Dual-Cavity Triple-Metal Gate-Underlap Dielectric-Modulated Charge-Plasma-based TFET for the Biomolecules Recognition

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doi: https://doi.org/10.21467/proceedings.114.68

Abstract

In this era of technology, biosensors play an essential role in living life. Today's research and investigation revolved around its higher responsiveness and speed of detection. Normal TFET has many disadvantages like fabrication complexity, random dopant fluctuation, and the lower ON-State current. We are introducing a device that is a Dual-Cavity Triple-Metal gate-underlap DM-CPTFET for label-free detection. This device has a dual cavity for sensing different types of biomolecules simultaneously. We used the tool i.e SILVACO ATLAS TCAD Simulator for the sensing applications. High K material and gate work function engineering help us to improve drain current and better sensitivity. We used this TCAD tool, for analyzing the different parameter variations like energy band variation, surface potential, transfer characteristic, and output characteristic using different biomolecules Gelatin(k=12), Keratin(K=8), Biotin(K=2.63), etc.

Keywords: Dielectric modulation, relative permittivity, Biomolecule Sensitivity

1 Introduction

In today's world, the research and analyses of biomolecules are essential for disease monitoring, controlling, and treatment purposes. Our primary focus is to designing biosensors, how efficiently it is responsive and how fast it will detect [1]. There is a lot of demand for biosensors in the healthcare industry [2], the food industry, etc. We have two methods for the detection of biomolecules. First is label detection method such as Fluorescence, Electrochemical, and Magnetic methods. But there have many problems like when we used those methods, they changed the inherent properties of biomolecules, consumed much time, and produced inaccurate results. For any biosensor, accuracy is always a primary requirement.

We shifted to the second detection method, which is label-free detection, where we don't need any linking biomolecules to analyze the target biomolecules. The intrinsic property such as dielectric permittivity mass, volume, and conductivity determines the presence or absence of target biomolecules. The first biosensor introduced by Bergveld in 1970 i.e. ion-sensitive field-effect transistor [FET] [3], (ISFET), which is the good performance with charge biomolecules but poor performance for a neutral biomolecule, and it is incompatible with the CMOS process.

To overcome this limitation, we shifted to dielectric modulated {DMFET} devices capable of detecting both charged and neutral biomolecules. In DMFET, there is a cavity formed under the gate electrode where the biomolecule is trapped [4-5]. As we know that the miniaturization of device dimension, which is directly proportional to its sensitivity. So in MOSFET, there has a short channel effect (SCE), higher leakage current, and subthreshold swing is greater than 60mv/dec that degrade the device performance[6]. We are looking to the next option tunnel field-effect transistor [TFET] with a lower subthreshold swing below 60mv/dec, lower Off-State current, and higher the I_{ON}/I_{OFF} ratio. But there are some limitations like the formation of the abrupt junction profile which requires costly doping techniques [7-8] such as ion implantation, low on-state current Random dopant fluctuation, and high-temperature annealing.

Proceedings DOI: 10.21467/proceedings.114; Series: AIJR Proceedings; ISSN: 2582-3922; ISBN: 978-81-947843-8-8

For improving ON-State current either by using lower bandgap material at the source side, or we use multiple-gate dielectric material. Negative conduction or ambipolar nature is reduced by using either higher bandgap material at the drain side or followed the gate work function engineering. So the limitations of the conventional TFET are overcome by using charge plasma doping- less technique. We used a suitable work-function at the source and the drain side for inducing charge carriers so it helps in reducing fabrication cost. We introduced the cavity at both tunneling junctions for label-free biosensor detection[9-11].In this paper, the Dual cavity triple metal gate underlaps dielectric modulated CPTFET which is a label-free biosensor and is used to analyze the biomolecule and to determine its presence, such as DNA Gelatin, Keratin, etc.

2 Device Structure and Simulation Model

In figure1, we proposed the new device Dual-Cavity Triple-Metal Gate-Underlap DM-CP-TFET. Here, we used the charge plasma concept [12-13], which has two essential conditions. The first condition is the electrode metal work function at the source side satisfied [$\varphi s > \chi si + Eg/2$] and at the drain side electrode metal work function satisfied [$\varphi d < \chi si + Eg/2$] condition where φd is drain work-function, φs is the source work function and χsi is the electron affinity 4.17eV, and Eg is the bandgap of silicon [14]. The second condition is the thickness of the silicon body must be less than Debye length $((\mathscr{E}si*VT)/(q+60*N))^{1/2}$, where N, VT, & si, are substrate carrier concentration, thermal voltage, and dielectric-constant of silicon [15-18]. We took the appropriate work function of the platinum 5.93(eV) at the source side for inducing the n+ region and the work function of hafnium 3.9(eV) at the drain side for inducing the p+ region.

