B. TECH. PROJECT REPORT

On

Design, Simulation and Optimization of Transistor Based Sensors

BY

REENA MEENA

DISCIPLINE OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY INDORE

December 2018

Design, Simulation and Optimization of Transistor Based Sensors

A PROJECT REPORT

Submitted in partial fulfillment of the requirements for the award of the degrees

of

BACHELOR OF TECHNOLOGY

in

ELECTRICAL ENGINEERING

Submitted by:
Reena Meena

Guided by:
Prof. Abhinav Kranti
Discipline of Electrical Engineering

Indian Institute of Technology Indore

INDIAN INSTITUTE OF TECHNOLOGY INDORE
December 2018

CANDIDATE'S DECLARATION

I hereby declare that the project entitled **"Design, Simulation and Optimization of Transistor Based Sensors"** submitted in partial fulfillment for the award of the degree of Bachelor of Technology in Electrical Engineering completed under the supervision of **Prof. Abhinav Kranti**, Discipline of Electrical Engineering, IIT Indore is an authentic work.

Further, I declare that I have not submitted this work for the award of any other degree elsewhere.

Reena Meena

CERTIFICATE by BTP Guide(s)

It is certified that the above statement made by the students is correct to the best of my/our knowledge.

Prof. Abhinav Kranti

Discipline of Electrical Engineering

IIT Indore

Preface

This report on **"Design, Simulation and Optimization of Transistor based Sensors"** is prepared under the guidance of **Prof. Abhinav Kranti,** Discipline of Electrical Engineering, IIT Indore.

Through this report I have tried to give detailed design of a Dielectric Modulated Field Effect Transistor (DMFET) based sensors while covering significant aspect of the biosensor design. I have tried to the best of my abilities and knowledge to explain the content in a lucid manner. I have also added graphs and figures to make it more illustrative. The simulated results shown in the report are obtained using TCAD simulation software (ATLAS from SILVACO Inc.).

Reena Meena

B.Tech. (IV Year)
Discipline of Electrical Engineering
IIT Indore

Acknowledgements

I would like to acknowledge IIT Indore for providing all necessary research infrastructures required for undertaking the project.

I would like to express my sincere and deepest gratitude to my final year B.Tech. project supervisor, Prof. Abhinav Kranti, for his continuous support and valuable guidance.

I would also like to take this opportunity to thank Mr. Manish Gupta and Ms. Nivedita Jaiswal, Ph.D. scholars in Low Power Nanoelectronics Research Group, Discipline of Electrical Engineering, IIT Indore. It was their kind support that helped me to learn the fundamentals required for this project. Without their guidance and support, this work would not have been completed.

I am thankful to all the members of the Low Power Nanoelectronics Research Group, Discipline of Electrical Engineering, IIT Indore for their support and encouragement during the work of B.Tech. project

Reena Meena

B.Tech. (IV Year)
Discipline of Electrical Engineering
IIT Indore

Abstract

The Field Effect Transistor (FET) based sensors offer various advantages such as miniaturization, the possibility for label-free electrical detection, high sensitivity and compatibility with traditional CMOS fabrication processes. Embedding a nanogap in a traditional Metal-Oxide-Semiconductor FET (MOSFET) structure is recently realized as a new type of FET biosensor, referred to as Dielectric Modulated Field Effect Transistor (DMFET), which detects targeted biomolecules that are confined in the nanogap according to changes in electrical parameters, such as the threshold voltage. This report presents the simulation based design and optimization of a DMFET biosensor. This biosensor design is used to detect the specific binding between the biomolecules Streptavidin (protein) and Biotin (ligand) over the Self Assembled Monolayer (SAM). The different biomolecules (streptavidin, biotin and SAM) in the nanogap cavity is replaced by insulator with dielectric constants of 2.1, 2.63 and 3.5, respectively. A shift of the threshold voltage is used as a parameter to ascertain the sensitivity after the biomolecule interacts with the DMFET. The effect on the sensing parameter of the DMFET biosensor with gate length and cavity length downscaling are analyzed. The impact of partially filled cavity length is investigated to comprehend the sensing performance of a real-time DMFET biosensor. Hence, this report can provide a useful guideline for the optimal design of a DMFET biosensor.

Table of Content

List of Figures

Fig 3.2.3(b) Case B (SAM+Biotin): Electron Concentration diagram vs Distance along the device (X axis) at V_{gs}=1.5V

Fig 3.2.3(c) Case A (SAM+Biotin+Streptavidin): Electron Concentration (along Y axis) vs Distance along the device(X axis) at V_{gs} = 1.5V

Fig 4.1(a) Transfer characteristics in semi-logarithmic scale at V_{ds} = 50 mV when biomolecules are introduced in the cavity for L_g = 1000 nm and L_{cavity} = 400 nm

Fig 4.1(b) Transfer characteristics in semi-logarithmic scale at V_{ds} = 50 mV when biomolecules are introduced in the cavity for L_g = 1000nm and L_{cavity} = 200nm

Fig 4.1(c) Transfer characteristics Of MOSFET in semi-logarithmic scale at V_{ds} = 50 mV when biomolecules are introduced in cavity for L_g =500nm and L_{cavity} = 200nm

Fig 4.2(a) When (SAM layer+ Biotin + Streptavidin) is inserted fully along the cavity length

Fig 4.2(b) When (SAM layer+ Biotin + Streptavidin) is introduced half-length along the cavity length towards middle of the gate.

Fig4.2(c) When (SAM layer+ Biotin + Streptavidin) is introduced half-length along the cavity length towards source/drain sides.

Fig 4.2(d) Transfer characteristics of MOSFET in semi-logarithmic scale at V_{ds} = 50mV when cavity is partially-filled and fully-filled as well as by exchanging the position of biomolecules in the cavity keeping parameters L_g = 1000nm and L_{cavity} = 400nm.

List of Tables

Chapter-1

Introduction

1.1 MOTIVATION:-

INTEREST in the use of a field-effect transistor (FET) for a range of biosensors has increased recently due to the numerous advantages that are achievable with such a design. These include miniaturization; the possibility for label-free electrical detection; high sensitivity; compatibility with traditional CMOS fabrication processes. A large number of FET-type biosensors have been investigated in research related to nanowire FETs, ion-selective FETs, carbon nanotube FETs, extended-gate FETs and many other types. Embedding a nanogap in a traditional metal–oxide–semiconductor FET (MOSFET) structure was recently realized as a new type of biosensor based on FET technology. This nanogap-embedded FET structure detects targeted biomolecules that are confined in the nanogap according to changes in electrical parameters, such as the threshold voltage.

The first demonstrated nanogap-embedded FET, which is termed dielectric-modulated FET (DMFET), uses the shift of the threshold voltage as the biomolecular sensing parameter. It includes a nanogap between the gate and gate oxide. The nanogap was created by carving some parts of the sacrificial layer preexisting between the gate and gate oxide.When biomolecules filled the nanogap,the threshold voltage V_T shifted due to the change of the dielectric constant K from unity, corresponding to air, to a certain number (K>1), corresponding to the biomolecules. Owing to this characteristic, the aforementioned FET was termed a DMFET. For MOSFET as a DMFET biosensor, optimization of the device dimensions to achieve high shift in threshold voltage is needed. For MOSFET to work as a DM biosensor, the dielectric-modulation effect as a result of mutual interaction between the biomolecules and the transistor is required. Therefore, the present project deals with the simulation based optimization of a MOSFET as a DMFET biosensor with different layers of biomolecules in a real time scenario. In this study, as a sensing parameter in the DMFET biosensor, the shift of the threshold voltage (ΔV_T) between empty cavity (air) and different biomolecule layers are used.

1.2 MOSFET:-

A metal–oxide–semiconductor field-effect transistor (MOSFET) is a field-effect transistor (FET with an insulated gate) where the gate voltage determines the conductivity of the device. It is a four-terminal device with source(S), gate (G), drain (D) and body (B) terminals. The body is frequently connected to the source terminal, reducing the terminals to three. It works by varying the width of a channel along which charge carriers flow (electrons or holes).The charge carriers enter the channel at source and exit via the drain. The width of the channel is controlled by the voltage on an electrode is called gate which is located between source and drain. It is insulated from the channel near an extremely thin layer. It is used for switching or amplifying signals. The ability to change conductivity with the amount of applied voltage can be used for amplifying or switching electronic signals. MOSFETs are now even more common than BJTs (bipolar junction transistors) in digital and analog circuits. MOSFET is by far the most common transistor in digital circuits, as hundreds of thousands or millions of them may be included in a memory chip or microprocessor. Since they can be made with p-type or n-type semiconductors, complementary pairs of MOS transistors can be used to make switching circuits with very low power consumption, in the form of CMOS logic.

