavity of effect.
- Widely used leading semiconductor companies

B). Atlas

ATLAS is a two- and three-dimensional device emulator that is physically grounded. It forecasts the electrical comportment of diverse semiconductor structures, and gives awareness into the internal physical mechanisms related with the device process. ATLAS is a standalone tool for predicting the impact of process variables on circuit performance. Device simulation fits between process simulation and SPICE model extraction. Simulations generally use two inputs which are: a text file that has commands for ATLAS to execute and a structure file that defines the structure of the device. The text file with simulator-specific commands is formed with DECKBUILD. Structure records are made with DEVEDIT and ATHENA. ATLAS has three kinds of output. The development of the simulation and error or warning messages are called the run-time output. Log files are generated with the currents and terminal voltages applied during device analysis. Lastly the solution files supply the two and three dimensional statistics relating to the values of solution variables within the device for a single bias point. The log files and the solution files are visualized using TONYPLOT.

C). Deck-build

Deckbuild is powerful communicating run-time environment tool that permits user to transparently go from process simulation to device simulation to spice model extraction.

It is easy to use run time environment for running core simulators such as ATLAS. Deckbuild helps in creating the input files to ATLAS. It can be modified any time. In simulation it shows runtime yield with the mistakes or warnings and the progress of the simulations.

Essential changes can be complete to the input deck according to the run time output. Besides using the interactive mode, one can also give simulator-specific statements. The code also has a provision to incorporate the user-defined functions from the C-interpreter.

D). Devedit

Devedit is collaborative tool for significant and changing structures. It uses SILVACO's Master structure file format to link with process and device simulators. Analytic functions in Devedit are helpful in defining and altering the doping profiles. It could be a stand-alone for defining structures and later invoked by Deckbuild to perform ATLAS simulation of the device structure. This tool is valuable as a pre- processor for 2D device simulators. A new mode of DEVEDIT supports the definition and meshing of 3D structures.

E). Tonyplot

This is the joint imagining tool in Silvaco TCAD products. It offers wide-ranging aptitudes for inspecting and investigating simulator output. The records can be designed as desired by the user either in 1D x-y data, 2D contour data, Smith charts or polar charts. Measured data can also be imported and plotted in the above-mentioned types. The overlays feature benefits in linking the multiple simulation runs. It interprets plots to create meaningful figures for reports and presentations. It supports plotting of user-defined equations with the variables being either electrical data, e.g., drain current or physical parameters, e.g., electric field.

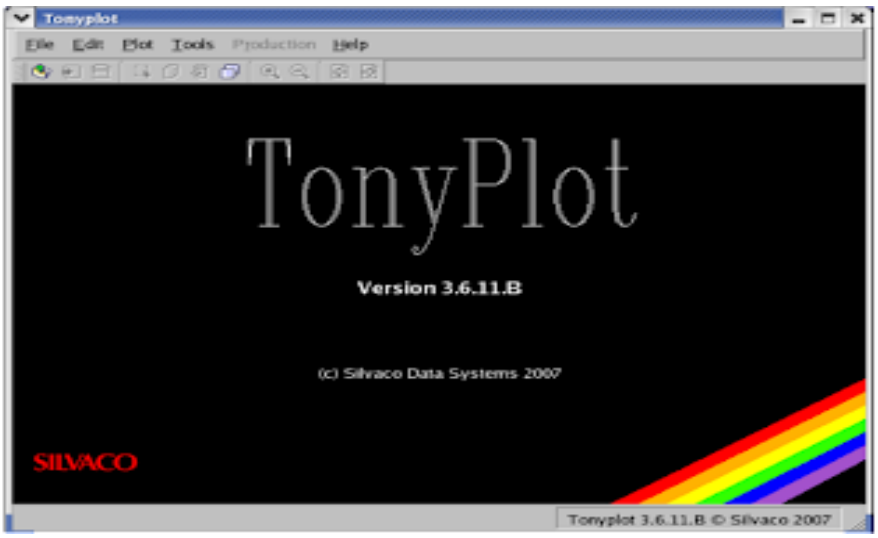


Figure 3.5 Tonyplot which is taken from silvaco manual

CHAPTER FOUR

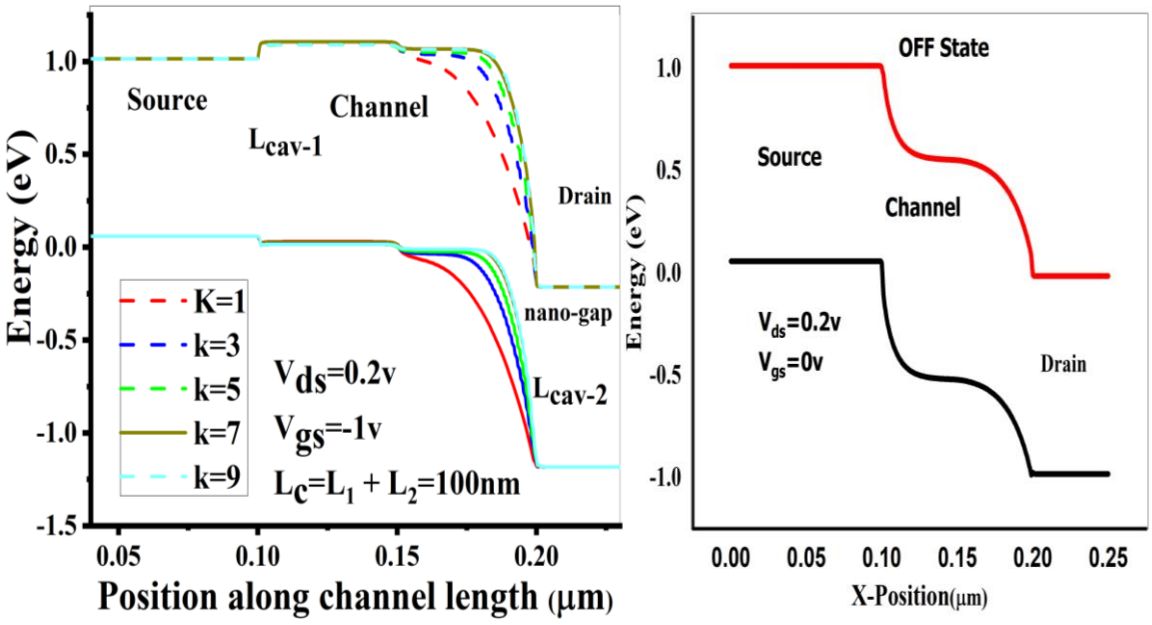
4. SIMULATION RESULTS AND ANALYSIS

4.1 Overview

Simulation is a realistic and systematic method of evaluating a complex system. In this study, the Dielectric Modulated DG-BSC-TFET, DG-FBSC-TFET, and DG-DSC-TFET for biosensor application is examined via simulation using the ATLAS tool. The DG-TFET simulation is used to estimate the electrical characteristics of the biosensors, such as ON-Current, ON current-to-OFF current ratios, and sensitivity. Finally, all the parameters are analyzed and observed to conclude this work. In this chapter the discussion on the result parts is discussed

4.2. Results and Discussions

A. Analysis of DG_DSC_TFET



(a) (b)

Figure 4.1 (a), (b) DG-BSC-TFET biosensor energy band diagrams with ON and OFF states at V_G=-1v, V_D=0.2v and V_G=-1v, V_D=0v, respectively.

As shown on figure 4.1 (a) the ON-state band diagram is depicted. From the figure 4.1 (a), the tunneling gap between the channel and the drain junction is decreased due to the negative gate voltage (V_g=-1v) application at the gate terminal to study the ambipolar behavior of the device.

