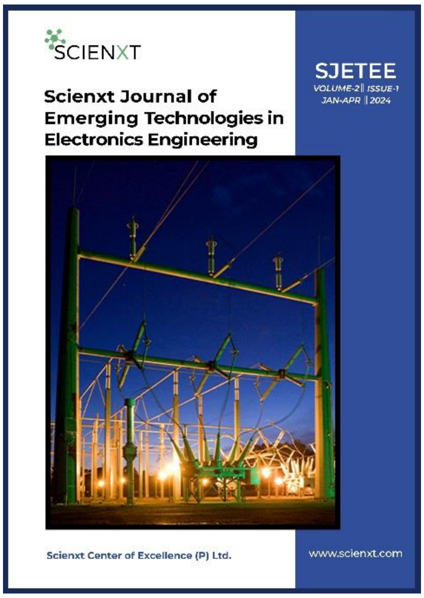

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Dual gate dielectrically modulated both sided cavity TFET biosensor using III-V Compound Semiconductor performance analysis

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Abstract:

An extensive analysis of dielectrically modulated TFET based biosensor has been done. Cavity on both side of the gate oxide is introduced, to make sure the biomolecules in the sensor cavity can cover more area over the gate-oxide channel interface. It will help to increase the electric field intensity at gate channel interface. III-V compound semiconductor is used here for the direct band gap nature and higher mobility of the carriers. Device parameters like ON-current (ION), Threshold voltage (VTH), ON-OFF current ratio (ION/IOFF), subthreshold swing (SVTH) all are recorded for different dielectric constant (K) and different charge density. A comprehensive analysis of the device parameter and device sensing ability has been done by considering various charge density inside the cavity.

Keywords— Dielectrically Modulated Tunnel Field Effect Transistor (DM-TFET), Dielectric Constant (K), ON-Current (ION), Threshold Voltage (VTH), Subthreshold Swing (SSVTH), ONOFF current ratio (ION/IOFF), Sensing ability.

1. Introduction:

Field effect transistor (FET) based biosensor became a major equipment for the rapid detection and analysis of health issues in the domain of medical science [2,4,6,10]. Since its' introduction as an ion sensitive FET (ISFET), FET based biosensor has evolved a lot [1]. In last few decades study on FET based biosensor has become extensive. Due to detection problem of target biomolecules the ISFET is got replaced by dielectrically modulated FET (DMFET) in biosensing application [30]. Metal oxide semiconductor field effect transistor (MOSFET) usage became popular after the introduction of DMFET. MOSFET's lower response time and sensing ability made an unparalleled mark in the evolution of FET based biosensors. MOSFET offered many edges to the betterment of biosensor but few issues were there due to the miniaturization and increasing packaging density with time. MOSFET based biosensor have encountered few drawbacks due to the structural specification and its' own characteristics like high subthreshold swing value, short channel effects [16,20]. To outwit the issues faced by MOSFET based biosensor, employment of TFET happened. The conduction mechanism of TFET, band-to-band tunneling (BTBT) consumes less power. Makes the device a perfect fit for low power biosensor application [3]. TFET has a drawback of lower drain ONcurrent (ION) [5]. As few other parameters like ON-OFF current ratio (ION/IOFF), subthreshold swing (SVTH) are partly dependent on ION. So, these parameters' values will be affected by lower value of ION. For the betterment of all these parameters, many major modification steps have been taken. Instead of full channel length TFET short gate TFET (SG-TFET) is introduced [8]. High dielectric constant (K) materials used as gate oxide, heavily doped pocket introduced at source-channel junction, vertical TFET is designed using n+ doped pocket at source and channel junction [7,9,11,12]. To make the variation in tunneling direction few structural modifications has been done also, III-V compound semiconductor usage is introduced for better mobility [13,24,28]. Here in this experiment a modification has been done on the biosensor reported in [14]. By changing the materials only and keeping the structure same the experiment has been done. Further detailed analysis on sensitivity and other parameters has been done. By changing the materials and few other structural parameters main point of this experiment was to improve the range of drain current compared to reported structure.