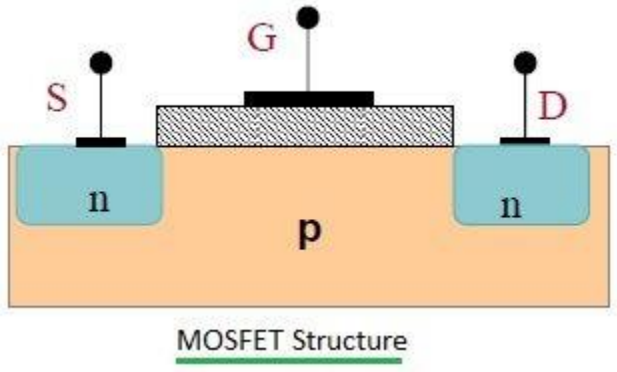

Fig 1.2(a) MOSFET structure

1.2.1 Why MOSFET?

MOSFETs are particularly useful in amplifiers due to their input impedance being nearly infinite which allows the amplifier to capture almost all the incoming signal. The main advantage is that it requires almost no input current to control the load current, when compared with bipolar transistors.

MOSFETs are available in two basic forms:-

- Depletion Type: The transistor requires the Gate-Source voltage (V_{GS}) to switch the device "OFF". The depletion mode MOSFET is equivalent to a "Normally Closed" switch.
- Enhancement Type: The transistor requires a Gate-Source voltage (V_{GS}) to switch the device "ON". The enhancement mode MOSFET is equivalent to a "Normally Open" switch.

1.2.2 MOSFET Operation:-

The working of a MOSFET depends upon the MOS capacitor. The MOS capacitor is the main part of MOSFET. The semiconductor surface at the below oxide layer which is located between source and drain terminals. It can be inverted from p-type to n-type by applying positive or negative gate voltages.

When we apply positive gate voltage the holes present under the oxide layer with a repulsive force and holes are pushed downward with the substrate. The depletion region populated by the bound negative charges which are associated with the acceptor atoms. The electrons reach channel is formed. The positive voltage also attracts electrons from the n+ source and drain regions into the channel. Now, if a voltage is applied between the drain and source, the current flows freely between the source and drain and the gate voltage controls the electrons in the channel. If we apply negative voltage, a hole channel will be formed under the oxide layer.

P-Channel MOSFET:-

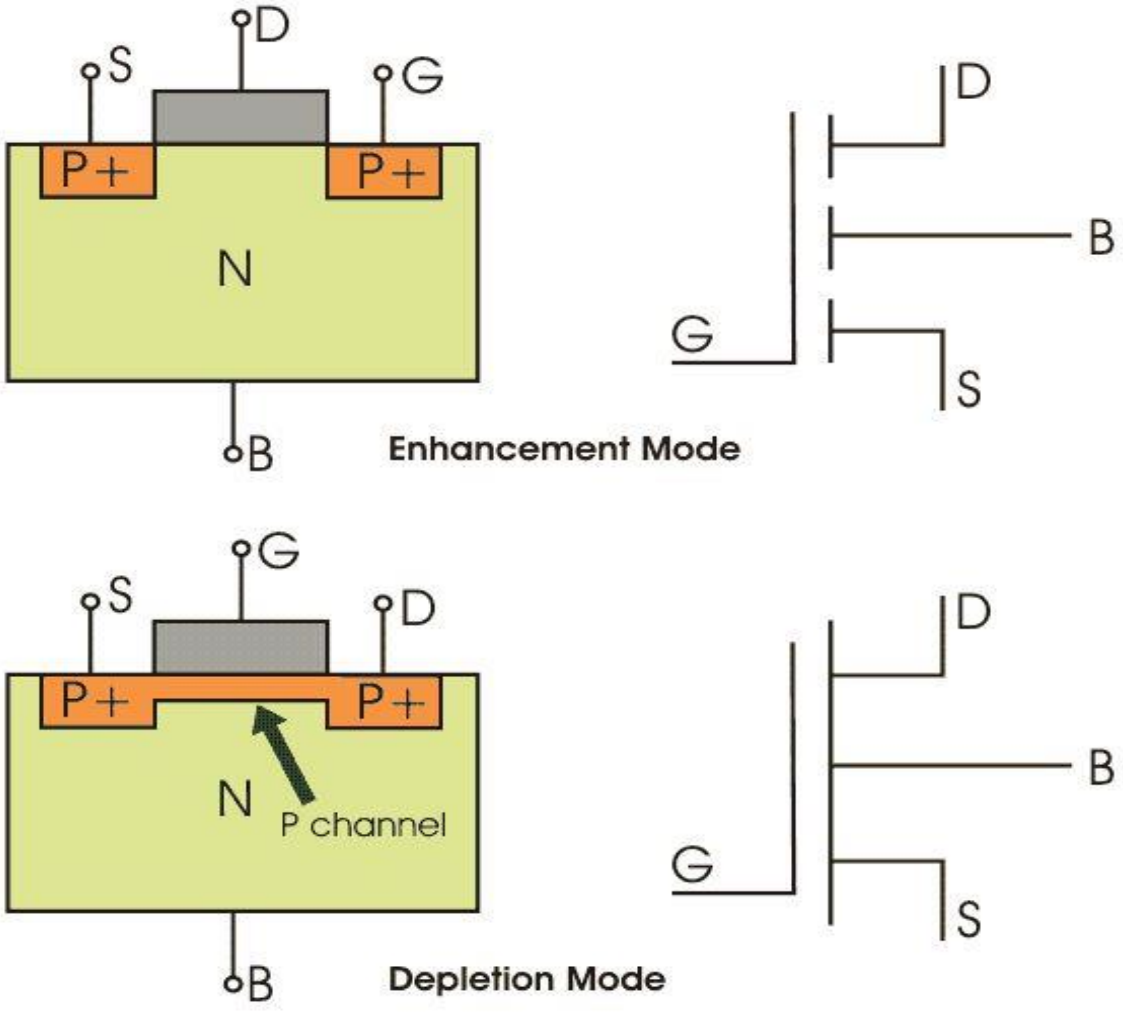

Fig 1.2.2(a) P-Channel MOSFET

The drain and source is heavily doped p+ region and the substrate is in n-type. The current flows due to the flow of positively charged holes also known as p-channel MOSFET. When we apply negative gate voltage, the electrons present beneath the oxide layer experience repulsive force and they are pushed downward in to the substrate, the depletion region is populated by the bound positive charges which are associated with the donor atoms. The negative gate voltage also attracts holes from p+ source and drain region into the channel region.

N-Channel MOSFET:-

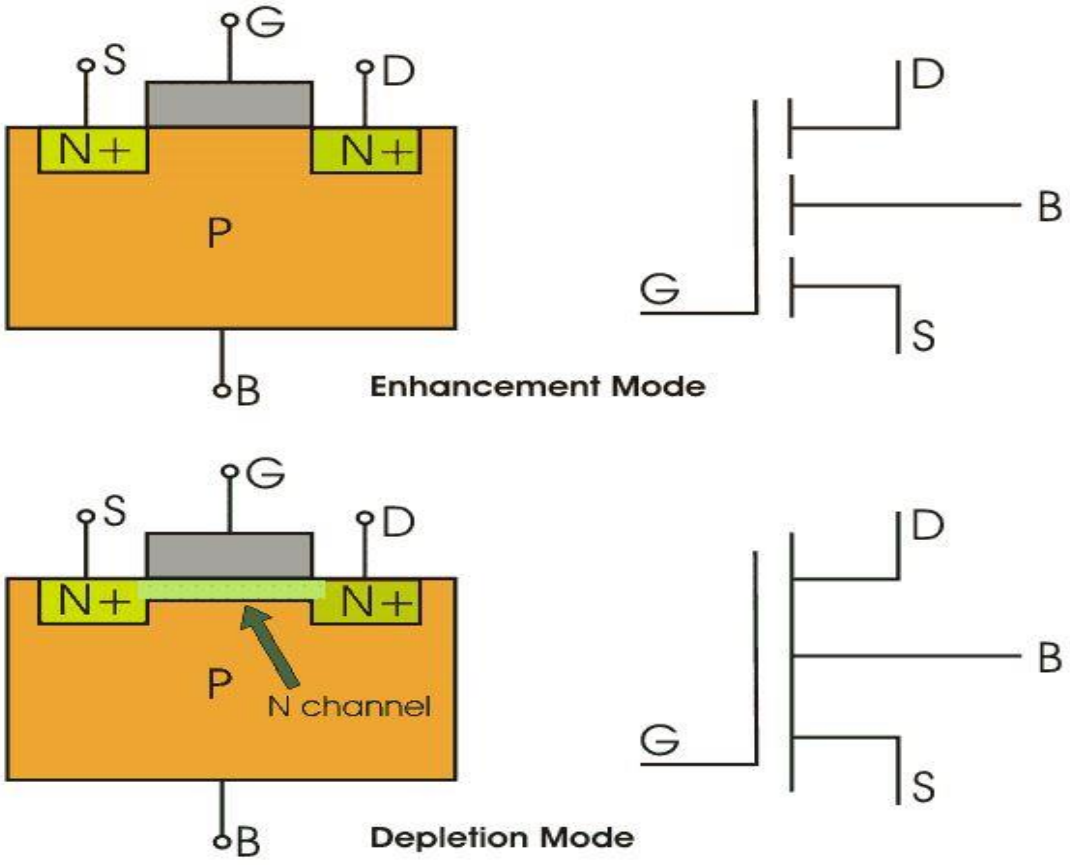

Fig 1.2.2(b) N Channel MOSFET

The drain and source is heavily doped n+ region and the substrate is p-type. The current flows due to the flow of negatively charged electrons, also known as n-channel MOSFET. When we apply the positive gate voltage the holes present beneath the oxide layer experience repulsive force and the holes are pushed downwards in to the bound negative charges which are associated with the acceptor atoms. The positive gate voltage also attracts electrons from n+ source and drain region into the channel.