In Figure 4.1 (b), the OFF-state energy band diagram of DG-BSC-TFET is given. The device is not in conduction because the applied gate voltage is 0v. In the ON-State because of the existence of biomolecules in the gap region, the Tunneling width between channel and drain junction is minimal, and electrons require little energy to move from the Valence band (VB) of the channel to the conduction band (CB) of the drain region. As the dielectric constant of the biomolecule is increasing, means k of the cavity gap is increasing than the tunneling gap is decreasing therefore, the probability of the tunneling is increased. In this work we have used five dielectric constant values to realize with the practical environment, here we used k=1, k=3, k=5, k=7 and k=9. We have done all the simulations using V_D=0.2v. As we have seen when we are increasing the K value the tunneling gap between the channel drain interface decreases, due to which the ambipolar current is increased.

The figure 4.2 presents the output characteristics of DG-BSC-TFET as a function of gate bias with different dielectric constant varying from k=1 to k=9 at V_{DS}=0.2v. From the graph we observe that the presence of neutral biomolecules with k varying has an effect on the transfer characteristics and a significant variation in ambipolar conduction. When the dielectric constant (k) increases the major variation is noted in the ambipolar current and the leakage of the current. As shown in figure 4.2 the ambipolar current is increased on filling the gap with high k biomolecules. The value of ambipolar current for k=3 at neutral charge is 3.56×10^{-11} $A/\mu m$ for DG_BSC_TFET. However, it has the unique attribute of am-bipolarity, which allows current to flow for both high negative and positive gate voltages. Because of the TFET's ambipolar conduction, it is less successful in complementary circuit applications, limiting its use in digital circuit design. Figures 4.3 shows the effect the presence of charged biomolecules like DNA, nucleoside triphosphate (negatively charged) and polyamine (positively charged), etc., on the transfer characteristics. In this work absence of biomolecules in the gap region are realizing with air (k=1) and the figure is drawn for 10 different charge values from -1×10^{11} cm^{-3} to 5×10^{11} cm^{-3}. To ease the simulation process the value of k is kept at 5.

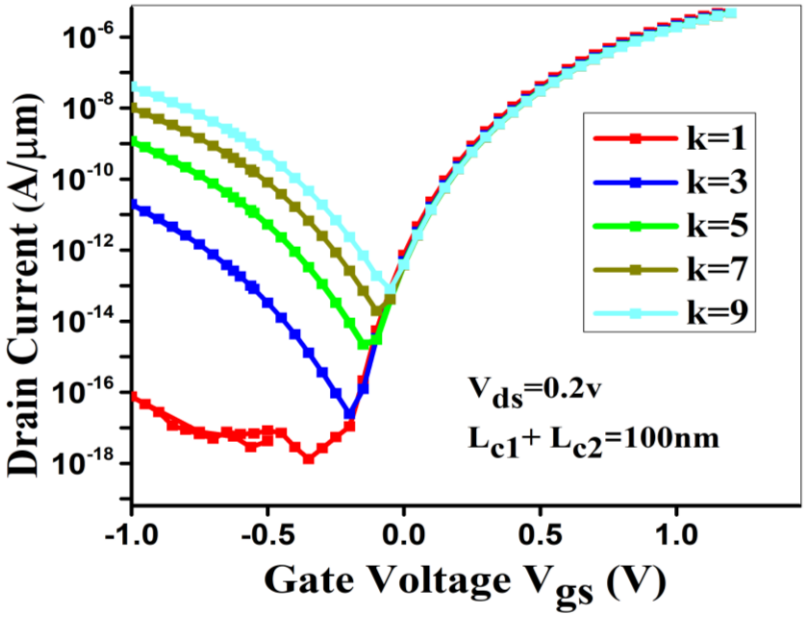


Figure 4.2 Transfer characteristics of DG-BSC-TFET with different dielectric constant (k).

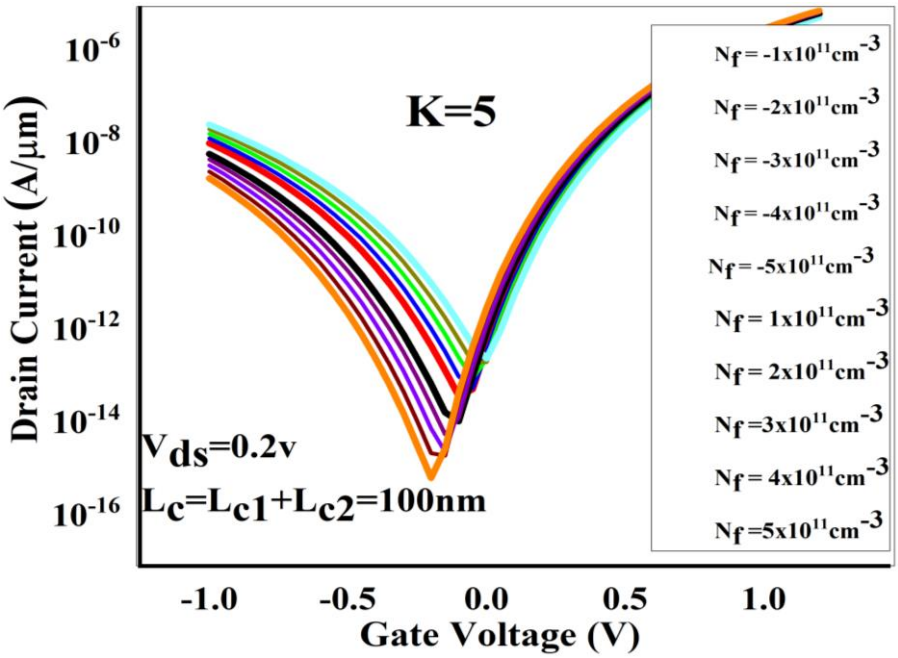
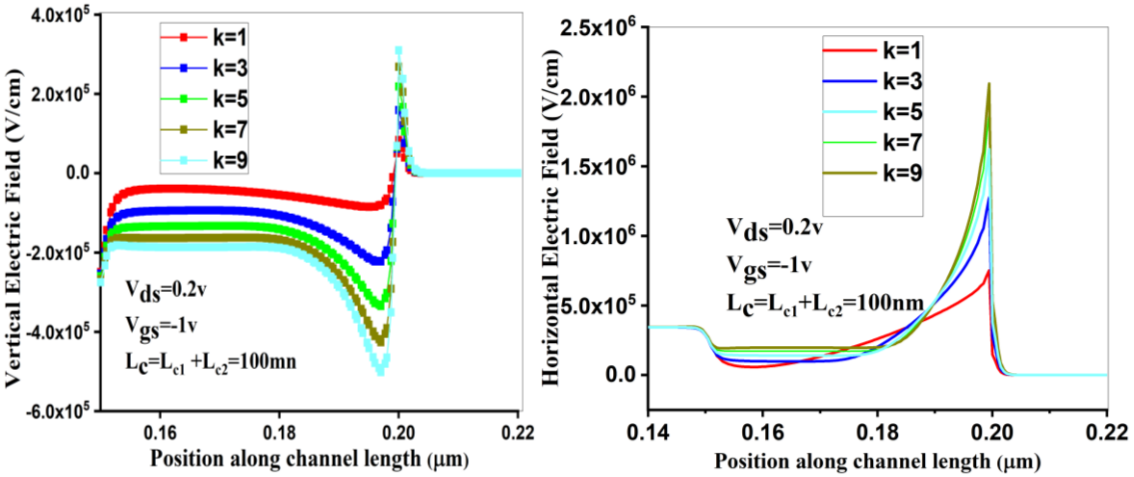


Figure 4.3 Impact of Positive charge and negative Charge biomolecules on transfer characteristics of DG_BSC_TFET at k=5.

From figure 4.3, when increasing the biomolecule charge value, there is no change in the drain current but the ambipolar current is decreasing. When the negative charged biomolecules are present in the cavity region, the on-current is approximately fixed 5.17x10^{-6}A/μm.