2. Device structure and simulation details:

Cross sectional view of simulated structure is shown in Fig.1. The dimensions of the corresponding device is same as reported in [14]. Only difference is III-V compound semiconductor materials are used in this experiment. Dimensions of the simulated device are, channel length Lch= 30 nm, cavity lengths Lcv1= 20 nm, Lcv2= 10 nm, source length Lso= 35nm, drain length Ldr= 35 nm. Body thickness of the device is Tb= 10 nm and thickness of cavities Tcv1, Tcv2 and oxide are Tox is 5nm, 5nm and 6nm respectively. Dimension of the pocket between source and channel is, length Lpoc = 10nm and thickness Tpoc = 4nm. Uniform doping profile is considered for simulation. Corresponding doping concentration of source, channel and drain, pocket 1E20/cm3, 1E15/cm3 and 1E18/cm3 , 5E19/cm3 respectively. Materials used in regions of the device are Ge for source and pocket, GaAs for channel and drain. HfO2 and SiO2 is used as a gate oxide. Dimensions of gates are thickness is 1nm, length is Lm1=25nm and Lm2 =15nm, work functions are Φm1=4.5eV and Φm2=5.1 eV.

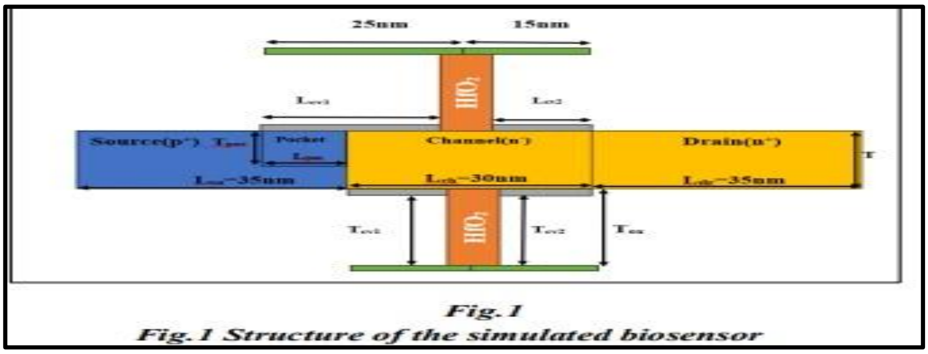

Figure. 1: Structure of the simulated biosensor

The proposed device structure in this particular experiment contains two cavities, both side of gate oxide. By doing the variation of dielectric constant inside the cavity, the electrical parameters recorded and the sensitivity of the device has been evaluated. Not only neutral biomolecules both positive and negatively charged biomolecules has been examined. Following biomolecules are tested using the simulated biosensor, Streptavidin (K=2.1), APTES (K=3.57), Ferrocytochrome C (K=4.7) and Keratin (K=8). Significance of the pocket is, it's injecting extra electrons in tunneling junction while tunneling from source to channel is occurring. It helps to increase the drain current.

3. Result and discussion:

This section is dedicated to the explanation of simulated biosensor's response in terms of various electrical parameters in presence of different kind of biomolecules inside the sensor cavity. The electrical parameters variations like change in energy band level, electric field intensity at gate channel interface, along with that change in device ON-current (ION) all has been recorded. Other electrical parameters taken into the account for the analysis are Threshold

Voltage (VTH), subthreshold swing (SVTH) and ON-OFF current ratio (ION/IOFF). All those parameter values are observed and plotted consider changing dielectric constant (K) of biomolecules. Three kinds of biomolecules are considered uncharged, positive and negative charged. Comparison is also done between the responses of air filled cavity (K=1) and biomolecules filled cavity (K>1).