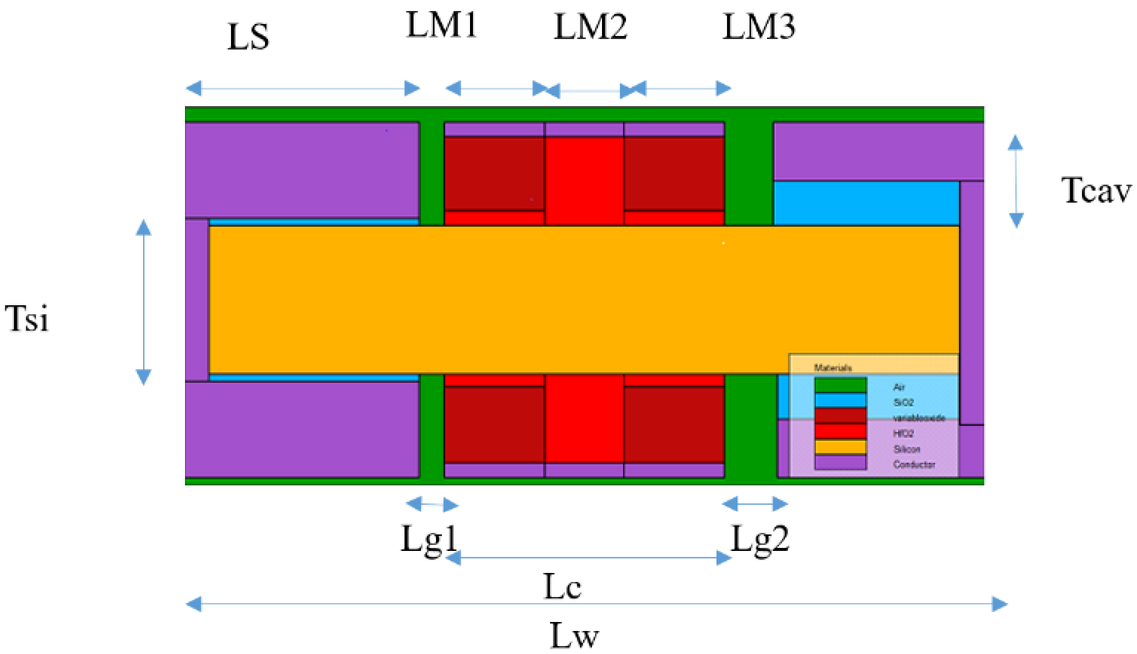

Figure 1 Cross-sectional device structure of Dual-Cavity Triple- Metal Gate-Underlap DMCPTFET

Here the channel length is (56 nm) and it has two underlap regions, one between the source and the gate (L_{g1}=5 nm) and the other one is between the gate & the drain (L_{g2}=10 nm). At the drain side, the gate underlap region reduces leakage and ambipolar current. The underlap at the gate & source region is used for various biosensor applications. To avoid the formation of silicide (6nm) SiO_2 is introduced between the source electrode and silicon substrate. The middle metal work function is 4.8 eV which is greater than the first and last work function 4.06 eV for optimum result. Here we used the HfO_2 layer under the nanogap-cavity to act as a biomolecule binding material.

Table 1. Dimensions of the proposed device

Length of the device [L_h]	155 (nm)
Width of the device [L_w]	23 (nm)
Length of the channel [L_c]	56 (nm)
Silicon oxide thickness	0.5 (nm), 6 (nm)
Length of the source and the drain [L_s, L_d]	42 (nm)
Length and width of a cavity	20 (nm), 5 (nm)
Length of underlap region [L_{g1}, L_{g2}]	5 (nm), 10 (nm)
Silicon thickness	10 (nm)
Length of L_{m1}, L_{m2}, L_{m3}	20 (nm) ,16 (nm), 20 (nm)
work function	4.06eV,4.8eV,4.06eV
Source work function	5.93 eV
Drain work function	3.9 eV

In Dual Cavity Triple-Metal Gate-underlaps DM-CPTFET, we used the SILVACO ATLAS TCAD tool for simulation purposes [19]. Here we have many models like the Shockeley-Read-Hall[SRH] is for recombination and generation models, Auger models, and Fermi – Dirac Statistics also used during the simulation. We have analyzed the effect of drain current, surface potential, an energy band at different charged and neutral biomolecules.