Chapter-2

MOSFET based Biosensor

2.1 MOSFET AS BIOSENSORS:-

Electrical biosensors rely solely on the measurement of currents and/or voltages to detect binding of biotarget to bioreceptor. For detecting biotarget (biomolecules) that are invisible to the human eye or nose, the biosensing devices must have feature sizes comparable to the biomolecule, be compact and provide a sufficient level of sensitivity often to a small biomolecules that are just a few nanometres in size. Due to the progressive downscaling of MOSFET to nanometer regime makes MOSFET an attractive choice for biosensing applications. In a number of reported FET biosensors, surface interactions with biomolecules in solution affect the operation of the gate or the channel. However, these devices often have limited sensitivity. Recently, electrical detection through nanogap cavity FET biosensors have emerged as a powerful technique for detecting small size or quantities of biomolecules through nanogap cavity embedded on gate region and offers high sensitivity. Nanosized biomolecules can be trapped into a nanogap which in turn changes the gate capacitance, and therefore, can be detected by observing the change in electrical behavior of MOSFET. A wealth of research is available discussing planar and vertical nanogap devices for biosensing applications.

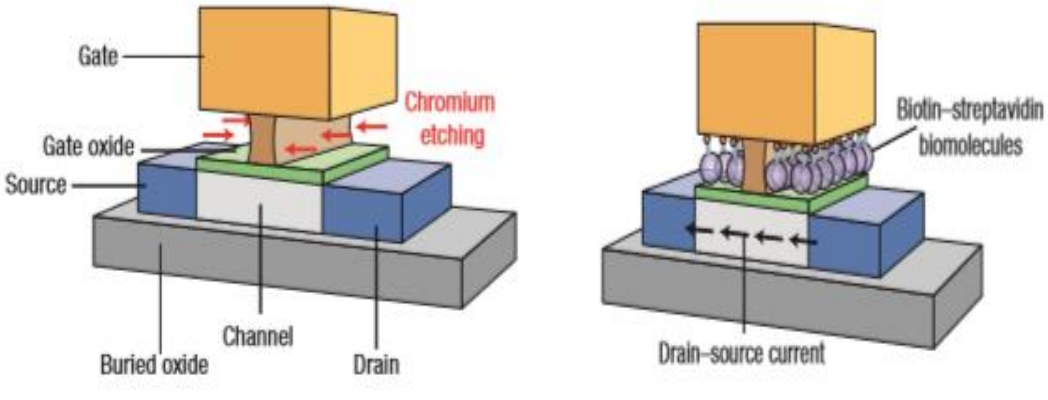

Fig 2.1 Schematic of a field-effect transistor (FET) for biomolecule sensing FET.

2.1.1 Planar Nanogap Devices for Biosensing:-

Label-free biosensing

Planar nanogap can be defined as both electrodes face each other horizontally in the device configuration Fig.2.1.1(a). A nanogap was fabricated in which two polysilicon electrodes were separated from each other by 50-100 nm. Immobilized within each nanogap is a single strand of reference DNA. A voltage is then applied across the nanogap and a measurement is taken of the capacitance, and this is determined by the dielectric (insulating) property of the material in the nanogap, which changes as a result of hybridization.

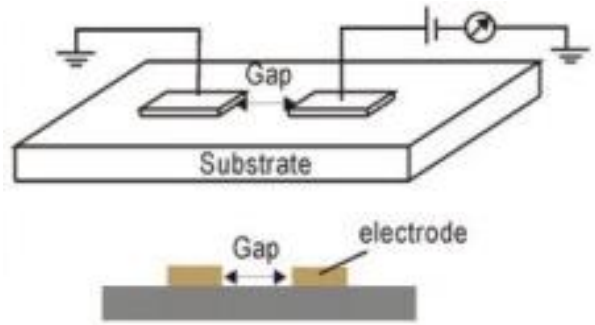

Fig 2.1.1(a) Label-free planar nanogap devices for biosensing.

Carbon nanotube nanogap devices for biosensing

Electronic devices based on carbon nanotubes (CNTs) are among the candidates to eventually replace silicon-based devices for biomolecular sensing applications. However, one of the greatest challenges in CNTs molecular electronics is the ill-defined bonding between molecules and metal electrodes. To eliminate this drawback, CNT-based FET (field-effect transistor) sensors can be replaced by such an improved strategy, in which a cut SWCNT with a sub-10 nm gap to be used as source (S) and drain (D) electrodes of a molecular electronics. The target molecule is covalently immobilized in a narrow gap between carbon nanotube electrodes.

After this insertion, the electric conductance across the electrodes increased, thus revealing the presence of the target. All of the elements in the resulting molecular circuits are naturally at small dimensions because the SWCNTs are one-dimensional conductors or semiconductors that are intrinsically the same size as the molecules being probed.

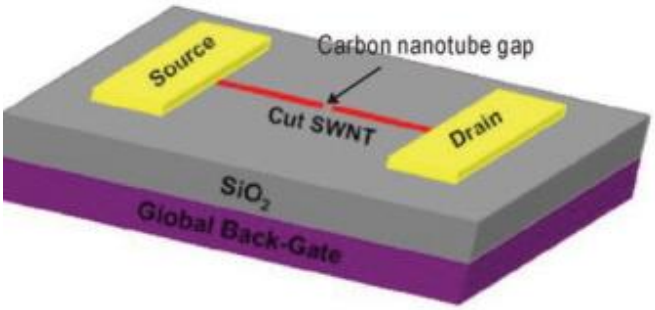

Fig. 2.1.1(b) Showing the carbon nanotube nanogap biosensor

2.1.2 Vertical Nanogap Devices for Biosensing:-

Nanogap device with three terminals

In the design of vertical nanogap, both electrodes are vertically situated in perpendicular direction. In a typical FET device, electric current flows between the source and drain electrodes when the voltage applied to the gate exceeds a threshold voltage (V_T). V_T is determined primarily by the gate capacitance between the gate electrode and the channel, and hence one can modulate V_T by changing the dielectric material of the gate. When biomolecules are introduced into the nanogap, they increase the gate capacitance relative to the air gap, and V_T shifts in the negative direction. Thus, by monitoring the change in V_T, it is possible to detect the specific binding of streptavidin to biotin**.** On the basis of this mechanism, Choi and co-workers suggested that a dielectric-modulated field-effect transistor (DMFET) for biosensing based on change in dielectric constant caused by the introduction of biomolecules in a nanogap located at the edge of the gate dielectric in the DMFET**.**

2.1.3 DMFET Device Structure and Dimensions:-

Parameter	**Symbol**	**Value**
Gate length	L_g	1000nm
Silicon film doping	N_A	10^{17} cm^{-3}
S/D doping	N_D	10^{20} cm^{-3}
Channel thickness	t_s	50nm
Gate oxide thickness	t_{ox}	10nm
Nanogap length	L_{cavity}	400nm
Nanogap thickness	T_{cavity}	15nm
Buried oxide thickness	t_b	300nm
Gate 1 workfunction	Φ_1	5.1V (for Au)
Gate 2 workfunction	Φ_2	4.5V (for Cr)

Biomolecule layers	**Dielectric Constant(K)**	**Thickness(nm)**
Air	1	15nm
Self Assembled Monolayer (SAM)	3.57	2nm
Biotin	2.63	3nm
Streptavidin	2.1	7nm

- The silicon body of the DMFET, consisting of the channel and source and drain electrodes, was formed on a p-doped silicon-on-insulator (SOI) wafer.