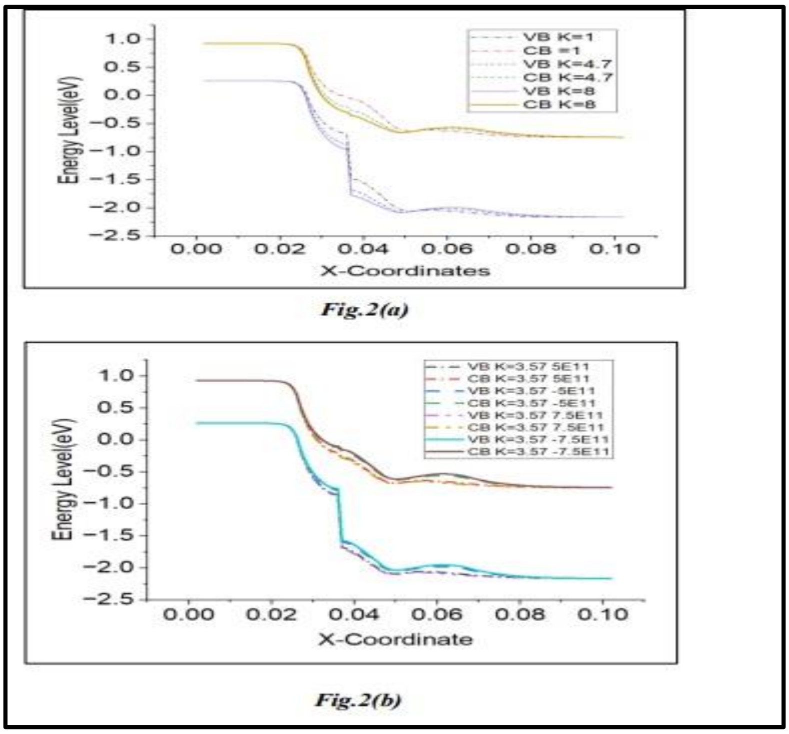

Figure. 2: (a) (b)

Fig. 2(a): Band diagram for uncharged biomolecules inside cavity for different dielectric constant (K). Fig. 2(b): Band diagram for positive and negative charged biomolecules at K=3.57. Fig. 2(a) shows the energy band diagram when the uncharged biomolecules are considered inside the cavity. From the figure it can be observed that the alignment of source side valance band and channel side conduction band becoming prominent with the increase in K of biomolecules inside the cavity. Potential drop across cavity decreases in presence of higher dielectric constant and potential drop increases at gate oxide interface. Due to this particular reason the electric field intensity increases at gate oxide and channel interface, it makes the band bending prominent. Fig. 2(b) shows the energy band diagram for charged biomolecules. In case of charged biomolecules, the increase in positive charge density causes better alignment compared to the neutral biomolecules. In presence of negative charge density inside the cavity opposite thing happens. Presence of positive charge induces electrons at channel region it will help to increase the rate of carrier transportation towards drain region. On the other hand the presence of negative charged biomolecules causes accumulation of holes in channel region. Means electron tunneling barrier width will decrease in presence of positive charge density and increase in presence of negative charge density. Fig.3 shows the variation of electric field intensity with varying dielectric constant (K).

