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Investigation and Design of Dual Gate Dielectrically Modulated Junction less TFET for Biomolecule Recognition

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Abstract: This paperwork includes a tunnelling transistor with dual gate and employing the use of dielectric modulation (DG-DM-JL-TFET) based structure. In order to recognize the biomolecule like protein, biotin, uricase etc a nano cavity is presented above the tunnelling. Charge plasma technique is used to form the drain and source regions into the substrate. High work function creates a hole in source and similarly a lower work function will create an electron in drain.

The "N" region is etched into the substrate using hafnium electrode with a work function of 3.9 eV. $Si0_2$ of 0.5nm thickness is inserted between electrode of source. The "P+" region is etched on intrinsic silicon substrate using Platinum electrode having a work function of 5.93 eV. The device structure proposed in this paper shows results for sensitivity for charged and neutral biological molecules. The sensitivity of the biological molecules having higher dielectric constant is greater than those biological molecules possessing lower dielectric constant.

Index Terms: Biosensor, Junctionless, Dielectric Modulation, Dielectric Constant, Tunnel Field Effect Transistor (TFET), Subthreshold Swing

I. INTRODUCTION

Over the years, size of semiconductor devices has been reduced to nanometer scale [1], but the shrinkage of these devices induces various short channel effects [2] which affects the performance of device. Initially, one of the major challenges for integrated circuits to solve power problems was to reduce supply voltage [1-2]. TFET was successful to reduce supply voltage by lowering the subthreshold swing to less than 60mV/decade [3] but there were certain drawbacks of TFET such as low drive currents. TFET's also suffer from ambipolar conduction in off state. Fabrication of TFET needs high thermal budget and ion implantation which is a costly procedure ion implantation is a procedure in which an ion beam is generated which then gets steered into the substrate enabling the ions to come in rest position beneath the surface. TFET's suffer from Random dopant fluctuations (RDFs) as TFET is a heavily doped device [4]. These fluctuations are responsible for the poor performance of device. The process of variation in the concentration of implanted impurity is termed as random dopant fluctuation. Current conduction mechanism is different in MOSFET and TFET device [5]. MOSFETS employ thermionic emission whereas the TFET uses BTBT mechanism. In band-to-band tunnelling (BTBT) process, there is tunnelling of electrons across the junction. At thermal equilibrium two depletions regions are formed. When gate to source voltage is 0 volts then the TFET is mainly off. On increasing the voltage energy bands in channel adjust according to the source. At certain value of gate to source voltage (VGS), valence band of source aligns with the conduction band of channel which causes electrons to cross through the potential blockade. Major drawback of MOSFET devices is the presence of off state current. For example, in N-MOSFET we have free charge carriers (electrons) in conduction band and since in the off-state electrons from conduction band will move to the drain region. This will constitute a larger OFF state current in MOSFET.

MOSFET's also suffer from several short channel effects in sub-50nm channel such as: charge sharing occurs between gate and drain, drain induced barrier lowering [2], threshold voltage roll of and many more. TFET's are much more immune to these effects in comparison with MOSFET's.

To improvise the limitations of TFET researchers have given several solutions such as to reduce the ambipolar current. This ambipolar current [6] is due to the tunnelling of charge carriers in drain-channel region. This current is observed when a negative gate potential is applied in TFET's. researchers have found that reducing the drain doping is able to reduce the current (ambipolar).

A couple of techniques are employed to improve the on current (ION) of device such as lessening of the gate work function in TFET would cause the formation of a larger inversion layer which in turn would cause the lowering of the energy bands of channel. This results in the increment of source-channel tunnelling and thereby decreasing the ON current.

TFET's require sharp convergence for proper enactment of band-to-band tunnelling, [15-16]. For sharp convergence a high thermal budget is needed in case of doped source and channel regions due to thermal annealing process and implantation technique [9-17]. The procedure of diffusion of charge bearers from drain region to passage of channel region makes an abrupt interface profile which is hard to achieve. High random dopant fluctuations cause variation in the output characteristics. [2-4] The charge plasma technique is used for making n-type or p-type section in TFET using the concept of doping less transistor. Doping less by the name suggest no need of doping. The source and drain regions are formed using charge plasma concept. High work function creates a hole in source and similarly a lower work function will create an electron in drain.