Table 2. Dielectric constants of various biomolecules

BIOMOLECULES	DIELECTRIC CONSTANT
Uricase	1.54
Uriease	1.64
Streptavidin	2.10
Biotin	2.63
ChOx	3.30
GOx	3.46
3-aminopropyltriethoxysilane (APTES)	3.57
Ferro-cytochrome c	4.70
Bacteriophage T7	6.30
Keratin	8
Gelatin	12

These observations help us to analyze the different neutral or charged biomolecule behaving differently corresponding to specific parameters like surface potential, energy-band, and variation in a cavity length. We know that every type of biomolecule has a different dielectric constant(k). If we talk about neutral biomolecule, it depends only on dielectric-constant(k) but on charge biomolecules that depend on dielectric-constant as well as charge density. Here we used the positive and negative charged biomolecules for different interface charge density (Nf) at k=6.

When the dielectric constant or relative permittivity increases, the tunneling barrier width at the source/channel interface reduces which causes the possibility of a lower electron tunneling process. In figure2, there is a variation in the drain current v/s gate voltage under which we observed the behaviour of different neutral biomolecules. As we know, charges and interface charge density(Nf) are directly proportional and the drain current depends on the interface charge. In the case of positively charged biomolecules which is present in the cavity, a decrease in tunneling barrier width for the positive gate voltage

Proceedings DOI: 10.21467/proceedings.114

Series: AIJR Proceedings
ISBN: 978-81-947843-8-8
ISSN: 2582-3922

source-channel junction is observed as seen in figure 3. It also degrades the barrier width between the conduction band valence band of the source & the channel. Similarly, the effect of negative charge biomolecules on the drain is observed as seen in figure 4.

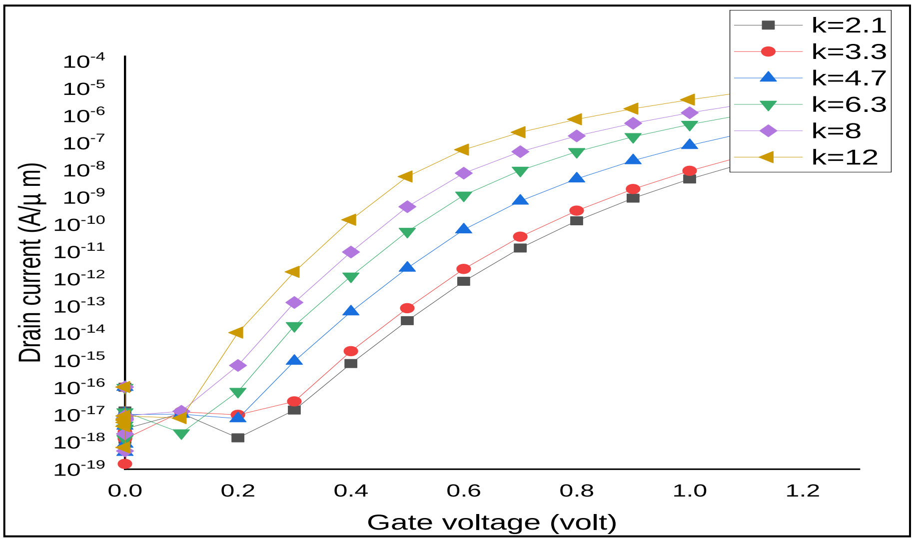

Figure 2 Transfer characteristics of neutral biomolecules at the different dielectric constant of cavity length = (20 nm).