- The starting material was a p-doped SOI wafer, with 300nm layer of buried oxide and a 50nm layer silicon body on the buried oxide.
- A 10-nm layer of silicon oxide was grown on the active silicon area to form the gate oxide, followed by 15 nm of chromium and 20nm of gold to form the gate electrode.
- The chromium was wet-etched to carve out a 15-nm vertical nanogap underneath the gold layer.
- The length of the nanogap, which defines how deep the channel is etched on either side, varied between 100 and 400nm.

- **When the nanogap cavity is empty (filled with air):**

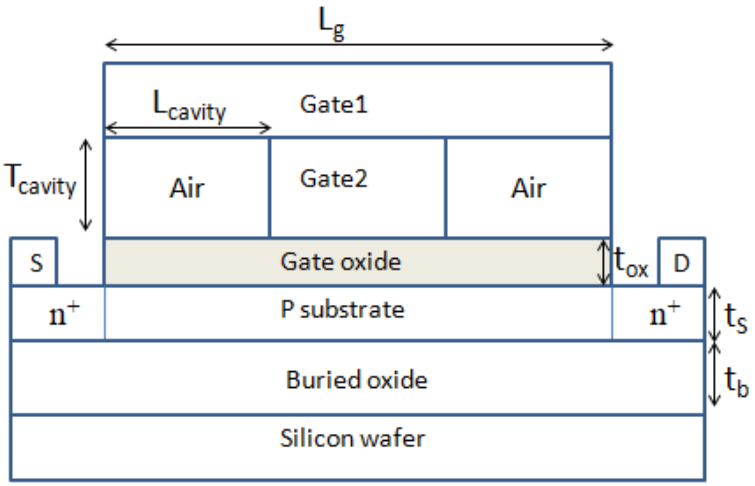

Fig 2.1.3(a) Basic structure of MOSFET when cavity is empty

- **When Biomolecules are introduced in the nanogap cavity:-**

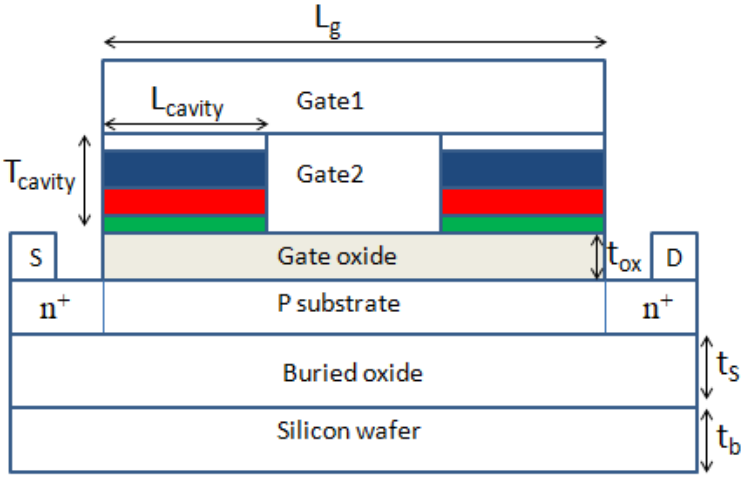

Fig 2.1.3(b) Basic structure of MOSFET when biomolecules are inserted inside the cavity.

Chapter-3

Simulation and Results

3.1 SIMULATION:-

3.1.1 Preliminary Study on MOSFET Simulation using Atlas:-

Silvaco (Silicon Valley Corporation) allows one to design and visualize the performance of semiconductor devices on the basis of physics-based simulation. This tool is helpful in modeling and designing the semiconductor device initially before fabrication to check the performance of the device. The physical models used in tool are based on efficient numerical methods and algorithms, new meshing techniques, optimized linear solvers and help in getting the optimized simulation results. TCAD products are used either for the process simulations using tools like ATHENA, Supreme4 or Device Simulations using ATLAS Framework. ATLAS has several simulators like S-Pisces, Luminous, Mixed Mode, TFT, Laser, Blaze and others.

In present work the Device Simulation is carried out using ATLAS simulators. Atlas is a software provides general potentials for physically-based two and three-dimensional (2D, 3D) simulation of semiconductor devices. Atlas is designed in such a way that it can be used with the VWF Interactive Tools. The VWF (Virtual Wafer Fabrication) Interactive Tools consist of the following: DeckBuild and TonyPlot. Their functions are explained below:-

- Deckbuild helps in creating the input files to ATLAS. Multiple windows provide menu-based or text-based input decks for the information entered. It offers complete control of run, kill, pause, and stop-at, restart, and single-step and history initialization operation to back-track a previous point in the deck and run it from that instance.
- Tonyplot is the common visualization tool in Silvaco TCAD products. It provides comprehensive potential for viewing and analyzing simulator output. Through TonyPlot the outputs which are actually the electrical characteristics of the device and the structure files generated for the designed device can be seen.

3.1.2 ATLAS Inputs and Outputs:-

ATLAS simulations use two input files. The first input file is a text file that contains commands for ATLAS to execute. The second input file is a structure file that defines the structure to be simulated. ATLAS produces three types of output files. The first type of output file is the run-time output, which gives the progress and error with warning messages as the simulation proceeds. The second type of output file is the log file, which stores all terminal voltages and currents from the device analysis. The third type of output file is the solution file, which stores 2D and 3D data relating to the values of solution variables within the device at a given bias point. The log files and the solution files are visualized using TONYPLOT.

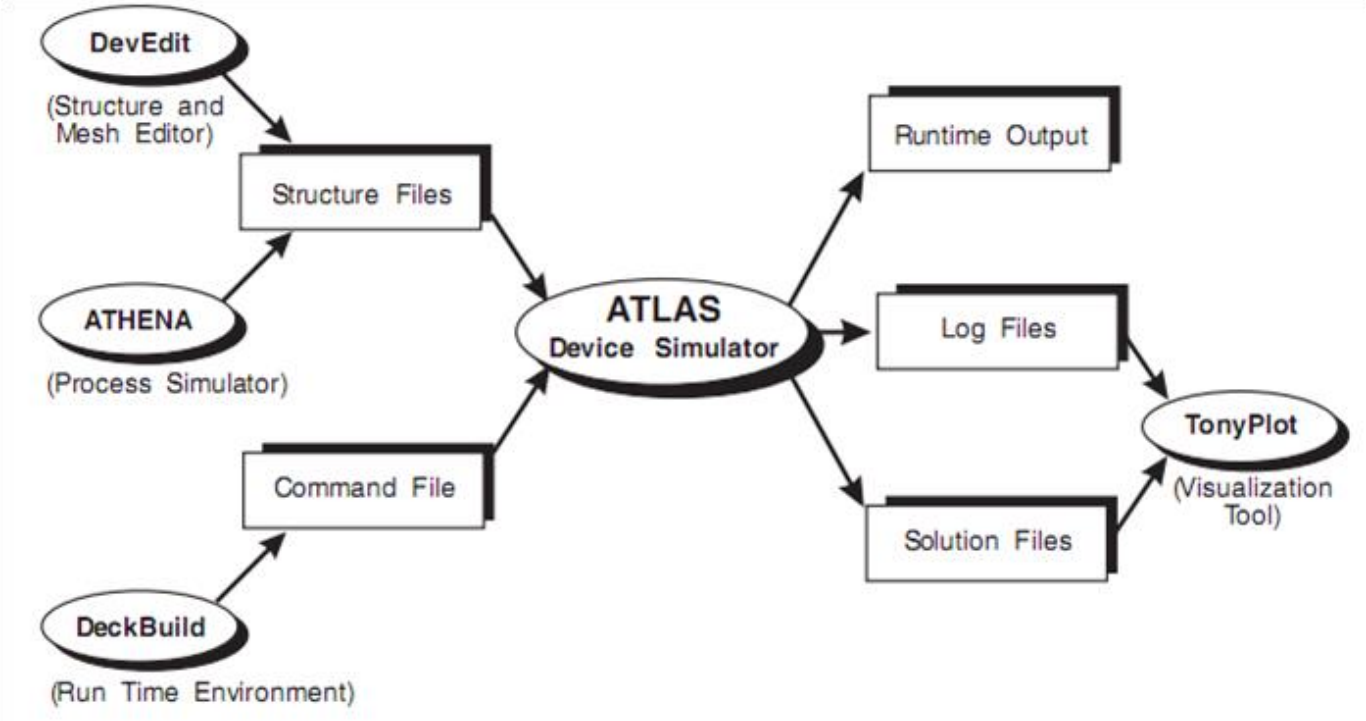

Fig 3.1(a) ATLAS input and output flow chart

3.2 RESULTS:-

There cases are studied in which different layers of biomolecules are introduced inside the nanogap cavity.

