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ORIGINAL PAPER

Design and Performance Analysis of Proposed Biosensor based on Double Gate Junctionless Transistor

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Abstract
In this paper, the label free detection of neutral and charged biomolecules with the potential capability of dielectric modulated double gate junctionless metal oxide semiconductor field effect transistor (DM-DGJLT) is explored. The design parameters of biosensor have been varied to investigate the sensitivity of the proposed device. The sensitivity of the proposed device is explored by using the high K oxide and the dielectric constant is further modulated by considering different biomolecules in the cavity. The proposed device offers best ON current of order ~ 10^{-4} A/um, OFF current ~ 10^{-16} A/um and ON/OFF current ratio of 10^{12}.The deviation in the threshold voltage found to be ΔV_{th}=0.34 V and ΔV_{th}=0.23 V for K = 10 and K = 1 respectively. Also, other performance parameters such as subthreshold slope, drain induced barrier lowering and central potential are also explored for the proposed device. The cavity length along with dielectric constant is also varied to study the performance of the biosensor. The OFF current reduces with the reduction in cavity length. Therefore, ON/OFF current ratio found to be higher for lower cavity length. It is also concluded that sensitivity for the biosensor is higher by the absorption of high-K protein biomolecules in the cavity region. Also, the effect of steric hindrance and Partial hybridization in proposed biosensor is also explored.

Keywords Dual Gate · High-K · Biosensor · Neutral and charged biomolecules

1 Introduction

With the development of semiconductor devices over the past few years, the conventional transistor with p-n junctions are overcome by junctionless(JL) transistors due to easiness in the fabrication, lesser short channel effects [1–6] thus making the junctionless transistors as promising candidate for low power applications and memory applications [7]. Also, in addition to these applications junctionless transistors have also become an emerging field in detecting the biomolecules. Thus biosensor is the powerful device that comprises of bio recognition component. The fundamental progress in semiconductor materials led to the development of such biosensors to achieve high sensitivity in biological sensor. The ion-sensitive field-effects-transistors (ISFET), where the number of free electrons that can be forced to drift through the sensitive material depend upon the amount of potential difference across the element. Still, there are numerous drawbacks associated with ion sensitive field effect transistor (ISFET) based biosensors as well [8]. The requirement of label process which demands the preparation of solution that involves synthesis, purification and requirement of the expansive probes which results low productivity or yields [9]. Therefore, the label free recognition of the biomolecules that incorporate the molecular properties such as dielectric constant (K) are introduced. Moreover, the label-free biosensors also allow to ignite rapid detection of biomolecules in absence of convoluted and overpriced electrodes [10]. The label free analytes are classified into neutral and charged biomolecules.

The increase in the sensitivity and selectivity of biomolecules uses various approaches which are based on MOSFET are discussed in [11–18]. An another method is based on asymmetric gate operation where analytes immobilize in the cavity located in front gate oxide which easily detect the species with respect to change in electrical characteristics of the analytes. Still, there are many challenges using conventional FET like weak selectivity, poor signal to noise ratio, long

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detection time. The major requirement is expansion of sensing area such that effective detection of the molecules could be achieved. There are different architectures of biosensors which are designed by various researchers using conventional MOSFET based on dielectric modulation within the cavity. In ref. both side cavity structure was proposed with very high concentration and without stack. In addition to enhance the sensitivity and increase signal to noise ratio the dimensions of the biosensor structure must be scaled down which further participate to detect small concentration of species Authors have also used tunnel FET for biosensing applications. Hence, the work presented in this manuscript mainly focus on the sensitivity based on optimum dimensions of the device with lower concentration such that dopant fluctuation could be reduced. In this paper, the dielectric modulated junctionless dual gate with high k oxide as a biosensor with neutral or charged biomolecules are investigated using different parameters. The effect of variable dose of biomolecules on the performance parameter of the proposed device is also explored. The neutral biomolecules in this work is considered as Streptavidin whose K = 2.1, protein with $K = 2.5$, biotin whose $K = 2.63$ and APTES with $K = 3.57$ [19] etc. Also, the effect of cavity length on ON/OFF current ratio along with different gate dielectric constants is also explored. The manuscript is catalogued as follows. Section 2 presents the simulation setup and device parameters used during simulation. The results and discussion along with conclusion are presented in Sections 3 and 4 respectively.

2 Device Structure and Simulation

The n-type dielectric modulated junctionless dual gate with high k oxide biosensor (DM-DGJLT) structure is shown in Fig. 1 where L1 and L3 are the length of the nanocavity. The use of high–k materials to separate the cavities of each under the gate are used that modulate the dielectric constant. When substrate is present to the air, a native growth of oxide layer as SiO_2 with thickness of 1nm is considered in the cavity regime and two cavities are differentiated with layer of high k as HfO_2 of thickness 10 nm. The t_{bio}, t_{si}, t_{ox} are nano cavity thickness, channel thickness and gate oxide thickness respectively. The length of cavity is altered from 9nm to 15nm.