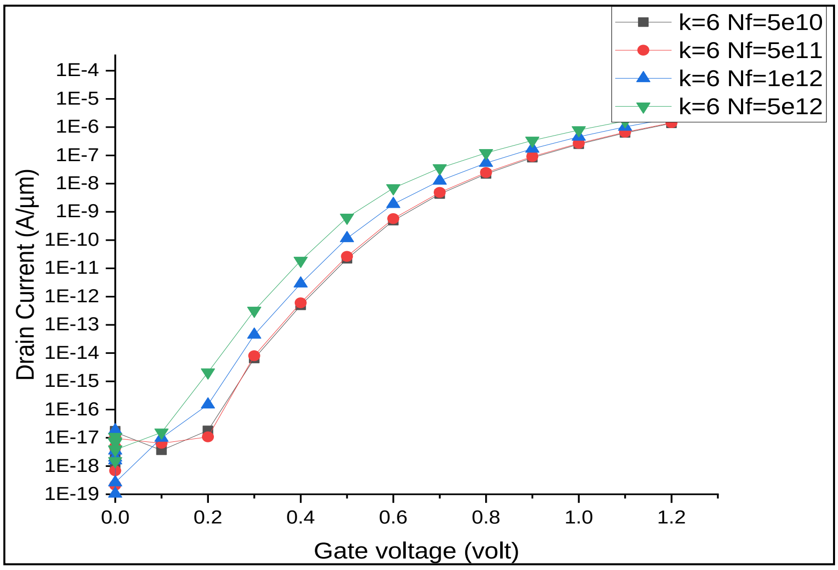

Figure 3.Transfer characteristics of positive biomolecules at the different dielectric constant of cavity length = (20 nm).

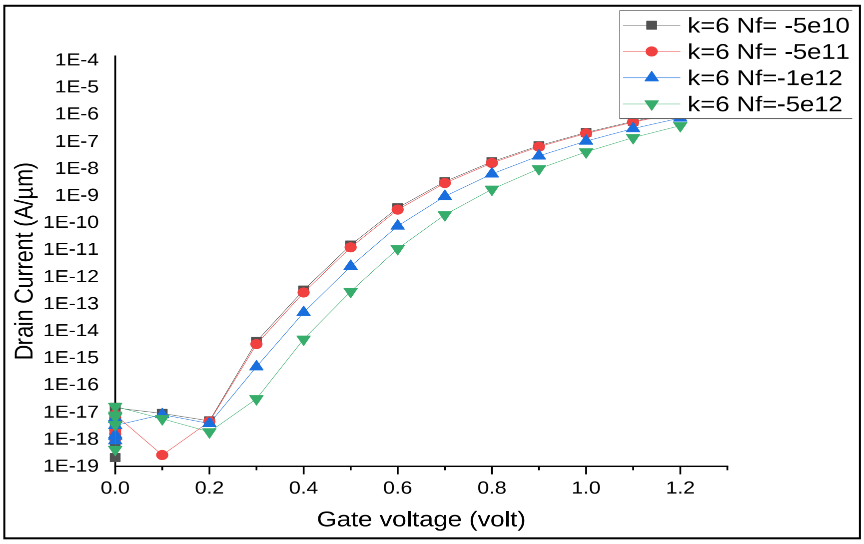

Figure 4. Transfer characteristics of negative biomolecules at the different dielectric constant of cavity length = (20 nm).

2.1 Impact on the energy band and surface potential

2.1.1 due to introducing different neutral and charge biomolecule in the cavity.

When the neutral biomolecule entered in a nanogap-cavity, an energy band shifted to the downward direction and the energy band is bent to its minimum level. The flat band voltage depends on relative permittivity, whenever a positive biomolecule entered into the source/channel junction then the energy band shifted to the downward direction as seen in Figure 5. In negatively charged density generation of the hole in channel increased that caused the band bending degradation in case of ON-State current as seen in figure 6.