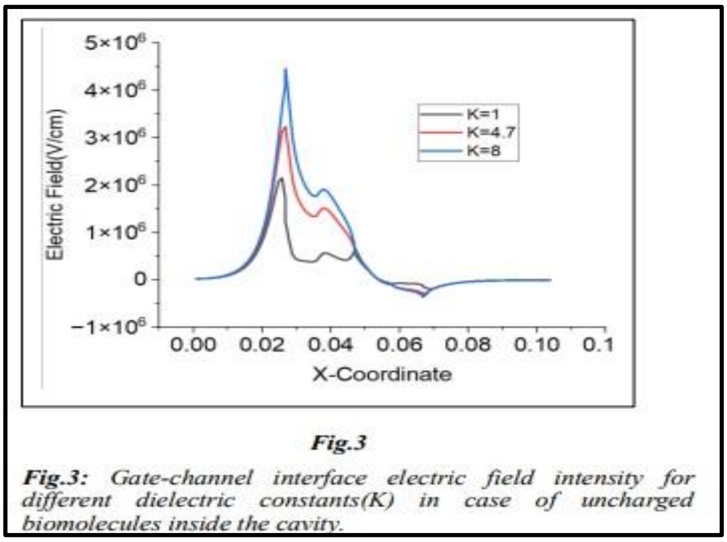

Figure. 3: Gate-channel interface electric field intensity for different dielectric constants (K) in case of uncharged biomolecules inside cavity

One of the major criteria for the fulfillment of electron transportation of TFET from source end to drain end is band bending. In case of higher dielectric constant, when neutral biomolecules are considered band bending will be prominent compared to lower values of K and electron tunneling rate will be more. It will result in increase in drain current of the device.

In Fig. 4(a) drain current vs gate to source voltage curve is shown for different dielectric constants. Again, tunneling width will be minimized in presence of positive charge density and opposite thing happens in case of negative charge density. Fig.4(b) shows how increasing positive charge density produces higher drain current and how it gets degraded when negative charge density is there inside the sensor cavity

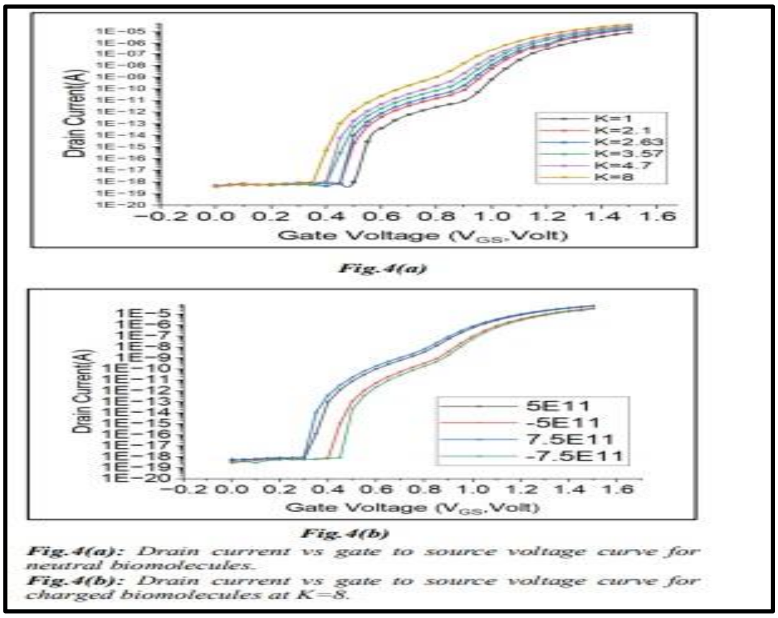

Figure. 4 (a): Drain current vs gate tosource voltage curve for neutral biomolecules

Figure. 4 (b): Drain current vs gate tosource voltage curve for charged biomolecules at K = 8

To start the carrier transportation from source region to drain region, occurrence of proper band bending is mandatory. For proper band bending, a certain amount of electric field intensity is needed. In case of higher dielectric constants the needed electric field intensity can be achieved at lower values of applied gate potential. Means, threshold will get decreased according to the increase in dielectric constant inside the cavity. Due to the injection of extra electrons in channel region in presence of positive charge density makes tunneling width thinner. In turn of that threshold voltage decreased more sharply compared to the neutral biomolecules, in case of increasing positive charge. Presence of negative charges, tunneling width gets increased and threshold voltage will decrease according to the change dielectric constant but certain differences in values will be there.