Case A:- When SAM (Self Assembled Monolayer) layer is introduced in the nanogap cavity

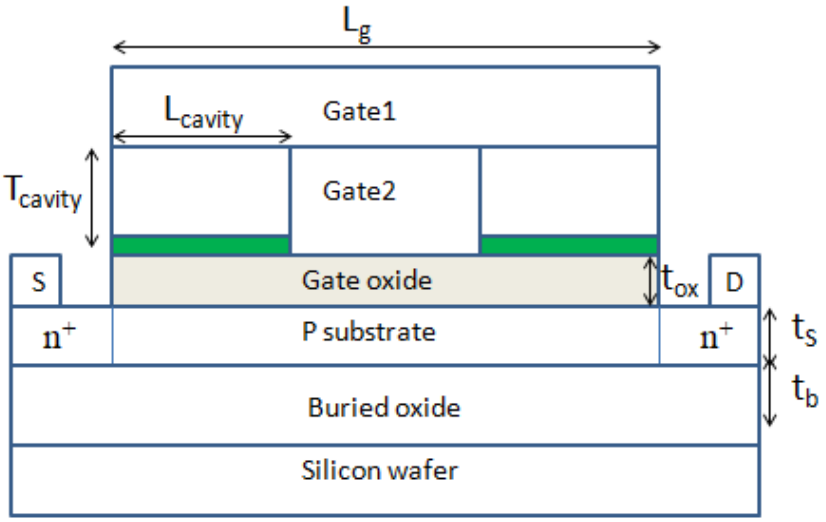

Fig 3.2(a) SAM layer is introduced in the nanogap cavity

Case B:- When SAM Layer + Biotin is introduced in the nanogap cavity.

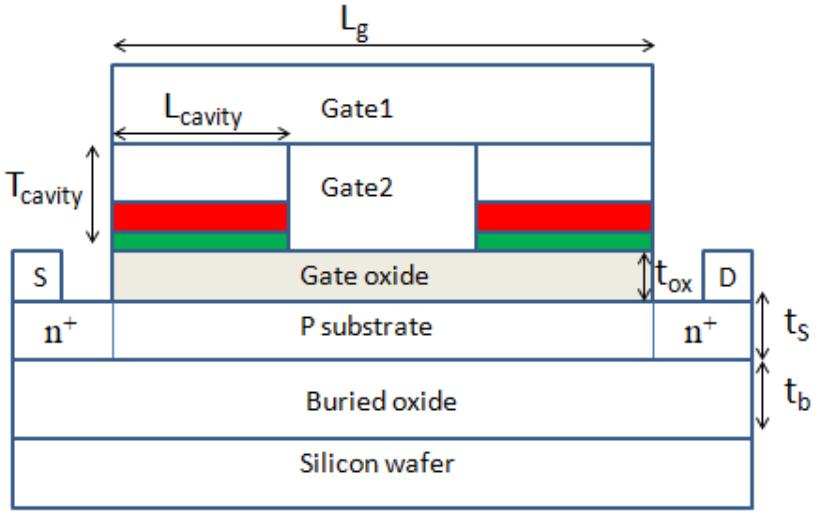

Fig 3.2(b) SAM layer + Biotin is introduced in the nanogap cavity

Case C:- When SAM Layer + Biotin + Streptavidin is introduced in the nanogap cavity.

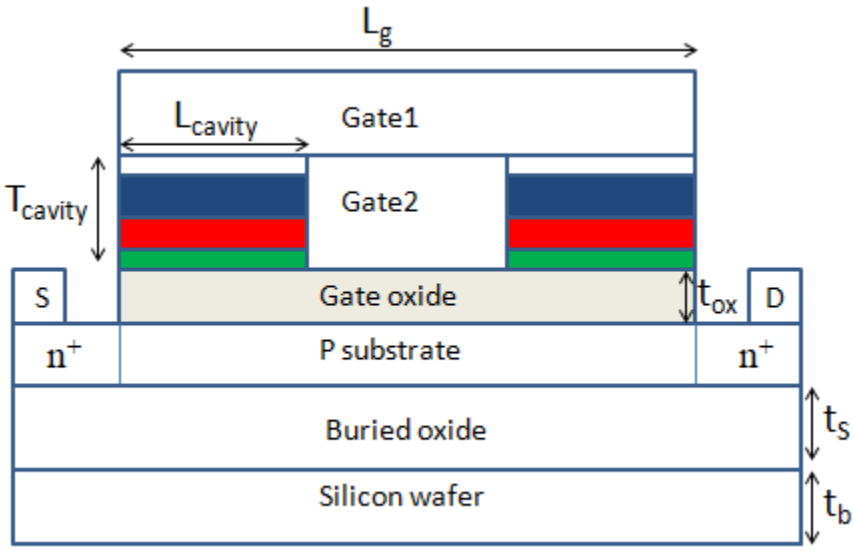

Fig 3.2(c) SAM layer + Biotin + Streptavidin is introduced in the nanogap cavity

3.2.1 I_{ds}-V_{gs} Characteristics for Three Different Cases:-

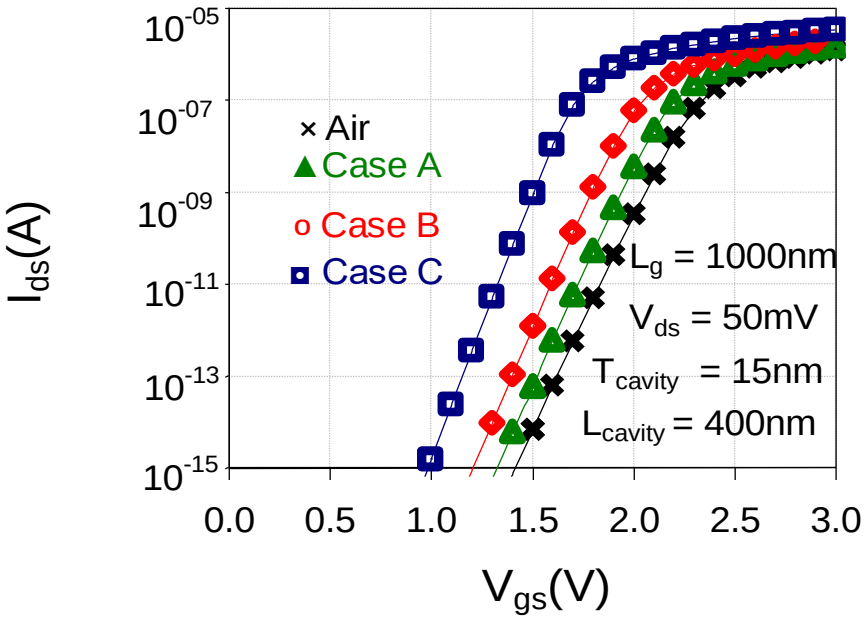

Fig 3.2(d) MOSFET transfer characteristics in semi-logarithmic scale at V_{ds} = 50 mV when biomolecules are introduced in the cavity.

- V_T depends on the gate capacitance, and hence we can modulate V_T by changing the dielectric material of the gate.
- When the chromium layer is etched to form an air gap, the dielectric constant of the gate and the total gate capacitance are decreased. As a result, V_T for the transistor shifts to a more positive value.
- In contrast, when biomolecules are introduced into the nanogap, they increase the gate capacitance relative to the air gap, and V_T shifts in the negative direction. Thus, by monitoring the change in V_T, it is possible to detect the specific binding of streptavidin to biotin**.**
- After Etching the 400-nm-long nanogap into the Cr layer, the total gate capacitance decreases by forming additional new air gaps on the gate dielectric at the edge of the gate, which can lead to fringing capacitance.
- After forming the SAM and immobilizing the biotin, VT shifts by only –0.14V as a result of the increase in gate capacitance at the gold side of the inner walls of the air gap.
- Because the thicknesses of the SAM and biotin layer are about 1–2 nm and 3nm, respectively, less than 30% of the air gap is filled in the vertical direction, and the increase in gate capacitance and corresponding shift in V_T are relatively small.
- In contrast, V_T shifts dramatically by -0.62V after the streptavidin binds to the biotin layer in the nanogap. Considering that streptavidin molecules are about 6–7nm in size, most of the 15-nm nanogap is filled when the streptavidin binds to the biotin, and the shift in V_T is much larger than in the case of biotin immobilization.