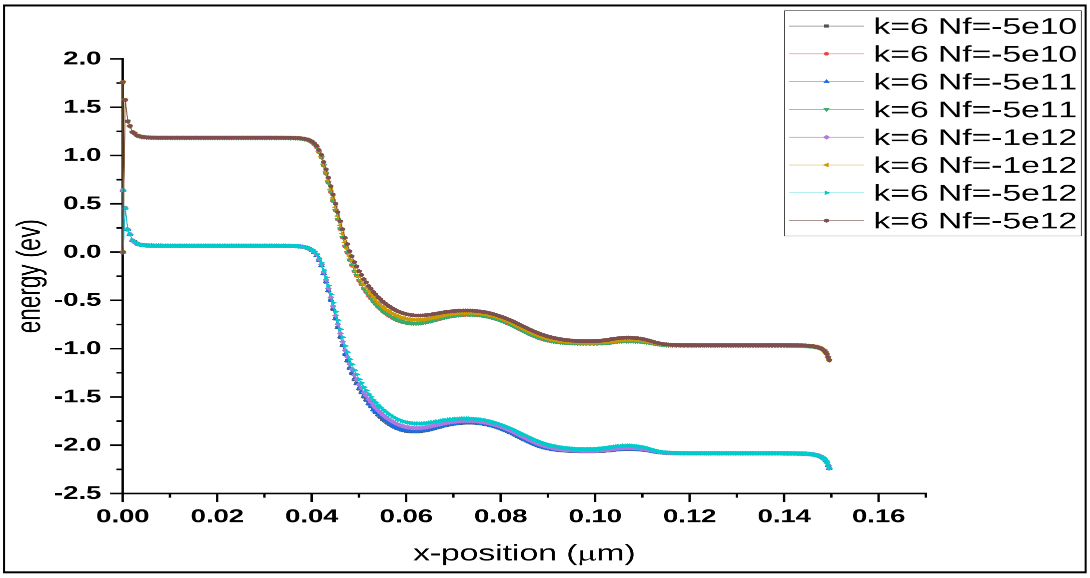

Figure 5. conduction band and valence band variation

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2.1.2 due to negative charge biomolecules.

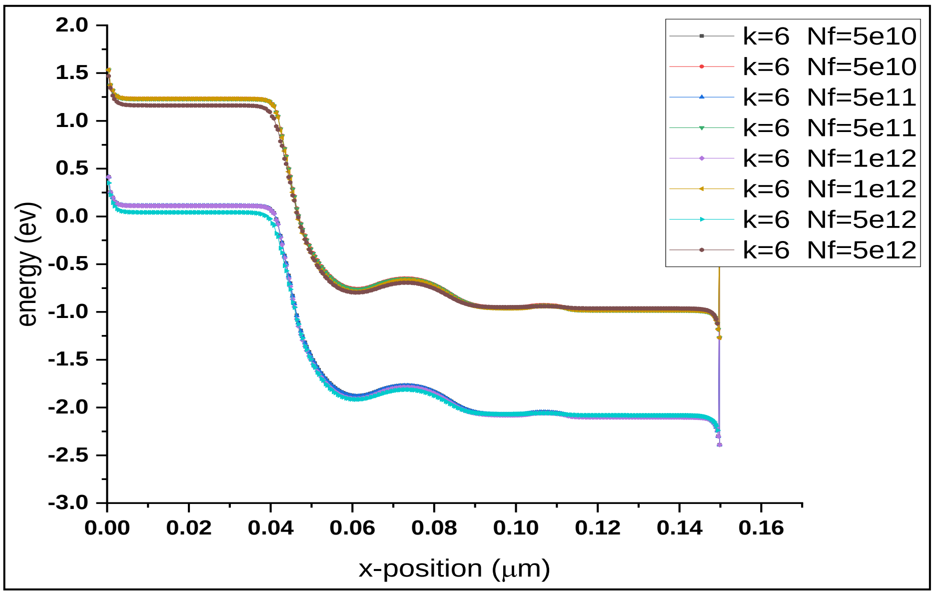

Figure 6. conduction band and valence band variation due to positive charge biomolecules.

2.2 Impact on the surface potential due to introducing different neutral and charge biomolecule in the cavity

In the surface charge potential under the different values of biomolecules, when the constant dielectric increases, it leads to effective gate capacitance that raises the value of the surface potential is observed as seen in figure 7.

There is a decrement in the flat band voltage (qNf/Ceff) in the gate underlap region for positive charge biomolecules presence in a cavity. That's why the increase in the value of surface potential is seen in figure 8. Similarly, there is an increment in flat band voltage for negative charge biomolecule (Nf) that causes a decrease in the surface potential as seen in figure 9.