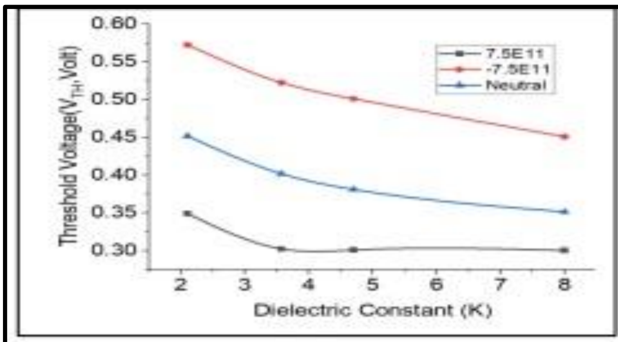

Fig.5(a)

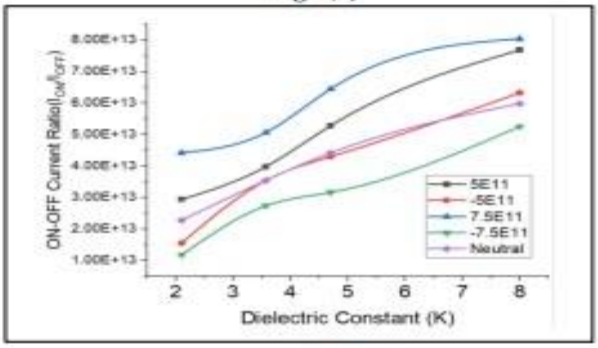

Fig.5(b)

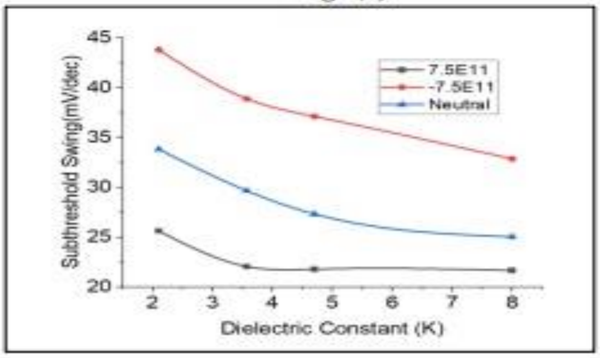

Fig.5(c)

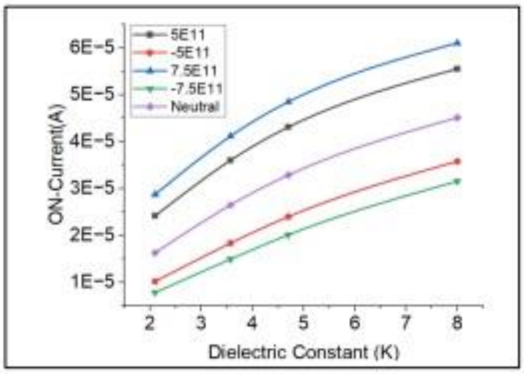

Fig.5(d)

Fig.5(a): *Threshold voltage vs dielectric constant for different charge densities.*
Fig.5(b): *ON-OFF current ratio vs dielectric constant for different charge densities.*
Fig.5(c): *Subthreshold swing vs dielectric constant for different charge densities.*
Fig.5(d): *ON-current vs dielectric constant for different charge densities.*