3.2.2 Energy Band Diagrams:-

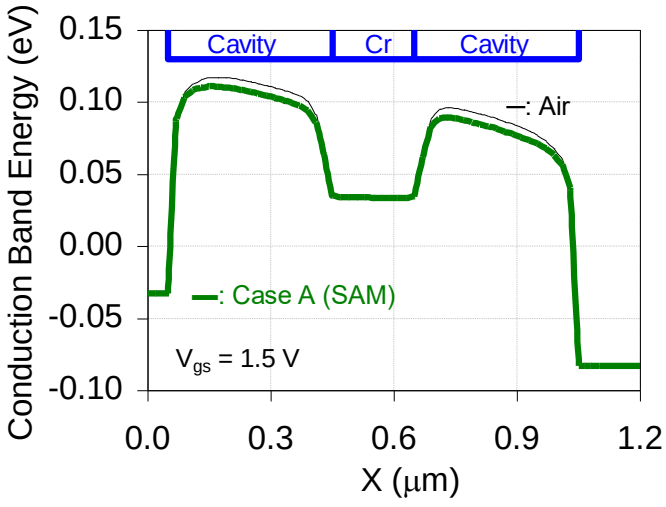

Fig 3.2.2(a) Case A (SAM): Conduction energy band diagram (along Y axis) vs Distance along the device(X axis) at V_{gs} = 1.5V

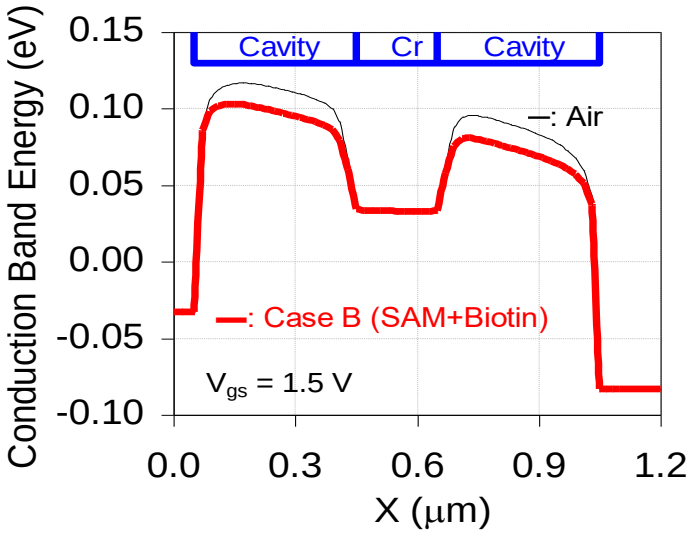

Fig 3.2.2(b) Case B (SAM+Biotin): Conduction band energy diagram vs Distance along the device (X axis) at V_{gs} = 1.5V

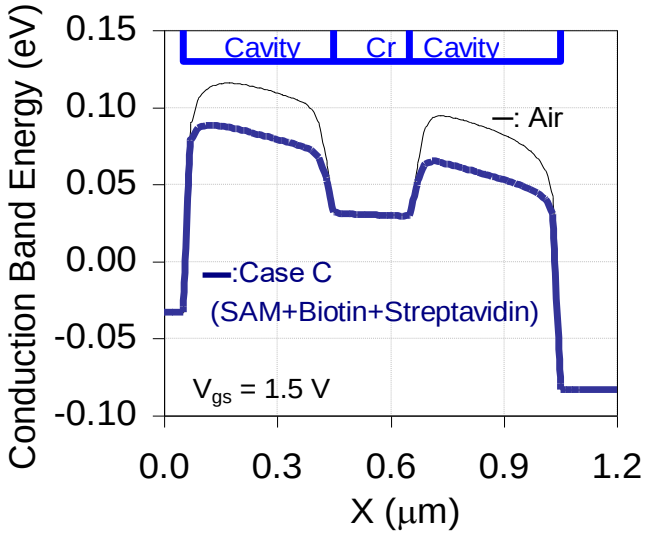

Fig 3.2.2(c) Case C (SAM+Biotin+Streptavidin): Conduction band energy diagram vs Distance along the device (X axis) at V_{gs} = 1.5V

- We plotted the following band diagrams to observe the behaviour of the device simulated.
- we observed that as the value of dielectric constant increases gate capacitance increases and threshold voltage decreases so the conduction band energy band diagram shift downward with respect to air in the cavity etched while at the gate side no bending occurs.
- Thus as the largest threshold voltage change is observed in Case C When biotin binds with streptavidin.

3.2.3 Electron Concentration Graph:-

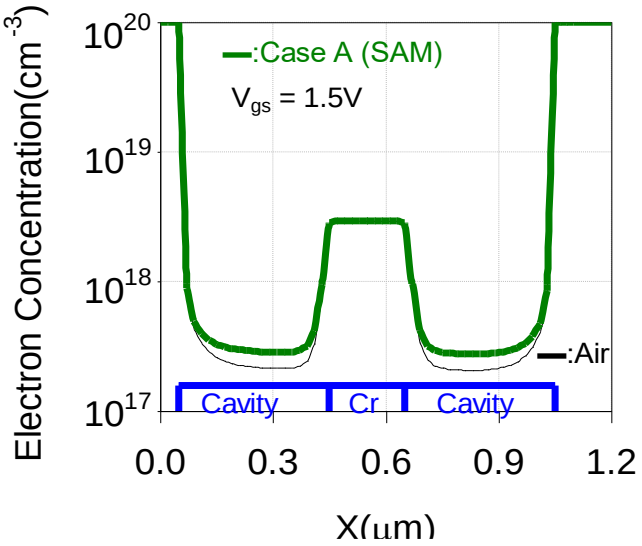

Fig 3.2.3(a) Case A (SAM): Electron Concentratiion (along Y axis) vs Distance along the device (X axis) at V_{gs}=1.5V

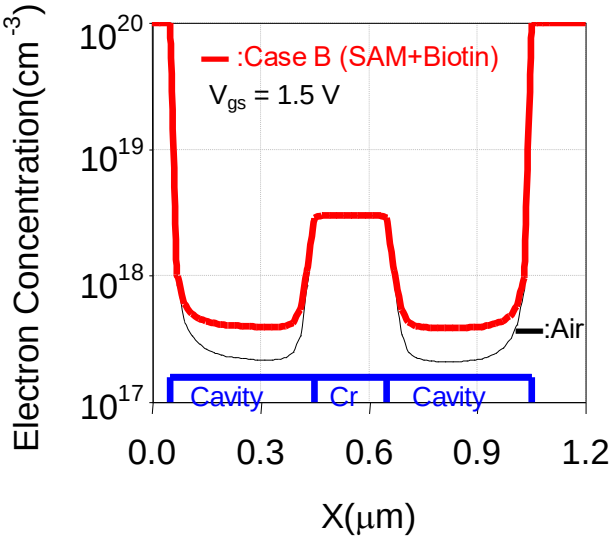

Fig 3.2.3(b) Case B (SAM+Biotin): Electron Concentration diagram vs Distance along the device (X axis) at V_{gs}=1.5V

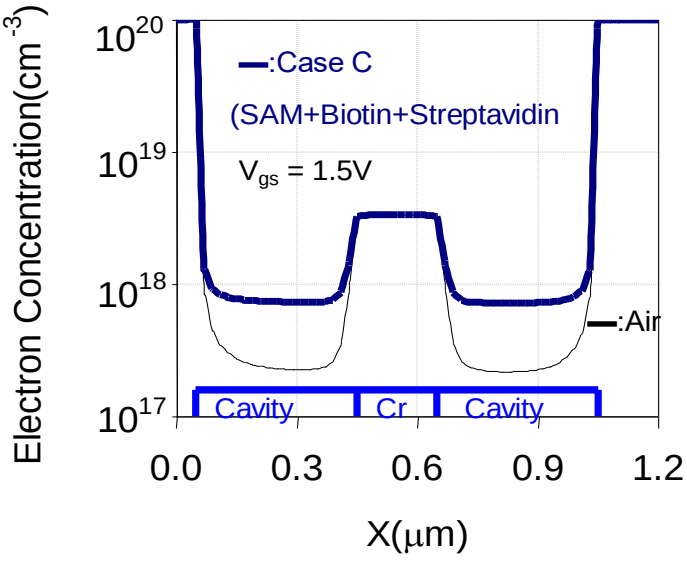

Fig 3.2.3(c) Case A (SAM+Biotin+Streptavidin): Electron Concentration (along Y axis) vs Distance along the device(X axis) at V_{gs} = 1.5V

Observation:-

- We plotted the following electron concentration graph to observe the behaviour of the device simulated.
- We observed that as the value of K increases electron concentration in the cavity increases w.r.t. to air while the concentration of electron at the gate side remain constant.
- Thus the largest threshold voltage change is observed when Biotin binds with streptavidin because the bound molecules have more no of electron to flow so concentration increases and shift is seen to be the largest.