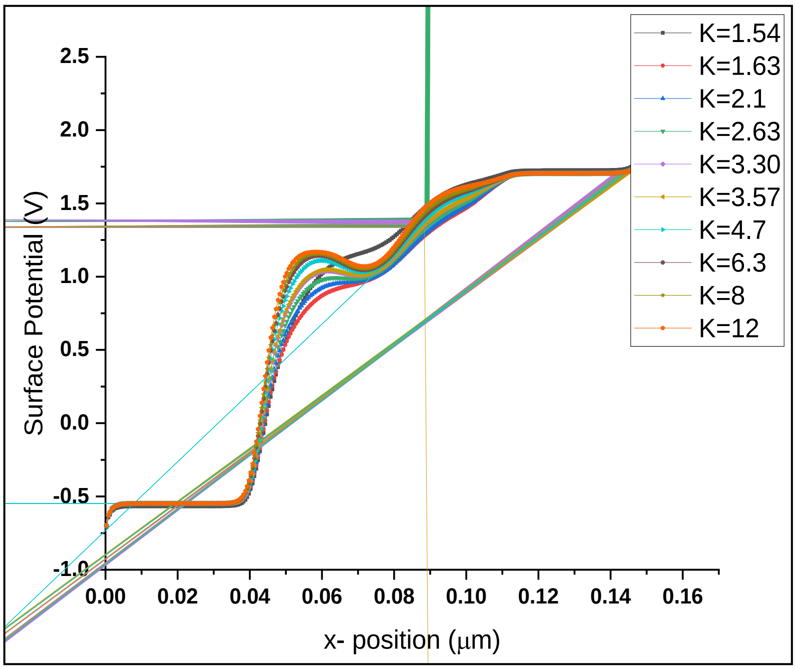

Figure 7. Variation of surface potential for different neutral biomolecules

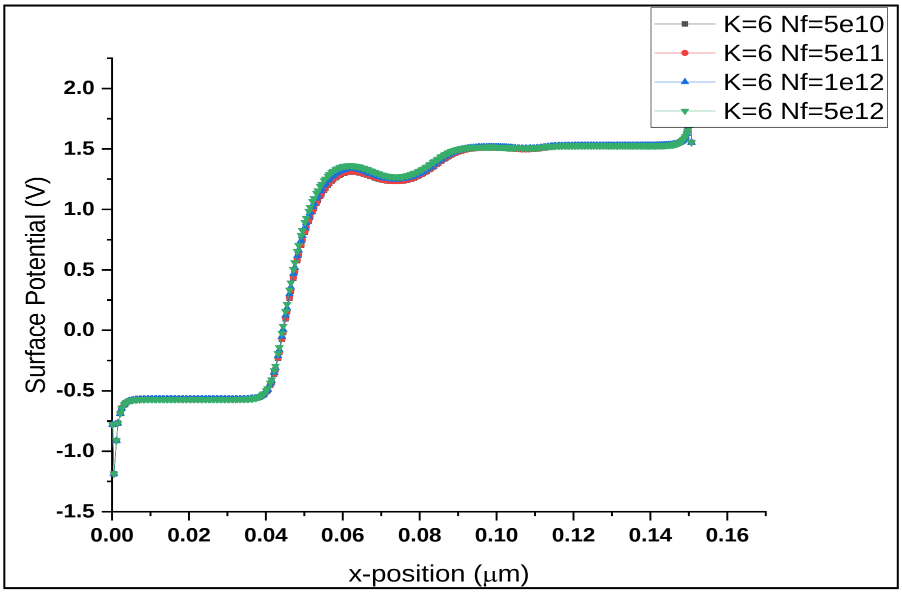

Figure 8. Variation of surface potential for positive biomolecules

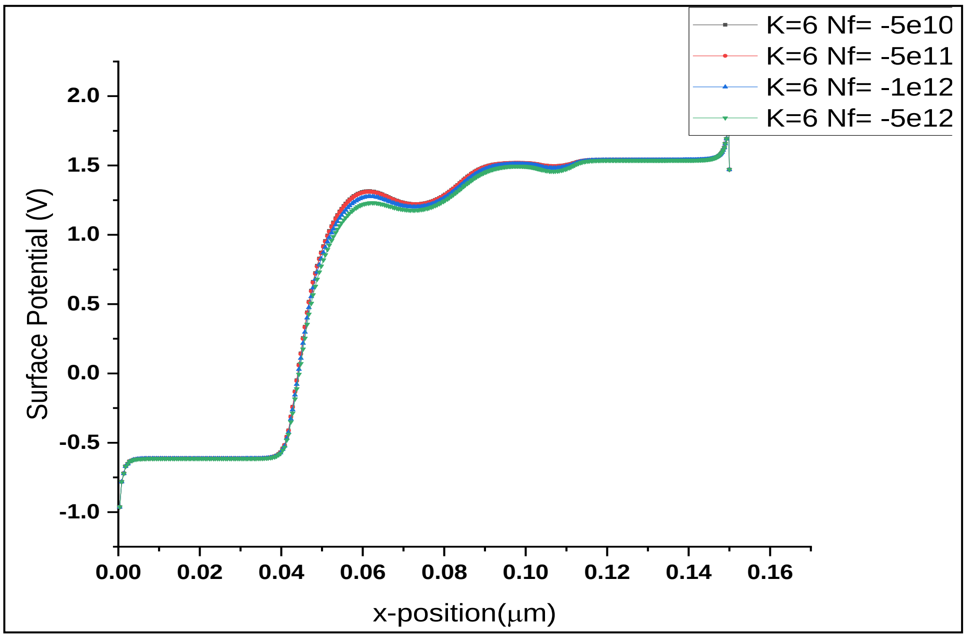

Figure 9. Variation of surface potential for negative biomolecules

According to the dual cavity triple metal DMCPTFET biosensor's output characteristic, we increase the drain voltage that causes advancement in tunneling probability and horizontal electric field. The drain current will saturate at a specific value of drain voltage because of the charge depletion as seen in figure.10. So that implies the tunneling process becomes independent of the drain voltage**.**

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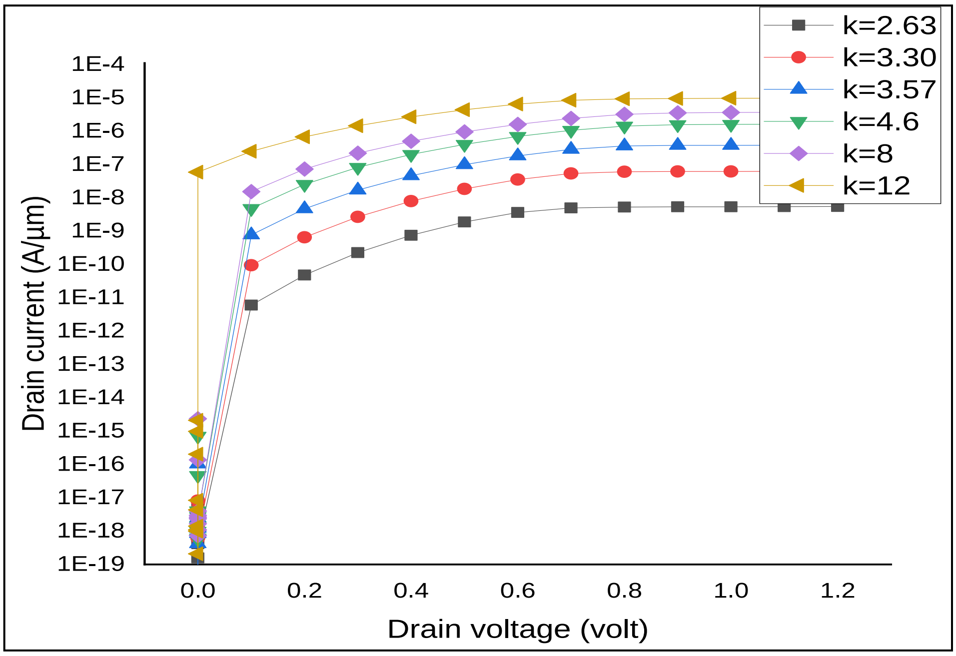

Figure 10. Impacts of Dielectric Constant on Drain Current at Different Drain voltage

The efficient biosensor depends on the sensitivity of the device. For higher the sensitivity, the greater the chances of detecting biomolecules. Sensitivity measure in the term of drain current at the different values of k. As constant dielectric increases, the positive gate voltage ON-State current raises due to the bandgap between source & channel decreases that increase the electron tunneling rate. It also the reason for improving the I_{ON}/I_{OFF} ratios.

3 Conclusion

So this paper proposed the dual cavity triple metal gate underlap dielectric modulated charge plasma TFET label-free biosensor for analyzing and understanding the behavior of different types of biomolecules, either neutral or charged. The charge plasma concept is used for reducing fabrication complexity. This model provides better responsiveness and speed of detection. We also understand biomolecule's behavior concerning energy band, surface potential, transfer characteristic, output characteristic.

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Proceedings DOI: 10.21467/proceedings.114

Series: AIJR Proceedings

ISBN: 978-81-947843-8-8

ISSN: 2582-3922