There is no any significant change when the positive charged biomolecule are present in the cavity region, for positive charged biomolecules the value of ON-Current is $5.76x10^{-6}$A/µm. It can be observed from the graph on increasing the value of charged biomolecules in the cavity region the ambipolar current is decreasing at charge $5x10^{11}$ the I_A is $1.6x10^{-9}$ A/µm and for charge $-5x10^{11}$ I_A is $2.3x10^{-8}$ A/µm. The variation in electric field of DG-BSC-TFET biosensor with different dielectric constant of biomolecule along x-position is shown in fig.4.4. It can be noticed that there is a decrease in the vertical electric field strength due to increase in dielectric constant of biomolecules. While on the horizontal electric field for cavity length of 100 nm on both sides the electric filed is increase when, high k biomolecules filling in the gap.



(a) (b)

Figure 4.4 (a) Vertical Electric Field (b) Horizontal Electric Field along, x axis for DG-BSC-TFET

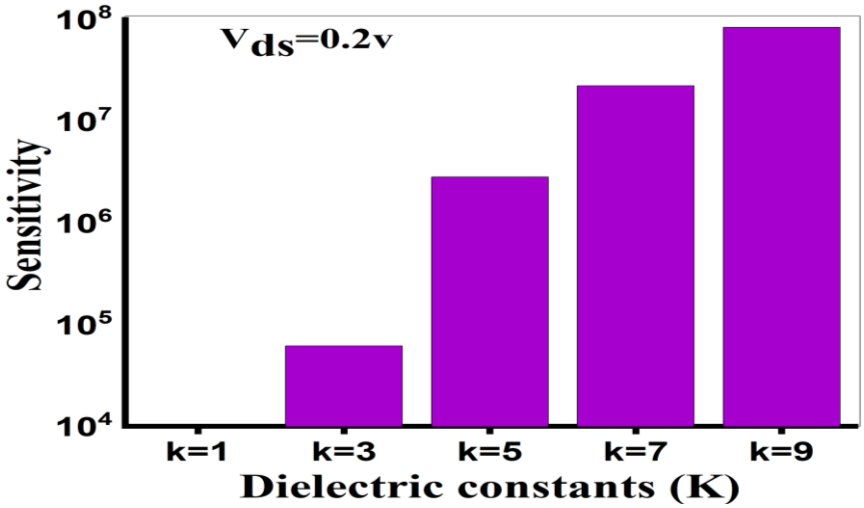


Figure 4.5 Sensitivity of DG-BSC-TFET at V_{GS}=-1v and V_{DS} =0.2v

Figure 4.4 (a) depicts the variation in the vertical electric field of a DG-BSC-TFET biosensor with varying dielectric strength and figure 4(b) shows the variation of horizontal electric field. Because of the increased dielectric constant of biomolecules, the electric field characteristics show a considerable decrease on vertical and horizontal position along channel length. The tunnel barrier width under the nanogap cavity grows when the value of dielectric constant are altered in the cavity region increases due to a smaller electric field, resulting in a decrease in tunneling electrons from the channel to drain region. When the charge density of the biomolecule is reduced, the on-current to off-current ratio of the DG-BSC-TFET based biosensor is also increased. When cavities are created on the source and drain sides but no biomolecules are present inside the cavity, the cavity gap region is filled with air, resulting in a minimum field strength under the cavity in the case of horizontal electric field. When neutral biomolecules with k>1 are present in the cavities, the smaller surface potential rises result in the variation in the electric field which helps in detecting the particular type of biomolecule.

Figure 4.5, shows the sensitivity graph for different dielectric constants. Here we have taken the ambipolar current as the sensitivity parameter. The sensitivity is calculated as the ratio between ambipolar current (I_A) at K=x and the (I_A) at k=1. As shown in the fig. 4.5 a considerable increase in the sensitivity is noticed when the dielectric constants of biomolecules are increasing. Sensitivity of DG-BSC-TFET is approximately increases linearly as dielectric constant of the biomolecule increase and it shows good improvement in the field of biosensor. For all three structures, the sensitivity is expressed as (Biosensor et al., 2017):

$$\text{Sensitivity} = \frac{\text{Ambipolar current (k = x)} - \text{Ambipolar current (k = 1)}}{\text{Ambipolar current (k = 1)}} - - - -4.1$$

Where, X is dielectric constant (1, 3, 5, 7, and 9). Figure 4.5 demonstrates the biosensor's sensitivity, which is defined as the ratio of ambipolar current in the absence and presence of biomolecules. Sensitivity rises when the effective dielectric constant of the nano-gap rises due to immobilized biomolecules, as shown on the sensitivity graph.

B. Analysis for DG-DSC-TFET

The energy band diagram for double gate drains side cavity- tunnel field effect transistor with cavity length 50nm is shown on fig.4.6.

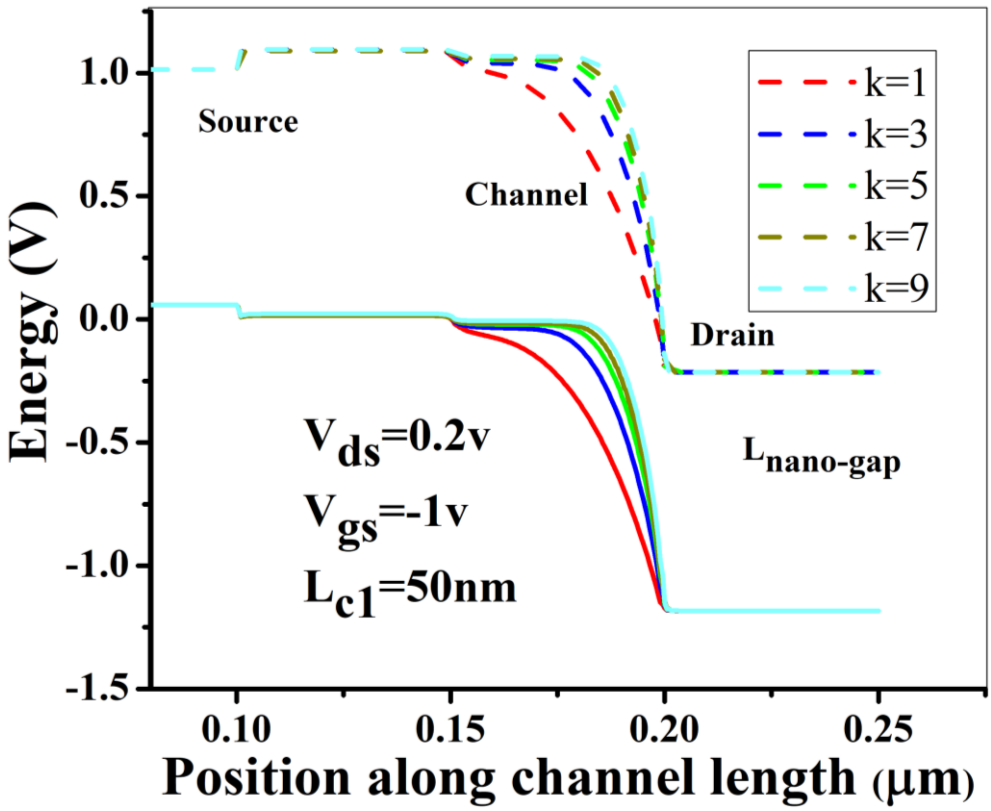


Figure 4.6 ON-State DG-DSC-TFET biosensor energy band diagrams at V_G=-1v, V_D=0.2v.