3.2.4 Calculations:

- Sensing parameter (ΔV_{th}) is evaluated as the shift in threshold voltage in the presence of biomolecules with respect to absence of biomolecules (i.e. air case)

$$\Delta V_{th} \text{ (w.r.t. to air)} = V_{th} \text{ (biomolecules)} - V_{th} \text{ (air)}$$

- Equivalent cavity capacitance per unit area (C_{cavity}) can be evaluated from the series combination of capacitance due to each individual layers inside the cavity

$$C_{eq} = (C_1 \times C_2)/(C_1 + C_2)$$

where C_1 and C_2 are the capacitance per unit area

- Effective dielectric constant ($K_{effective}$) of the cavity can be evaluated as

$$(K_{effective}) = (C_{cavity} \times T_{cavity})/\varepsilon_0$$

where ε_0 is the permittivity of free space and is equals to 8.85×10^{-12} F/m

Table 3.2.4 Results obtained from different cases introduced for T_{cavity} = 15nm

Biomolecule Layers inside the Nanogap Cavity	**$K_{effective}$**	**C_{cavity} (10^{-8} F/cm^2)**	**Threshold Voltage V_{th} (V)**	**Change in ΔV_{th} (w.r.t. air) (V)**
Air	1	5.903	2.340	0
Case A: SAM	1.106	6.530	2.200	-0.140
Case B: SAM+ Biotin	1.282	7.567	2.040	-0.300
Case C: SAM+ Biotin+ Streptavidin	1.867	11.020	1.720	-0.620

Effects of Dimension Scaling and Real Time Analysis

4.1 DIMENSION SCALING:-

In order to accommodate more number of biosensors onto a single chip, it is essential to understand the effect on biosensing mechanism with downscaling of MOSFET dimensions. Therefore, in this section, the effect on the sensing parameter is observed when the gate length (L_g) and length of cavity (L_{cavity}) are reduced.

- **Initial Case :** When the gate length is at 1000 nm and cavity length is at 400 nm:-

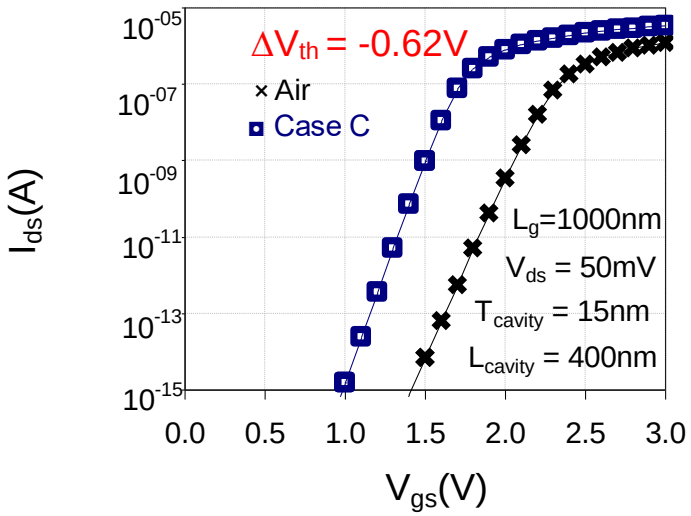

Fig 4.1(a) Transfer characteristics in semi-logarithmic scale at V_{ds} = 50 mV when biomolecules are introduced in the cavity for L_g = 1000 nm and L_{cavity} = 400 nm

- **Case 1:** When the gate length is kept fixed at 1000nm and cavity length is reduced to 200nm:-

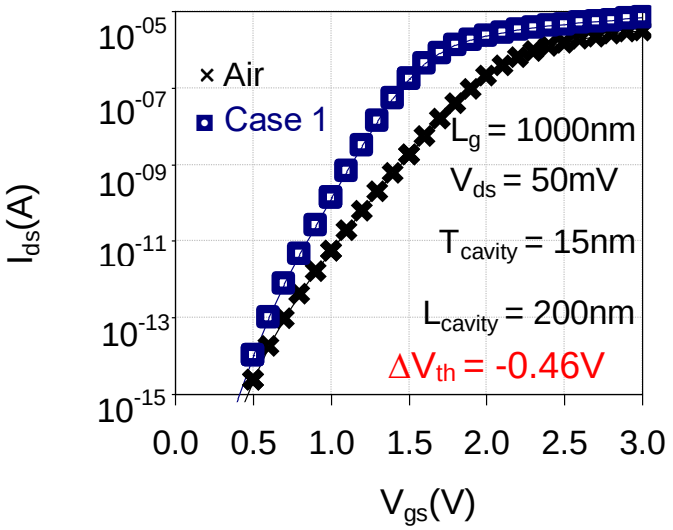

Fig 4.1(b) Transfer characteristics in semi-logarithmic scale at V_{ds} = 50 mV when biomolecules are introduced in the cavity for L_g=1000nm and L_{cavity} = 200nm

- **Case 2:** When both the gate length and cavity length are reduced to 500nm and 200nm, respectively.

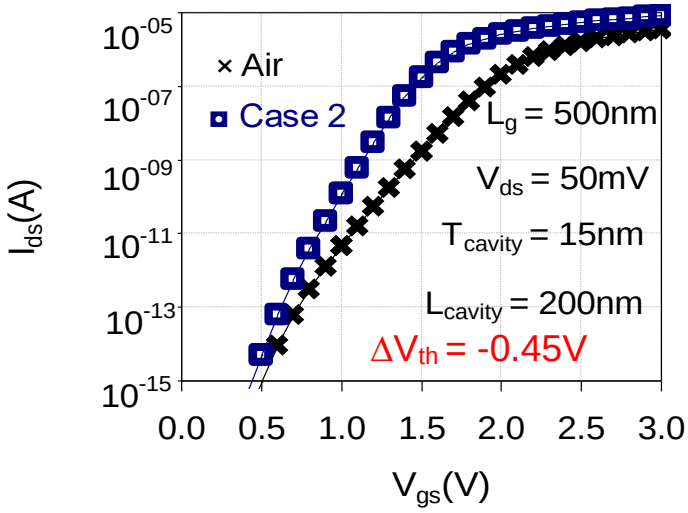

Fig 4.1(c) Transfer characteristics of MOSFET in semi-logarithmic scale at V_{ds} = 50 mV when biomolecules are introduced in cavity for L_g=500nm and L_{cavity}=200nm

Table 4.1 Results obtained from different cases of dimension scaling

Cases	V_{th} (V) Air	V_{th} (V) Biomolecule	ΔV_{th} (V) (w.r.t. Air)
Initial (Case-C)	2.34	1.72	-0.62
Case-1	1.91	1.45	-0.46
Case-2	1.92	1.47	-0.45

Observation:-

- Initially we have taken the gate length to be 1000nm and Cavity length to be 400nm as shown in fig 4.1(a). Since further reduction in gate length is not Possible because we have etched the cavity on both the side of the gate so the gate length should be greater than 800nm.
- So we have reduced the cavity length from 400nm to 200nm keeping gate length constant to 1000nm as shown in fig 4.1(b)
- We observed that threshold voltage change (ΔV_{th}) was reduced to -0.46V from -0.62V Now reduction in the gate length is possible because of cavity length reduced to 200nm .So we have reduced the gate length to 500nm keeping the length of cavity fixed as shown in fig 4.2(c)
- We observed that the threshold voltage change(ΔV_{th}) was reduced to -0.45V from -0.62V w.r.t to initial Case while the change in threshold voltage with respect to (Case -1) is almost neglected.
- Hence we conclude that the change in threshold voltage get reduced if we reduce the gate length as well as the length of cavity.

4.2 REAL TIME ANALYSIS:-

In practical applications of FET biosensor, the accumulation of biomolecules can be disordered, random and complex due to the low binding probability of biomolecules in the nanogap cavity. Therefore, the location of biomolecules in the partially filled cavity is expected to be an important consideration in the functioning of biosensor. The effect on the sensing parameter is observed when the cavity is partially filled along the cavity length.