The term biosensor was first used in the 1960's to define the use of bioelectrodes. These are basically the recognition devices that consists of major elements i.e., an analyte that is to be detected, a bio recognition element which is used to bind the target molecule, then a bioreceptor which is a biological component that the target analyte binds to [9-17]. Old FET devices were inefficient in many ways as ISFET gave better results with charge biomolecules but on the other hand deliver poor performance with neutral biomolecules. A newer version of FET that was dielectric modulated FET overcome the above stated problem in conventional FET. But DM-FET was unsuccessful in providing high sensitivity, lower power consumption and a smaller detection time. There are diverse nanoscale structures previously proposed for a low power device. From the point of novelty, we have chosen junction less FET. Fabrication of JL-FET is easy. Double gate dielectric modulated JLTFET biosensor is recommended for the spotting of unbiased and charged biomolecules. This paper reasons that an all-encompassing number of gate electrodes in the proposed design can improve the electrostatic regulation of the channel, which can lessen the SCEs [9-18].

II. PROPOSED DEVICE DESIGN

Fig. 1 portrays the DG-DM-JLTFET device structure. By using proper metal work function the source is formed. The "P+" region is etched on intrinsic silicon substrate using Platinum electrode having a work function of 5.9 eV.

Si substrate has the intrinsic concentration of

$n_i = (1.5*10^{10})/cm^3$. The other parameters used for the simulation purposes apart from intrinsic concentrations are: length of channel is taken to be 20nm. Film thickness of silicon is taken to be 5nm. Cavity length (Lcav) is taken to be 7nm and 8nm. Dual gate functions of different material are 3.9eV and 4.5eV. Although a nanocavity has been induced in the biomolecule for immobilization purposes the properties of conventional junction less TFET are found to be similar to those of DG-DM-JLTFET. Physical models of ATLAS such as: Graded and abrupt heterojunctions, Shockley-Read-Hall recombination model for considering the effect of impurity atom in the channel region. For numerical implementation we have used certain models provided by ATLAS such as Kramer- Brillouin technique. Various other models have been used to study the device structure such as trap assisted tunnelling demonstrated by Schenk. The width of substrate is determined using the Debye length $((\varepsilon Si * V_T)/q + 60 * n)1/2$, for the uniform of carrier concentration uniformly where V_T is the thermal voltage and $V_T = KT/q$ and n is the concentration of carrier in the substrate, εSi determines the dielectric value of silicon and $q=1.6*10^{19}C$.

The "N" region is etched into the substrate using hafnium electrode with a work function of 3.9 eV [17], [18]. SiO_2 of 0.5nm thickness is implanted between source metal electrode and Si substrate to prevent the development of silicide.

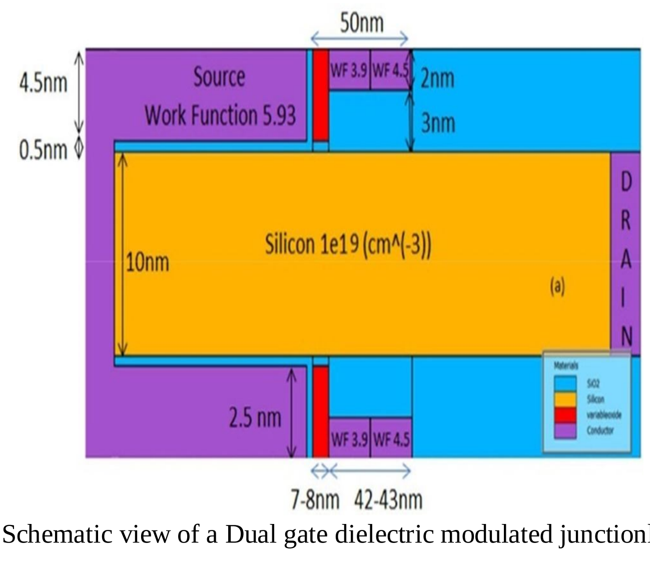

Figure1: Schematic view of a Dual gate dielectric modulated junctionless TFET

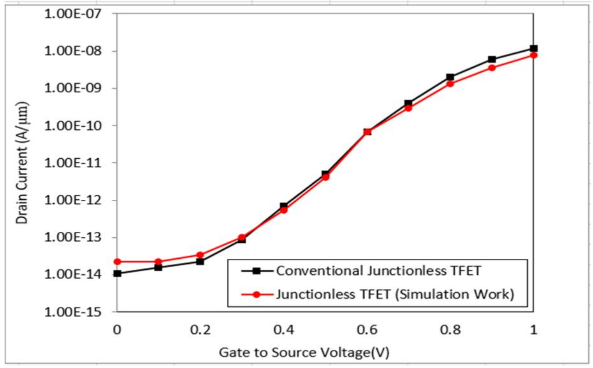

Figure2: Empirical values of output drain current of JL-TFET in comparison with the given junction less TFET at drain to source voltage=1V