For varying dielectric constants of biomolecules in the nano-gap, the tunneling barrier width at the channel-drain interface is clearly affected by changes in the dielectric constant in the nano-gap on the drain side, resulting in a considerable variation in the ambipolar current. The fluctuation of tunneling barrier width at the channel-drain interface when the negative charge density increases is not as dramatic. Findings display that in the overlapping gate-on-drain TFET structure, variations in the dielectric constant have a greater impact on the ambipolar current than variations in the charge density of the biomolecules in the nano-gap. As a result, by observing changes in the ambipolar current produced by the dielectric constant and/or the charge of the biomolecules, the overlapping gate-on-drain TFET can be efficiently used for detecting immobilized biomolecules. Real sensing event of the immobilized biomolecules in the nano-gap was simulated by modifying the dielectric constant of the nano-gap, based on the fact that various biomolecules have varying dielectric constants (Syu et al., 2018).

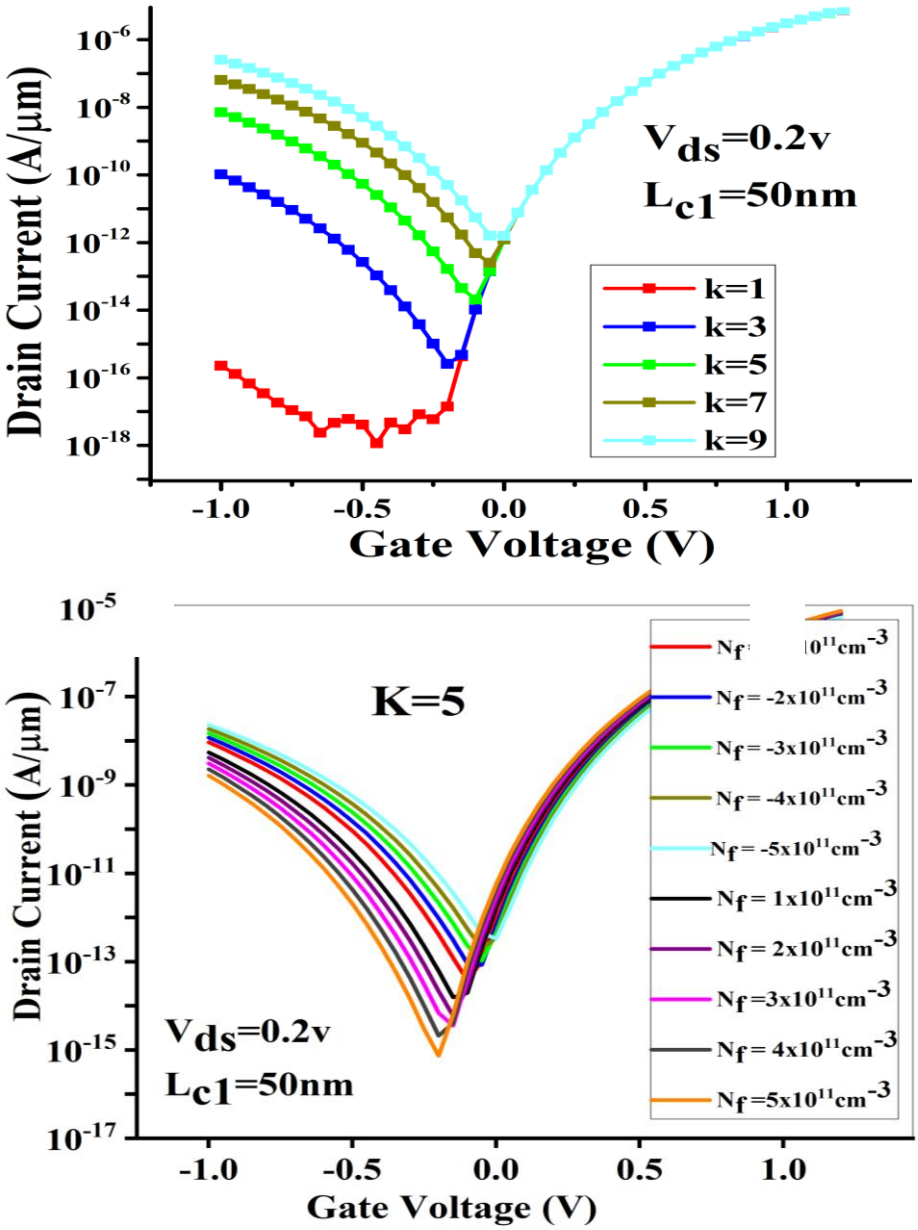
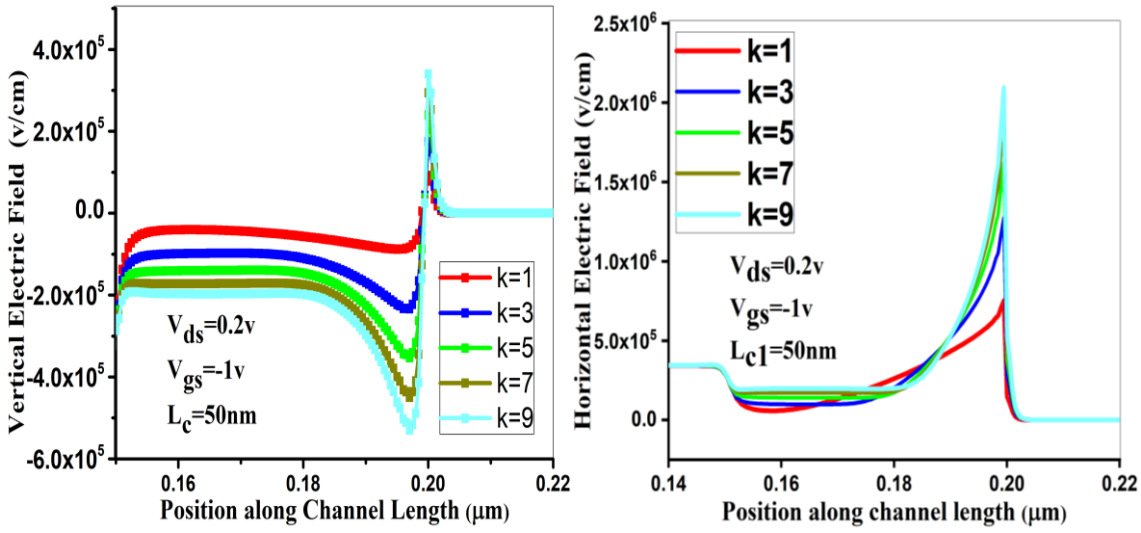


Figure 4.7 (a) Effect of Dielectric Constant, k (b) and Impact of Positive charge and negative Charge biomolecules, on transfer characteristics of DG_DSC_TFET at k=5.

Figure 4.7(a) shows the dielectric strength of biomolecules without charge interference (i.e. charge neutral) increases, the ON-current increases while the ambipolar current increases of current is decreasing at 0v. The dielectric constant k=3 is shown to be the optimal value for this graph, with low ambipolar current and same ON-current values of $1.43x10^{-10}$A/μm and $8.7x10^{-6}$ A/μm, respectively. Form this observed that as dielectric constant of the biomolecule is increase for neutral charge, there is significant change on ratio of I_{ON}/I_{OFF} of $1.5x10^{10}$A/μm. Figure 4.7(b) presents the impact of charged biomolecules on the transfer characteristics of DG_DSC_TFET.

There is a no change in the drain current but the ambipolar current is varying when the charged biomolecules are embedded into the cavity region. On increasing the charge value, the I_A is decreasing, so by this mechanism we can able to distinguish between different types of biomolecules. The major cause in a reduction in I_A due to a decrease in electric field with an increase in negative charge density. The major cause is a decrement in I_A due to rise in electric field with an increase in negative charge density. Similarly, when positive charge density increases the drain current sensitivity is increasing as seen on figure 4.9 (a). The positive charge density has grate effect on the transfer characteristic of DM-TFET based biosensor.