- **Initial Case :** When cavity length is fully filled with biomolecules (Case c: SAM layer + Biotin + Streptavidin):

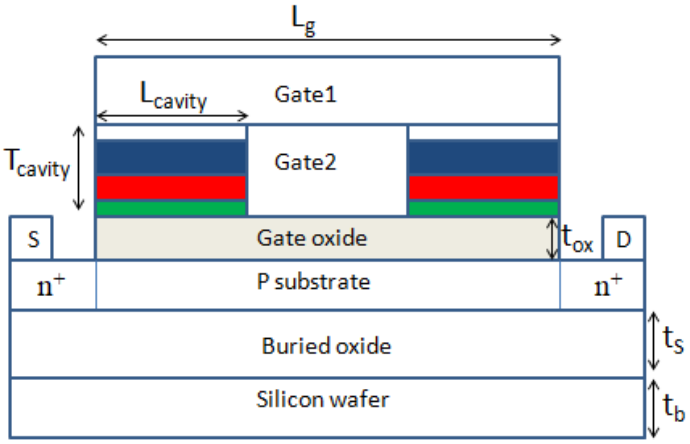

Fig 4.2(a) When (SAM layer+ Biotin + Streptavidin) is inserted fully along the cavity length

Case 1: When cavity length is partially filled with biomolecules (Case c: SAM layer + Biotin + Streptavidin) towards the middle of the gate:

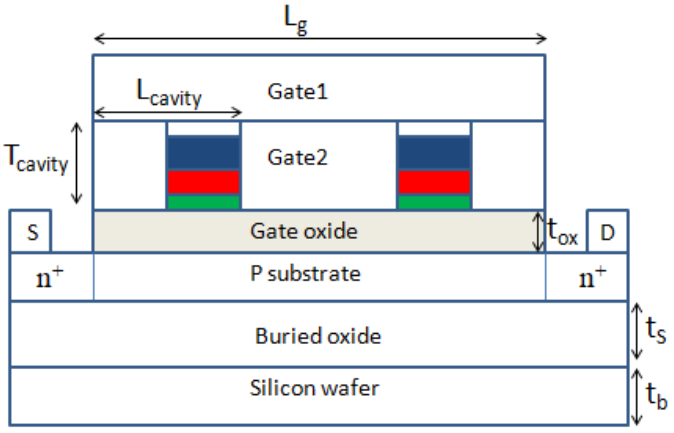

Fig 4.2(b) When (SAM layer+ Biotin + Streptavidin) is introduced half-length along the cavity length towards middle of the gate.

Case 2: When cavity length is partially filled with biomolecules (Case C: SAM layer + Biotin + Streptavidin) towards the source/drain sides:

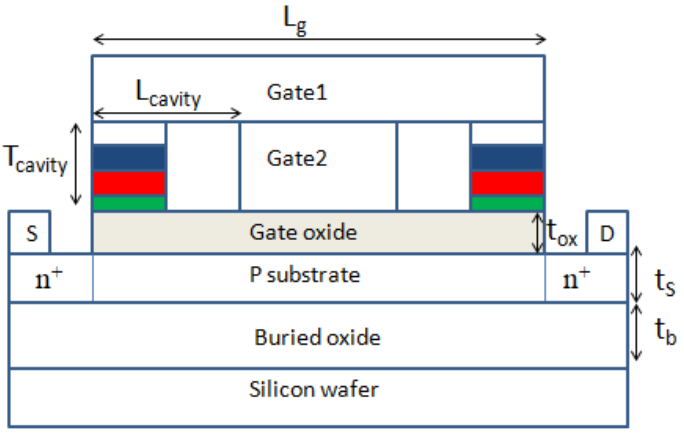

Fig4.2(c) When (SAM layer+ Biotin + Streptavidin) is introduced half-length along the cavity length towards source/drain sides.

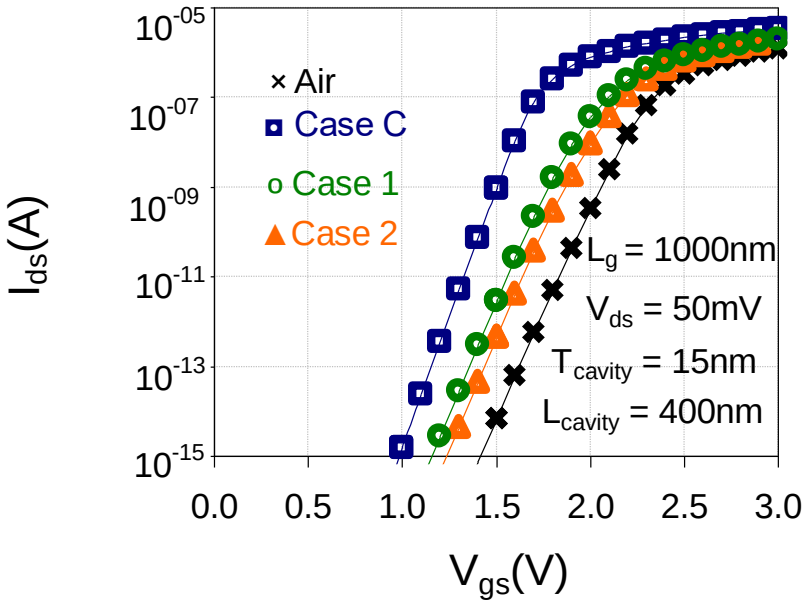

Fig 4.2(d) Transfer characteristics of MOSFET in semi-logarithmic scale at V_{ds} = 50mV when cavity is partially-filled and fully-filled as well as by exchanging the position of biomolecules in the cavity keeping parameters L_g = 1000nm and L_{cavity} = 400nm.

Table 4.2 Results obtained from different cases of real time analysis

Cases	**V_{th}(V) biomolecule**	**ΔV_{th} (V) (w.r.t. Air)**	**ΔV_{th} (V) (w.r.t. Case B: SAM+Biotin)**
Initial (Case-C)	1.72	-0.62	-0.32
Case-1	2.09	-0.25	-0.10
Case-2	2.20	-0.14	-0.04

Observation:-

- We observed that the threshold voltage change(ΔV_{th}) get reduced when the cavity is half-filled with biomolecules in comparison with fully-filled cavity with biomolecules.
- By changing the position of the biomolecules in the half -filled cavity, ΔV_{th} reduces.
- Hence we conclude that by changing the position of biomolecules in the cavity as well as by filling the cavity by biomolecules (either fully-filled or partially filled) affect threshold voltage.

Chapter-5

Conclusion and Future Work

5.1 CONCLUSION:-

- The proposed device shows much better sensitivity than several previously reported FET nanogap biosensors for detecting biomolecules, especially protein–ligand binding.
- We verified that biotin–streptavidin binding is the dominant factor in determining the shift in the threshold voltage.
- We also verified that reducing the gate length as well as length of cavity also affect the threshold voltage.
- Further we did more analysis and concluded that changing the position of biomolecules in the (half-filled) cavity as well as the way in which the cavity (fully- filled or half -filled) filled by biomolecules also affect the threshold voltage.
- It is expected that such DMFET-type biosensors will have the capability to detect a number of protein molecules, such as DNA, cancer markers and antibodies, and could be used as a part of a lab-on-a-chip for full electronic detection.

5.2 SCOPE OF FUTURE WORK:-

In the future, further analysis of various parameters that will affect the threshold voltage can be explored. However, the flexibility of these devices in detecting other biomolecules or an unknown mixture of biomolecules remains to be evaluated. However, in nature, there are many biomolecules that show charged behaviors; DNA is one of the most important of these biomolecules, as it is known be the largest negatively-charged molecule. When charged biomolecules such as DNA are introduced into the nanogap of a DMFET, its operation can be affected by this charge effect despite the known dielectric constant effect. To achieve the best possible performance of nanogap DMFET device towards different types of biomolecules it is necessary to study their charge effect of DMFET during electrical measurements.

5.3 REFERENCES:-

[1] Semiconductor device fundamentals by Robert F. Pierret.

[2] https://www.silvaco.com/products/tcad/device_simulation/atlas/atlas.html [online]

[3] Atlas User's Manual (2015)

[4] IM, H., Huang, X.-J., Gu, B., and Choi, Y.-K. (2007) A dielectric-modulated field effect transistor for biosensing. Nature Nanotechology, 2, 430-434

[5] Kim, S., Baek D., Kim, J. Y., Choi, S.-J., Seol, M. L., and Choi, Y.-K. (2012) A transistor-based biosensor for the extraction of physical properties from biomolecules. Applied Physics Letters, 101, 073703

[6] Choi, J.-M., Han, J.-W. Han, Choi, S.-J. Choi, and Choi, Y.-K. Choi (2010) Analytical Modeling of a Nanogap-Embedded FET for Application as a Biosensor. IEEE Trans. Electron Devices, 57, 12, 3477-3484

[7] Gu, B., Park, T. J., Ahn, J.-H., Huang, X.-J., Lee, S. Y., and Choi, Y.-K. (2009) Nanogap field-effect transistor biosensors for electrical detection of avian influenza. Small, 5, 21, 2407–2412.

[8] Kim, C.-H., Jung, C., Park, H. G., and Choi, Y.-K. (2008) Novel dielectric modulated field-effect transistor for label-free DNA detection. Biochip Journal, 2, 2, 127–134.

[9] Yi, M. Q., Jeong, K. H. & Lee, L. P. (2005) Theoretical and experimental study towards a nanogap dielectric biosensor. Biosensors and Bioelectronics, 20, 7, 1320–1326

[10] Star, A., Gabriel, J.-C. P., Bradley, K. & Gruner, G (2003) Electronic detection of specific protein binding using nanotube FET devices. Nano Letters, 3, 4, 459–463.