Various models are used for creating DG-DM-JLTFET such as CVT model [13], band to band tunnelling model and Fermi Dirac model. The junction less idea proposed the formation of a thin and narrow semiconductor layer for complete depletion of charge carriers when the device is in off condition. There is an essential requirement of this semiconductor layer to be highly doped. Since we apply a high work assessment to the top gate a junction gets formed by depleting carriers of one type into region of another type. Several variables of DG-DM-TFET are enlisted in the table 1 down below.

Device Values Of DG-DM-JLTFET

Different Parameters	Values
Gate work assessments of Gate1 and Gate2	*3.9eV and 4.5eV*
Thickness of gate oxide (t_{ox})	*3nm*
Gate length of overlap region	*42nm and 43nm*
Spacer length	*3 nm*
Cavity region width	*2.5nm*
Gate1, Gate2 and Gate3 length	*25nm, 15nm and 10nm*
Work function of Gate1 ($M1$) and Gate2 ($M2$)	*3.9 eV and 4.5 eV*

1) *Calibration Attributes:* The simulated outcome of experimental result is calibrated with the reported work in [13] is depicted in Figure 2. Plot Digitizer tool has been employed to give the output data.

III. RESULTS AND DISCUSSIONS

The n-type Dual Gate junction less tunnel field effect transistor (DG-DM-JLTFET) is explored in this manuscript sensor by using the SILVACO ATLAS [13] tool. We observed that the value of relative permittivity i.e., k>1 is higher in comparison with the permittivity of air i.e., k=1. This represents the point where biomolecules fill the nanocavity space. When the biomolecules get immobilized in the cavity, the value of relative permittivity gets changed. In order to recognise the biomolecules which are confined in the nanogap area, certain biomolecules [8-9] are coordinated with the dielectric constant of material present in the nanogap. The efficiency of biosensors is calculated by employing ON current sensitivity as given below:
Formula of Sensitivity of drain current is given by following equation:

$$\Psi_{drain\,current}(\%) = [((\Psi_{bio} - \Psi_{air})/\Psi_{air})X100] \quad (3)$$

Where Ψ_{bio}, Ψ_{air} depicts the drain current values in both the cases of nanogap possessing the biomolecule or without the biological molecule respectively. [12].

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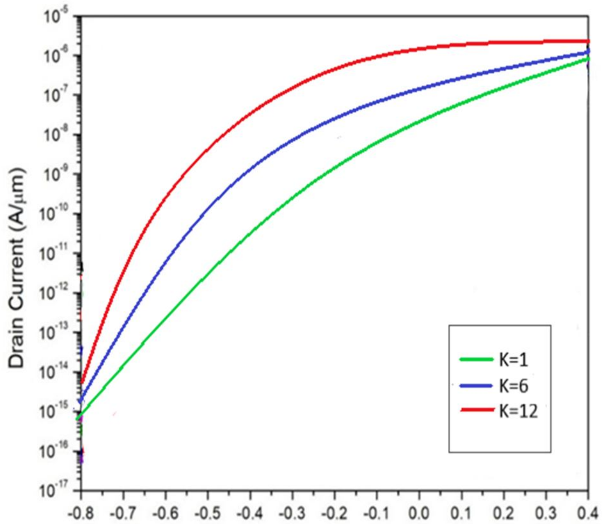
A. Effect Of Cavity Length On Drain Current