Figure 4.8 (a) and (b) shows the electric field along the channel length in the absence and presence of biomolecules with neutral charge and different dielectric constant k. The charge carriers are electrons or hole, which flow from source to drain through an active channel. This flow electron from source to drain is controlled by the voltage applied across the gate and source terminal. There is decrease in the electric field at the tunnel junction, which, in turn, governs the BTBT generation rate and the tunneling probability. Since the generation rate depends exponentially on the electric field. Therefore, with increasing electric field, the generation rate increases, which leads to a decrease in I_A.



(a) (b)

Figure 4.8 (a) Vertical Electric Field (b) Horizontal Electric Field along, x axis for DG-DSC-TFET

Electric Field is another important parameter to be considered. It can be noticed that there is a significant rise in the electric field characteristics due to increase in dielectric constant of biomolecules. Figure 4.8 (a) and (b) describes the variation in the electric field of a DG-DSC-TFET device structure which is proposed as the biosensor. Because of the increased dielectric constant of biomolecules, the electric field characteristics show a considerable increase. Although the charge density is not considered in the figure 4.8 but it is shown from the 4.7 (b) the tunnel barrier width under the nanogap cavity grows when the negative charge density in the cavity region increases due to a smaller electric field, resulting in a decrease in tunneling electrons from the source to the channel region. The sensitivity is calculated as the ratio between ambipolar current (I_A) at k=x and the (I_A) at k=1. As shown on the fig. 4.9, a considerable increase the sensitivity is noted when the dielectric constants of biomolecules are growing. Sensitivity of DG-DSC-TFET is approximately increases linearly as dielectric constant of the biomolecule increase and it shows good improvement in the field of biosensor.

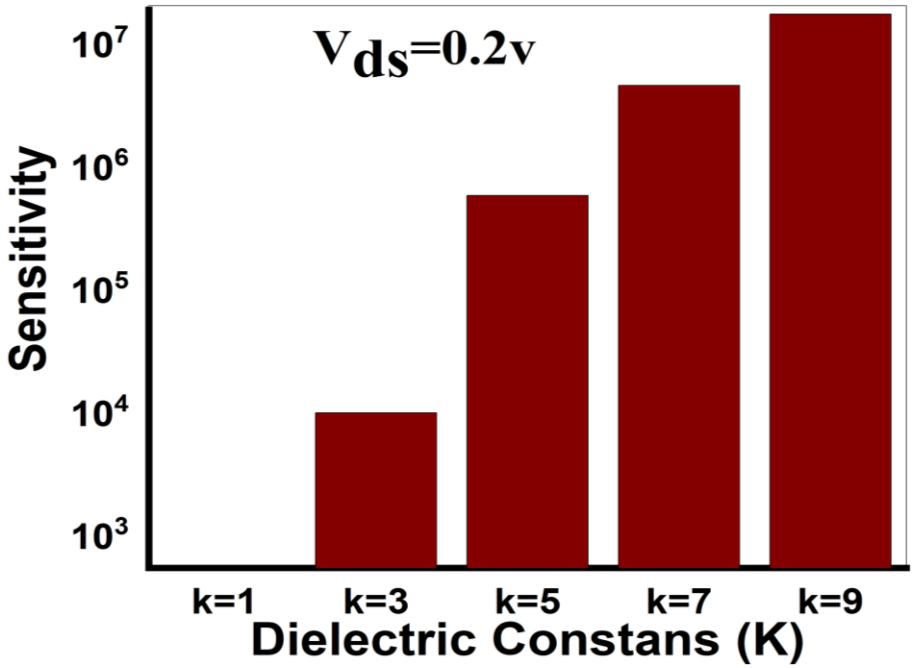


Figure 4.9 Sensitivity of DG-DSC-TFET at V_{GS}=-1v and V_{DS} =0.2v

C. Analysis for DG-FBSC-TFET

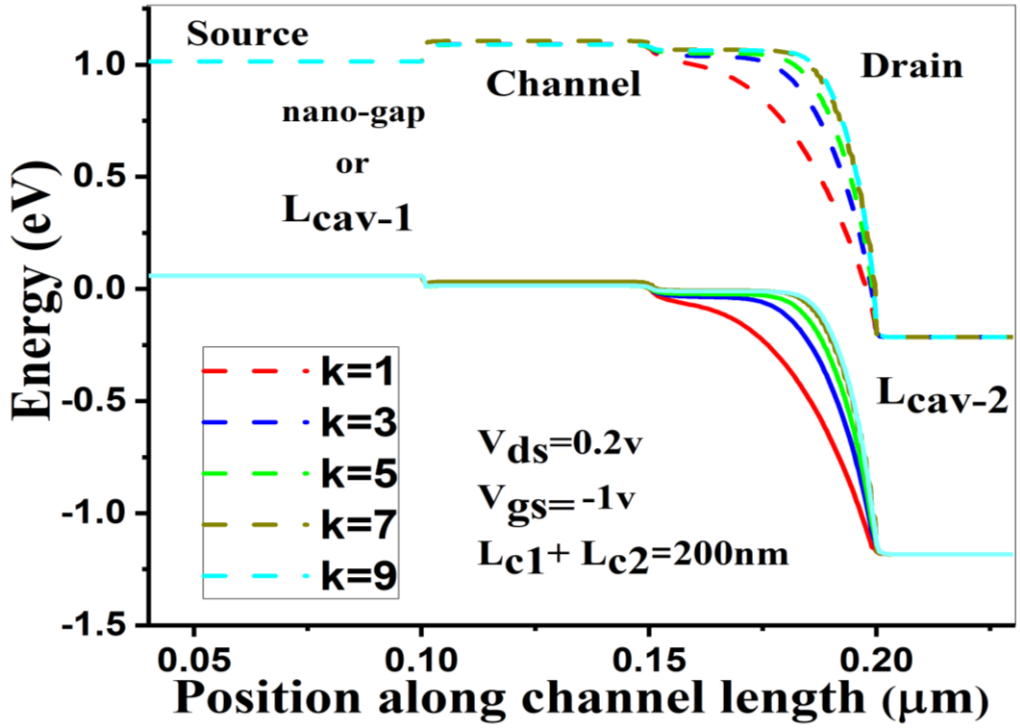
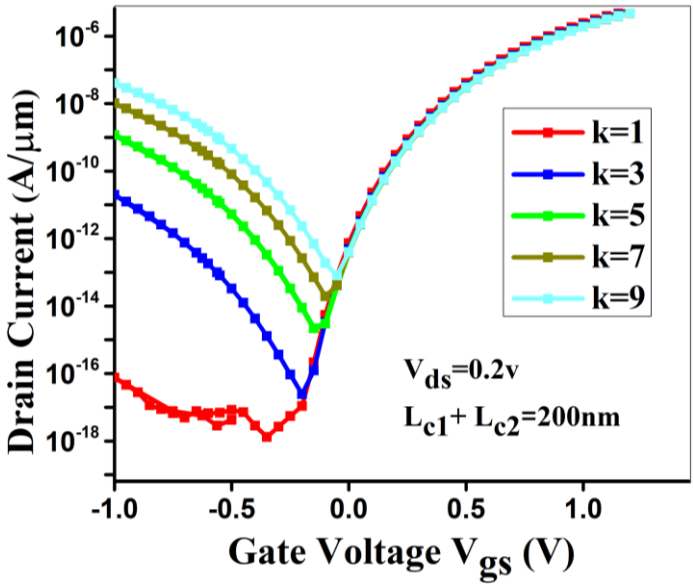
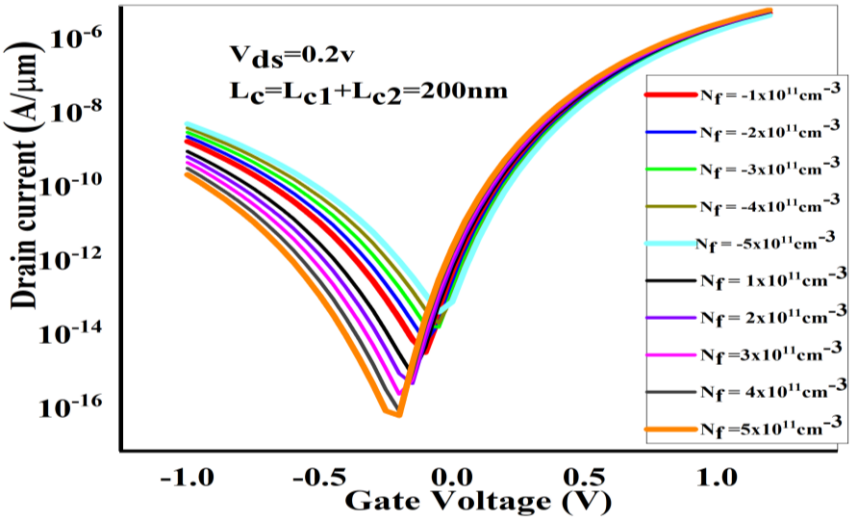