Fig. 5(a), shows how threshold voltage is changing in presence of uncharged and charged both kind of biomolecules. Fig. 5(d), shows how ON-current is getting varied according to the change in dielectric constant, in case of every particular biomolecule considered inside the cavity of the sensor. The gradual change in ON-current can be observed there. But in the curve shown in Fig. 5(b), ON-OFF current ratio is variation has been plotted over there. Gradual change cannot be observed there, increase in this particular parameter is bit irregular. When the positively charged biomolecules are immobilized inside the cavity, population of negative charge carriers increases in channel region. Again, in case of positive charge density when the dielectric constant of the particular biomolecules gets higher the electric field intensity also gets higher at gate channel interface compared to lower dielectric constant in OFF-state. Due to that the OFF-current of device having a minor increase. This is the reason with the increasing positive charge and at higher dielectric constant, ON-OFF current ration curve is getting a bit downward. At lower end and mid-range of the curve is changing in a sharp way, more specifically at mid region. At lower dielectric constant OFF-current is low, but due to positive charge density ON-current is high. That's why sharp change is there. In case of negative charge density, at higher dielectric constants ON-OFF current ratio is having a sharp change. From the curve Fig. 5(b) it is visible the ON-OFF current ratio at K=8 for charge density -5E11/cm2 is crossed the neutral biomolecules value. Due to the immobilization of negative charge density injection of holes causes the lack of electrons in channel region. So, in OFF-state number of electrons will be lesser compared to ON-state. From Fig. 4(b), it is clearly visible that ON-current degradation happens with increasing negative charge density. Means, lower negative charge density produces higher ON-current and OFF-current is also lower in this case. That's why -5E11/cm2 curve is changing more sharply compared to -7.5E11/cm2 curve. Fig.5(c), shows the variation in subthreshold swing (SVTH) for different kind of biomolecules. In presence of positive charge density subthreshold swing is getting decreased sharply compared to other kind of biomolecules. For the fruitful operation of the device the value of subthreshold swing must be bounded within 60mV/dec. In this case the achieved value of subthreshold swing is lower than the 60mV/dec in every cases. Subthreshold swing parameter is dependent on the major electrical parameters of the device, like threshold voltage (VTH) and ON-OFF current ratio (ION/IOFF). Previously, it is discussed that the value of VTH is low and ION/IOFF value is high for positive charged biomolecules. SVTH is the ratio of those two parameters, that's why the curve is getting lowered sharply for positive charge density. Lower values of SVTH is good for device operation.

4. Sensitivity analysis:

Detecting any distinct biomolecules on the basis of variation of electrical parameters of the sensor with respect to the air filled cavity, is the analysis of the sensitivity of biosensor. In case of neutral biomolecules higher dielectric constants produce higher values of electrical parameters. Means, biomolecules having higher dielectric constant will produce higher sensitivity. In between positive and negative charged biomolecules, positive charged produces higher values of electrical parameters and higher sensitivity. Drain ON-current sensitivity (SION) is analyzed using the equation defined in [9], SION= [ION(K=X) – ION(K=1)]/ION(K=1); X>1 ION(K=X) means the ON-current in presence of different biomolecules and ION(K=1) means the ON-current when the cavity is filled with air. Fig. 6(a) has shown the ON-current sensitivity curve for different charge densities with varying dielectric constant. When positive charged biomolecules considered inside the cavity it is producing best sensitivity result. From the ON-current sensitivity curve [Fig. 6(a)], it is visible that sensitivity is increasing gradually in every cases. ON-OFF current ratio sensitivity (SION/IOFF) is measured using the following equation reported in [9], SION/IOFF= [ION/IOFF(K=X) – ION/IOFF(K=1)]/ION/IOFF(K=1); X>1 ION/IOFF(K=X) means the ON-OFF current ratio in presence of different biomolecules and ION/IOFF(K=1) means the ONOFF current when the cavity is filled with air. In Fig. 6(b) ONOFF current ratio sensitivity curve is shown. Positively charged biomolecules are producing better result compared to other two kind of biomolecules. But curves are not increasing in a regular manner. Only the curve of neutral biomolecules is increasing in a gradual manner. Charged biomolecules curves are not increasing gradually. If Fig. 5(b) and Fig. 6(b) is compared, it can be seen that both the cases curves are following almost same pattern. The reason is same as described in case Fig. 5(b).