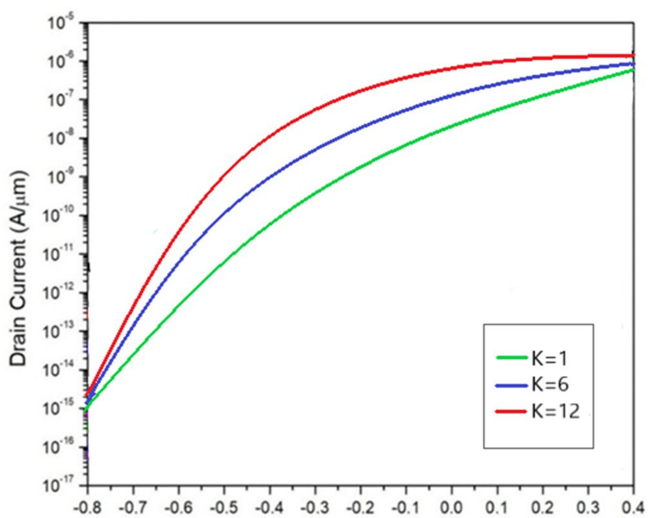
When the several neutral biomolecules are bounded in the nanocavity then we can observe the pattern of drain (output) current with respect to different values of potential present at gate at the given cavity length of 6nm and 7nm respectively in figure 3. There is a sufficient change in the characteristics of drain current of the device in ON state. The drain current increases when the cavity length is decreased from 7nm to 6nm. Moreover, an increase in drain current is observed as the value of K increases from unity. In figure 3 we observe the value of drain current for three different biomolecules having dielectric constant K=1,6,12 respectively. The drain current increases for biomolecules having higher dielectric constant from unity (K>1). At K=12 the drain current obtained is $2.45*10^{-6}$ (A/µm).



Gate Voltage (V)

Figure3: Drain current improvement when neutral biomolecules are bounded in the nanogap region of length 6nm

In figure 4 the analysis is done at the results obtained at 7nm. Since, here the cavity length is more than in previous figure therefore tunnelling will be reduced as a result there will a decrease in the drain current obtained for different biomolecules. But in both the figures the drain current will rise for biomolecules having higher dielectric constant. At K=12 the drain current obtained is $9.26*10^{-7}$ (A/µm).



Gate Voltage (V)

Figure4: Drain current improvement when neutral biomolecules are bounded in the nanogap region of length 7nm.

B. Drain Current Sensitivity Variation On Cavity Length

Variation of drain current sensitivity for neutral biomolecules is observed for different cavity length in the suggested junction less device. In figure 5 the channel length of 6nm and 7nm is taken respectively. The highest sensitivity of drain current obtained at 7nm is 85 and at 6nm is 75. The biomolecule having relative permittivity of K=6 is taken for reference. To calculate sensitivity ratio of two drain currents is considered i.e., the drain current obtained when cavity is filled with air and the drain current obtained when cavity is filled with biomolecules.

$$Sensitivity = \frac{drain\ current(bio)}{drain\ current(air)}$$

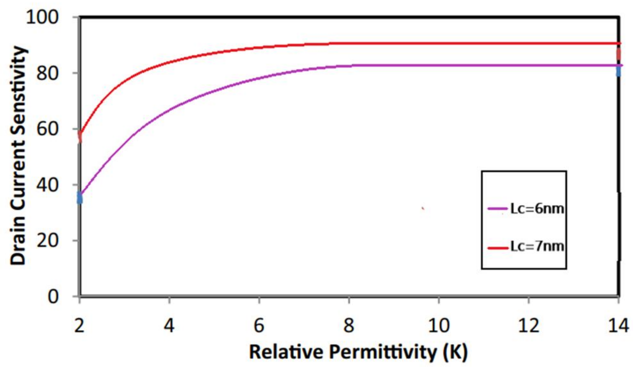


Figure5: Drain current variation w.r.t to gate to source voltage having cavity length =7nm; K=6

IV. CONCLUSION

However, DG-DM-JLTFET has higher sensitivity, specificity pertaining to biosensor application. High sensitivity for neutral and charged biomolecules is possible through label free detection of biological molecules by the proposed DG-DM-JLTFET device structure. Another advantage is that it suffers through less amount of short channel effects. Biosensors suffer problems in its fabrication processes and evaluation of biosensors under wet and dry conditions. When there is an expansion of immobilized biomolecules in the nanocavity it induces in increase in sensitivity for the proposed deign structure. label free detection enables to achieve higher sensitivity for various biomolecules. It is observed that the proposed design of device structure possesses higher drain current at lower cavity length and higher drain sensitivity for neutral biological molecules at larger cavity length.

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