Figure 4.10 Energy-band profiles of conventional double gate full both side cavity-tunnel field effect transistors (DG-FBSC-TFEF)

The energy band diagram for double gate-FBSC-TFET based biosensor shown on fig.4.10. As we have seen in the above graph on increasing the dielectric constant the tunneling barrier is decreased. The band diagram is made at V_{gs}=-1v and V_{ds}=0.2v due to which the source channel junction tunneling not possible.



(a)



(b)

Figure 4.11 (a) Effect of Dielectric Constant (k), and (b) Impact of Positive charge and negative Charge biomolecules, on transfer characteristics of DG_FBSC_TFET at k=5.

The orientation of low-k biomolecules boosts or lowers the sensitivity of dielectric modulation-based biosensors, depending on whether the material is n-type or p-type under the nanogap applied to immobilize the biomolecules (Ahangari, 2016). We have seen on the graph that, ambipolar current varying (I_A) improves dramatically on both charged biomolecules as the dielectric constant rises from unity to a larger value seen on figure 4.11. As the positive charge density increases, the ambipolar current decreases. From fig.4.11 (a) graph has low ambipolar current is Occurred at k=3 ($1.77454x10^{-11}$ A/μm) for neutral biomolecules. From figure 4.11(b), we found that for DG_FBSC_TFET as charged biomolecules immobilization increases the ambipolar current is decreasing on increasing the charge value.

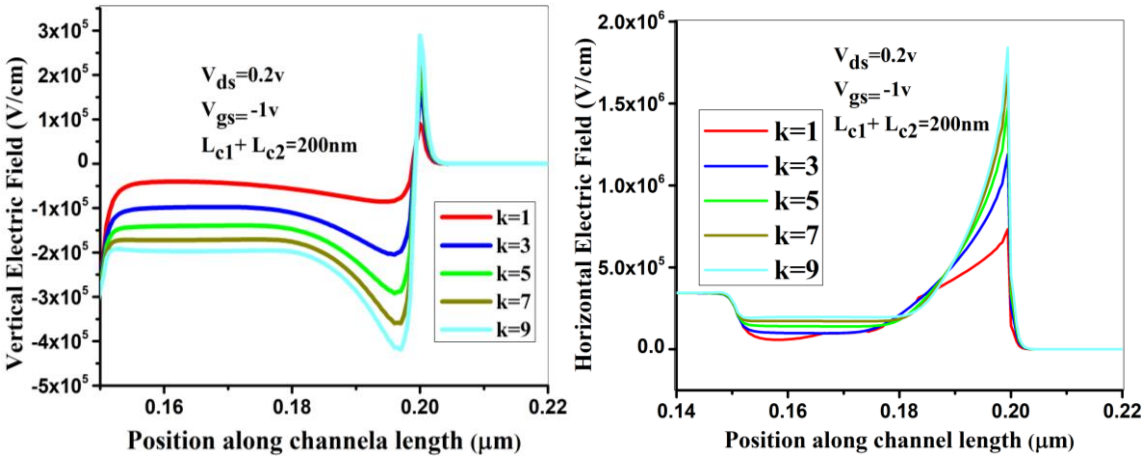


Figure 4.12 (a) Vertical Electric Field (b) Horizontal Electric Field along, x axis for DG-FBSC-TFET

The ratio between the ambipolar current (I_A) at k=x and the (I_A) at k=1 is used to compute the sensitivity. When the dielectric constants of biomolecules increase, as illustrated in the graph below, the sensitivity increases significantly. The sensitivity of the DG-FBSC-TFET rises approximately linearly as the dielectric constant of the biomolecule increases, indicating a significant advancement in the field of biosensors.

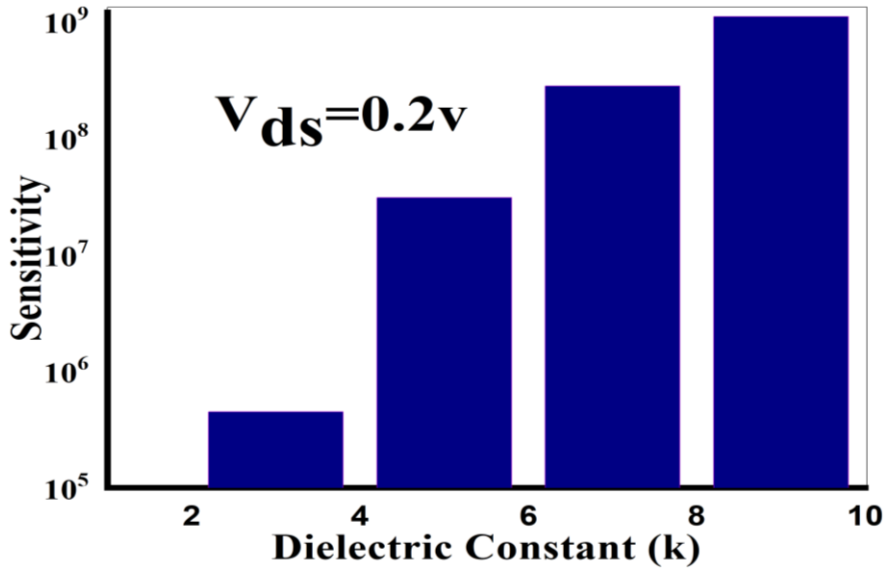


Figure 4.12 Sensitivity of DG-FBSC-TFET at V_{GS}=-1v and V_{DS} =0.2v

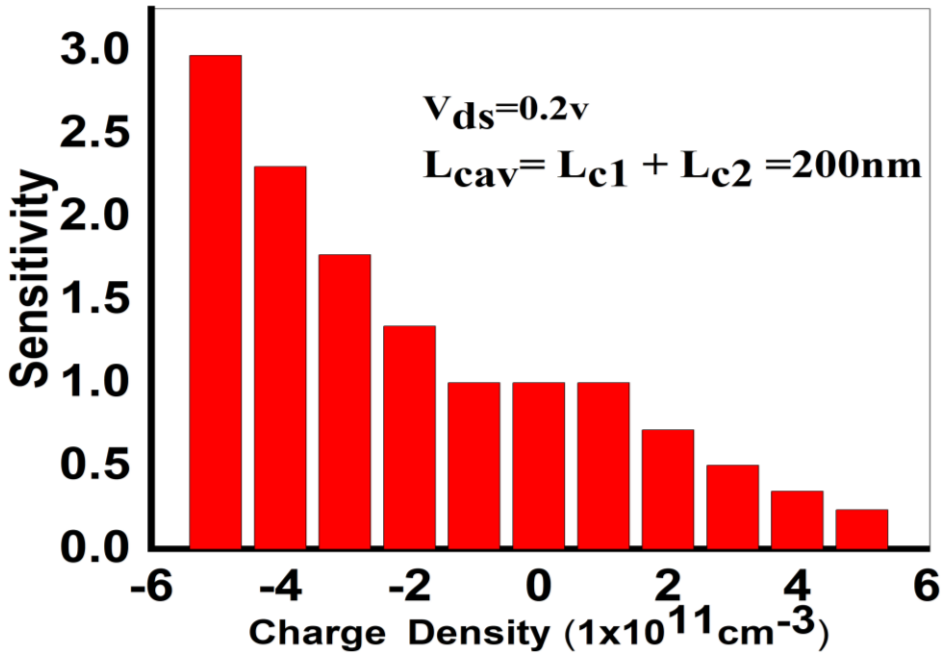


Figure 4.13 Sensitivity (charge) versus Charge Density for DG_FBSC_TFET

On figure 4.13 we have calculated the sensitivity related to the charge density for DG_FBSC_TFET. In this graph it is observed that when we are increasing the charge values from -5 x10^{11} cm^{-3} to 5 x$10^{11}$$cm^{-3}$ the related sensitivity is decreasing.