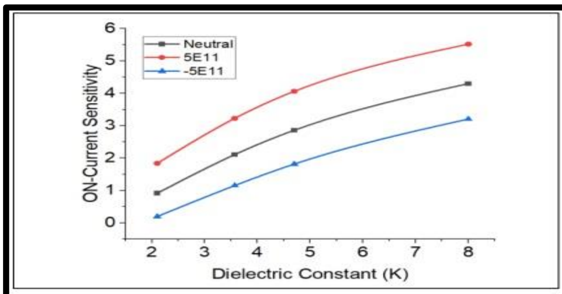

Fig.6(a)

Figure.

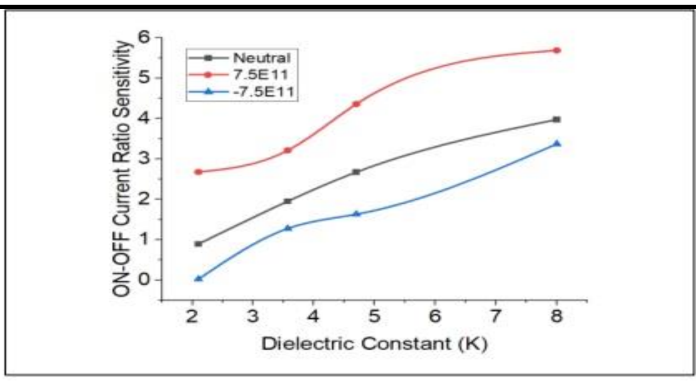

Fig.6(b)

Figure.

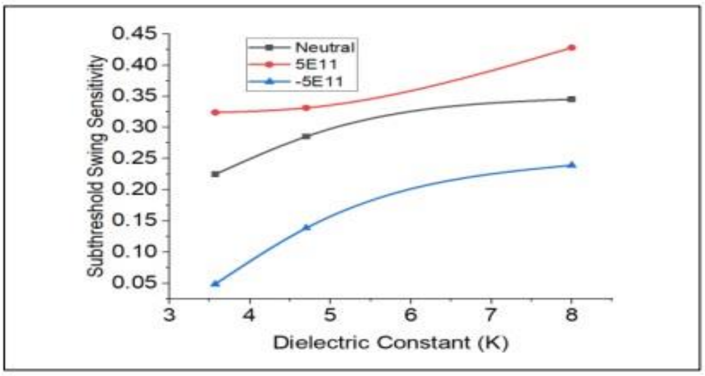

Fig.6(c)

Fig.6(a): *ON-current sensitivity (S_{ION}) vs dielectric constant for different charge density.*

Figure. 6(a): On-current sensitivity (Sions) vs dielectric constant for different charge density

Fig. 6(b): ON-OFF current ratio sensitivity (SION/IOFF) vs dielectric constant for different charge density. Fig.6(c): Subthreshold swing sensitivity (Ssvth) vs dielectric constant for different charge density. Subthreshold swing sensitivity is measured using the following equation as reported in [9], SSVTH = [SSVTH (K=X) – SSVTH (K=1)]/SSVTH (K=1); X>1 From Fig.6(c) it can be seen that positive charge density biomolecules are showing better result. But curve for charge density 5E11/cm2 is different than others. After the dielectric constant K=4.7 it is having sharp increase. At this charge density SVTH value at K=3.57 and K=4.7 is 25.8467 mV/dec, 25.5663 mV/dec respectively. When K=8 the value is 21.8706 mV/dec. A sudden change in subthreshold swing value is there, that’s why it is also having an impact on sensitivity value.

5. Conclusion:

The biosensor structure simulated here the device structure is same as [14]. But the different materials are used here. After completing the simulation, it has been seen that the device ONcurrent has been increased compared to the reported structure and the simulation is done at lower drain to source voltage (VDS). In VDS was 1 Volt but in this simulation has been done at VDS=0.7 Volt. The fill factor dependency test can also be done to observe how the parameters of the device get varied when the sensor cavity is partly filled with biomolecules.

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