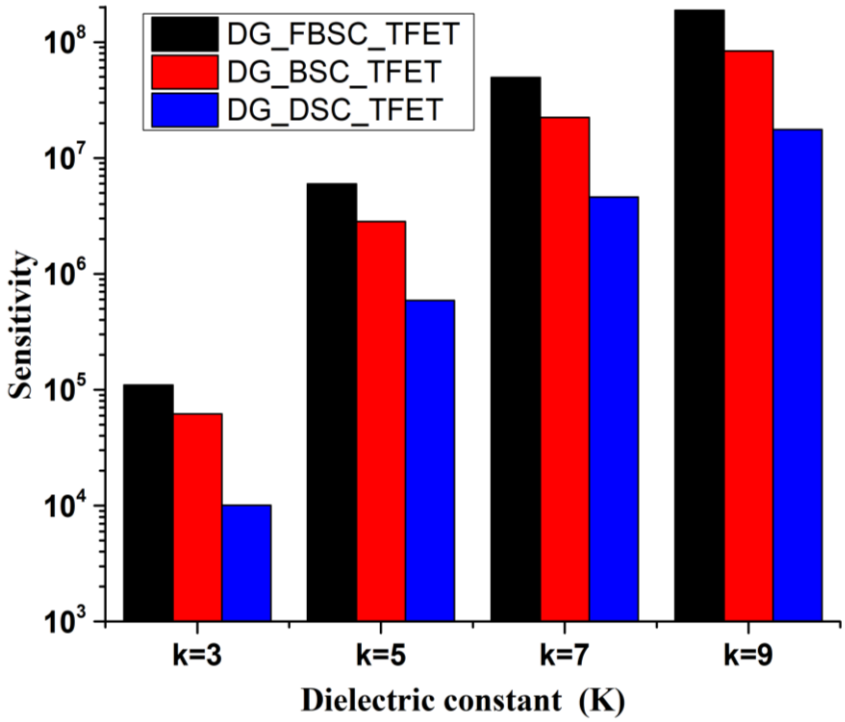


Figure 4.14 Sensitivity Comparison between three proposed structures i.e., DG_BSC_TFET, DG_DSC_TFET and DG_FBSC_TFET

Out of them one is sensitivity, as we have already defined that we are using the ambipolar current as the sensitivity parameter and in figure 4.14 the comparison between the three proposed structures are given in the form of bar diagram. Out of them three structures the sensitivity of DG_FBSC_TFET is best for all the neutral biomolecules. This is due to the fact that volume to surface ratio in this structure is more compare to the other structures.AS for K=5 the Sensitivity of FBSC structure is two folds (10^2) more than DSC structure. Table 4.1 shows the impact of charged biomolecules immobilization in the cavity region on the ambipolar current ,sensitivity of the biosensor and the ON-current to OFF-current ratio for the three proposed structures which we have discussed in the previous chapters . The table specified the biomolecule which have charge N_f=-1x10^{11} cm^{-3} and N_f=1x10^{11} cm^{-3} for the varying k values. As shown in table the sensitivity increases as the effective dielectric constant of the nano-gap increase due to the presence of the biomolecules.

From the tubular comparison among three proposed structures for biosensor application, the DG-FBSC-TFET found to be better option. DG-FBSC-TFET also shows better sensitivity and improved ambipolar current when compared with both DG-BSC-TFET and DG-DSC-TFET for biosensor application. The major advantage in the DG_FBSC_TFET structure is it has more volume to surface area due to which the more area comes into contact of the neutral ad charged biomolecules.

Table 4.1 Optimization of electrical parameters determined for our planned DG-TFET work

S.No.	Parameters	DG-FBSC-TFET	DG-BSC-TFET	DG-DSC-TFET	
		$K=5, N_f = -1x10^{11}cm^{-3}$			
1	I_{ON}	$6.204x10^{-6}$	$4.28x10^{-6}$	$5.85x10^{-6}$	A/μm
2	I_{OFF}	$2.98x10^{-14}$	$2.5916x10^{-14}$	$3.97x10^{-14}$	
3	I_{ON}/I_{OFF}	$2.0818x10^{8}$	$1.6514x10^{8}$	$0.717x10^{8}$	
4	Ambipolar current (I_{amb})	$1.69x10^{-9}$	$5.049x10^{-9}$	$9.38x10^{-9}$	
	$K=5, N_f = 1x10^{11}cm^{-3}$				
	I_{ON}	$7.27x10^{-6}$	$8.47x10^{-6}$	$7.70x10^{-6}$	A/μm
	I_{OFF}	$6.739x10^{-16}$	$9.612x10^{-16}$	$9.98x10^{-16}$	
	I_{ON}/I_{OFF}	$1.078x10^{10}$	$0.88x10^{10}$	$0.715x10^{10}$	
	Ambipolar current (I_{amb})	$1.60x10^{-10}$	$1.9117x10^{-9}$	$2.026x10^{-9}$	

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this thesis work we have simulated and analyzed dielectric engineered Tunnel Field Effect Transistor (TFET) for biosensing applications. Three Different proposed structures i.e., Double Gate Both side Cavity TFET, Double Gate Full both side Cavity TFET and Double Gate Drain side cavity TFET were discussed. All the simulations were done in ATLAS TCAD from SILVACO. We used the Kane model of tunneling to realize the band to band tunneling in all the simulations. The immobilization of the biomolecules in the cavity regions realize using the variation in dielectric constant and charge density. Further the energy band diagram, horizontal and vertical electric fields, transfer characteristics are observed to finally calculate the ambipolar current sensitivity, and I_{ON}/I_{OFF} ratio. The sensitivity and ambipolar current of the three proposed sensor are compared. The sensitivity of the DG-FBSC-TFET sensor is relatively high, which is very suitable for applications in the field of ultra-sensitivity, low consumption biosensors. DG-FBSC-TFET also shows better sensitivity and improved ambipolar current when compared with both DG-BSC-TFET and DG-DSC-TFET for biosensor application. The major advantage in the DG_FBSC_TFET structure is it has more volume to surface area due to which the more area comes into contact of the neutral ad charged biomolecules. Therefore, DG-FBSC-TFET sensor have insightful development potential and market views for future low power biosensors.

5.2 Recommendations

Due to increasing demand of label free biosensors, huge investment have been done into research worldwide, more specifically, for healthcare based sensors and their applications. Because of this academia comes near to the industry in order to provide commercially viable products. Biosensors aimed as a more practical devices to be used to detect the biomolecules. As a result, there are not addressed mandatory points concerning the development of a commercial biosensor have to be focused, such as:

- Finding of the market place that is much interested in a specific biosensor for a particular biomolecules interest.
- Advantages over other existing biosensors.
- Disease based biosensor have to be developed
- Biosensor Testing and performance have to check in timely manner.

- Costs Stability and easy process of manufacturing are the important merits of the biosensor.

6. REFERENCES

Ahangari, Z. (2016). Performance assessment of dual material gate dielectric modulated nanowire junctionless MOSFET for ultrasensitive detection of biomolecules. RSC Advances, 6(92), 89185–89191. https://doi.org/10.1039/c6ra17361f

Ahn, J. H., Choi, S. J., Han, J. W., Park, T. J., Lee, S. Y., & Choi, Y. K. (2011). Investigation of size dependence on sensitivity for nanowire FET biosensors. IEEE Transactions on Nanotechnology, 10(6), 1405–1411. https://doi.org/10.1109/TNANO.2011.2157519

Anand, S., Singh, A., Amin, S. I., & Thool, A. S. (2019). Design and Performance Analysis of Dielectrically Modulated Doping-Less Tunnel FET-Based Label Free Biosensor. IEEE Sensors Journal, 19(12), 4369–4374. https://doi.org/10.1109/JSEN.2019.2900092

ATLAS Device Simulation Software Santa Clara CA USA:Silva... - Google Scholar. (n.d.). Retrieved March 31, 2022, from https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=ATLAS+Device+Simulation+Software+Santa+Clara+CA+USA%3ASilvaco+Int.+2016.&btnG=

Biosensor, D. M. T., Verma, M., Tirkey, S., Yadav, S., Sharma, D., & Yadav, D. S. (2017). Performance Assessment of A Novel Vertical. 1–8.

Chong, C., Liu, H., Wang, S., & Chen, S. (2021). Simulation and Performance Analysis of Dielectric Modulated Dual Source Trench Gate TFET Biosensor. Nanoscale Research Letters, 16(1). https://doi.org/10.1186/s11671-021-03486-2

Chong, C., Liu, H., Wang, S., Chen, S., & Xie, H. (2020). micromachines Sensitivity Analysis of Biosensors Based on a Dielectric-Modulated L-Shaped Gate Field-Effect Transistor. https://doi.org/10.3390/mi1201

Chong, C., Liu, H., Wang, S., Chen, S., & Xie, H. (2021). Sensitivity analysis of biosensors based on a dielectric-modulated l-shaped gate field-effect transistor. Micromachines, 12(1), 1–10. https://doi.org/10.3390/mi12010019

Kanungo, S., Chattopadhyay, S., Gupta, P. S., & Rahaman, H. (2015). Comparative performance analysis of the dielectrically modulated full- gate and short-gate tunnel FET-based biosensors. IEEE Transactions on Electron Devices, 62(3), 994–1001. https://doi.org/10.1109/TED.2015.2390774

Li, C., Liu, F., Han, R. U., & Zhuang, Y. (2021). A Vertically Stacked Nanosheet Gate-All-Around FET for Biosensing Application. 9.

https://doi.org/10.1109/ACCESS.2021.3074906

Mani, A. P., Engineering, C., John, S. K., Engineering, C., Ravindran, A., Engineering, C., Varghese, A., Engineering, C., & Engineering, C. (2015). Comparative Study of Silicon and Germanium Doping-less Tunnel Field Effect Transistors. 2(5), 144–149.

Mehrotra, P. (2016). Biosensors and their applications – A review. Journal of Oral Biology and Craniofacial Research, 6(2), 153–159. https://doi.org/10.1016/J.JOBCR.2015.12.002

Mendiratta, N., & Tripathi, S. L. (2020). A review on performance comparison of advanced MOSFET structures below 45 nm technology node. Journal of Semiconductors, 41(6). https://doi.org/10.1088/1674-4926/41/6/061401

Moon, D. Il, Han, J. W., & Meyyappan, M. (2016). Comparative Study of Field Effect Transistor Based Biosensors. IEEE Transactions on Nanotechnology, 15(6), 956–961. https://doi.org/10.1109/TNANO.2016.2615855

Reddy, N. N., & Panda, D. K. (2021). A Comprehensive Review on Tunnel Field-Effect Transistor (TFET) Based Biosensors: Recent Advances and Future Prospects on Device Structure and Sensitivity. Silicon, 13(9), 3085–3100. https://doi.org/10.1007/s12633-020-00657-1

Sadighbayan, D., Hasanzadeh, M., & Ghafar-zadeh, E. (2020). Trends in Analytical Chemistry Biosensing based on fi eld-effect transistors (FET): Recent progress and challenges. Trends in Analytical Chemistry, 133, 116067. https://doi.org/10.1016/j.trac.2020.116067

Samuel, T. S. A., Balamurugan, N. B., Sibitha, S., Saranya, R., Vanisri, D., Arun Samuel, T. S., Balamurugan, N. B., Sibitha, S., Saranya, R., Vanisri, D., Samuel, T. S. A., Balamurugan, N. B., Sibitha, S., Saranya, R., Vanisri, D., Arun Samuel, T. S., Balamurugan, N. B., Sibitha, S., Saranya, R., … Vanisri, D. (2013). Analytical Modeling and Simulation of Dual Material Gate Tunnel Field Effect Transistors. J Electr Eng Technol, 8(6), 1481–1486. https://doi.org/10.5370/JEET.2013.8.6.1481

Sang, S., Wang, Y., Feng, Q., Wei, Y., Ji, J., & Zhang, W. (2015). Progress of new label-free techniques for biosensors : a review. Critical Reviews in Biotechnology, 00(00), 1–17. https://doi.org/10.3109/07388551.2014.991270

Singh, D., Pandey, S., Nigam, K., Sharma, D., Yadav, D. S., & Kondekar, P. (2017). A charge-plasma-based dielectric-modulated junctionless TFET for biosensor label-free detection. IEEE Transactions on Electron Devices, 64(1), 271–278. https://doi.org/10.1109/TED.2016.2622403

Syu, Y.-C., Hsu, W.-E., & Lin, C.-T. (2018). Review—Field-Effect Transistor Biosensing: Devices and Clinical Applications. ECS Journal of Solid State Science and Technology, 7(7), Q3196–Q3207. https://doi.org/10.1149/2.0291807jss

Tahi, I., Rezaie, M. N., & Article, R. (2018). Design and Simulation of InP and Silicon Nanowires With Different Channel Characteristic as Biosensors to Improve Output Sensitivity. 0–24.

Tamak, P., & Mehra, R. (2017). Review on Tunnel Field Effect Transistors (TFET). International Research Journal of Engineering and Technology(IRJET), 4(7), 1195–1200. https://irjet.net/archives/V4/i7/IRJET-V4I7265.pdf

Venkatesh, P., Nigam, K., Pandey, S., Sharma, D., & Kondekar, P. N. (2017). A dielectrically modulated electrically doped tunnel FET for application of label free biosensor. Superlattices and Microstructures, 109, 470–479. https://doi.org/10.1016/j.spmi.2017.05.035

Verma, M., Tirkey, S., Yadav, S., Sharma, D., & Yadav, D. S. (2017). Performance Assessment of A Novel Vertical Dielectrically Modulated TFET-Based Biosensor. IEEE Transactions on Electron Devices, 64(9), 3841–3848. https://doi.org/10.1109/TED.2017.2732820

Wang, C., Wu, C. L., Wang, J. X., Huang, Q. Q., & Huang, R. (2015). Analytical current model of tunneling field-effect transistor considering the impacts of both gate and drain voltages on tunneling. Science China Information Sciences, 58(2), 1–8. https://doi.org/10.1007/s11432-014-5196-3

Zhang, M., Guo, Y., Zhang, J., Yao, J., & Chen, J. (2020). Simulation Study of the Double-Gate Tunnel Field-Effect Transistor with Step Channel Thickness. Nanoscale Research Letters, 15(1). https://doi.org/10.1186/s11671-020-03360-7