The entire simulation is performed using Cogenda simulation tool [20]. There are various models used during simulation which includes Lombardi, Analytical, Constant mobility model and Boltzmann transport statistics used for drain current along with other statics of device. The quantum mechanical effects and ballistics transport effects are not considered in our work. The various design parametric values used during simulation of biosensor are tabulated in Table 1.

In order to validate the simulation models used in our work, the calibration of biosensor for channel length 100nm with I_d vs. V_{gs} characteristics from ref. [21] are reproduced in Fig. 2 and found to have close match between them.

3 Results and Discussion

The sensitivity of biosensor is investigated by substituting the analytes in nanogap cavity with air whose K = 1 that indicates none of the biomolecules is immobilized in contrast when K > 1 by simulating for both neutral and charged analytes. The neutral biomolecules in this work is considered as Streptavidin whose K = 2.1, protein with $K = 2.5$, biotin whose $K = 2.63$ and APTES with $K = 3.57$, Zein with K=5–7, Gluten with K=7 and Keratin with K=8–10 [15, 22, 23]. The thickness

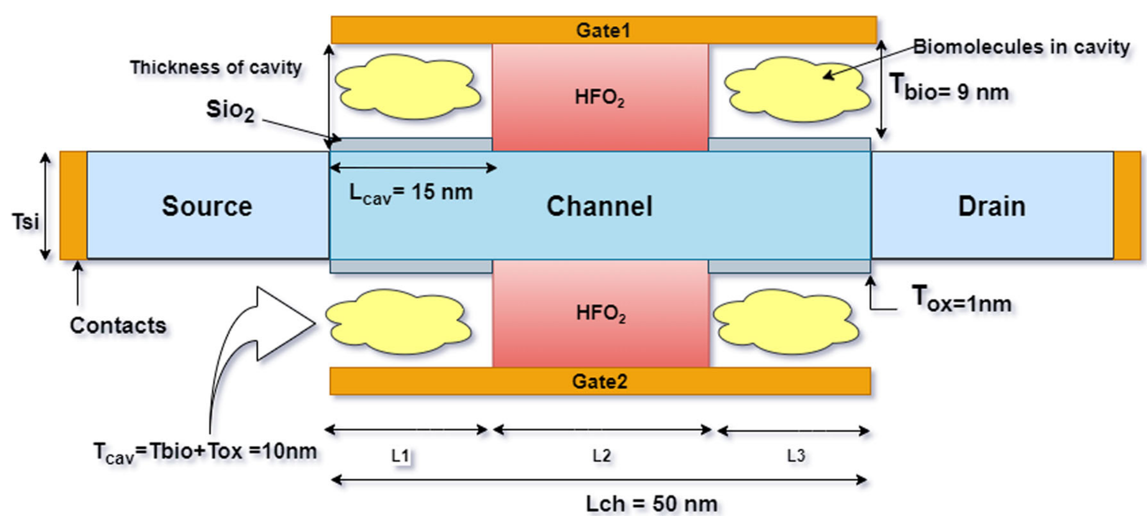

Fig. 1 Structure of dielectric modulated junctionless dual gate high-k (DM-DGJLT) biosensor

Table 1 Physical parameters of dielectric modulated junctionless dual gate high-K biosensor

Physical Parameters	Values
Gate Length (L_g)	50nm
Length of cavity (L_{cav})	15nm
Source and Drain Length	20nm
Thickness of $SiO_2(t_{ox1})$	1nm
Thickness of $HfO_2(t_{ox2})$	9nm
Diameter of Si channel(t_{si})	10nm
Si channel doping concentration (N_d)	10^{15}- 3×10^{18} cm^{-3}
Work function of gate electrode (m)	5.1-5.3 eV

and permittivity of biomolecules are tabulated in Table 2. This paper also investigates the charged analytes either positive or negative fixed oxide trap charges.

The operation of the dielectric modulated junctionless dual gate high-K field effect transistor (DM-DGJLT) is based on the work function difference between the gate material and the channel region. The work function difference helps to deplete the charge carriers in the OFF state of the operation. The depletion of the carriers helps to obstruct the flow of current and widens the depletion region. For n-type DGJLT, when positive voltage is applied at the gate, the carriers starts coming in the channel region, reducing the depletion region and hence conduction starts. The nanogap cavity is filled either with air or other biomolecule whose K > 1, alters the gate capacitance which further alters the potential in the channel and hence performance parameters gets changed. Based on the performance parameters, the sensitivity of the biosensors could be determined. Therefore, whenever a biomolecule encounters in the nanogap cavity, the performance parameters

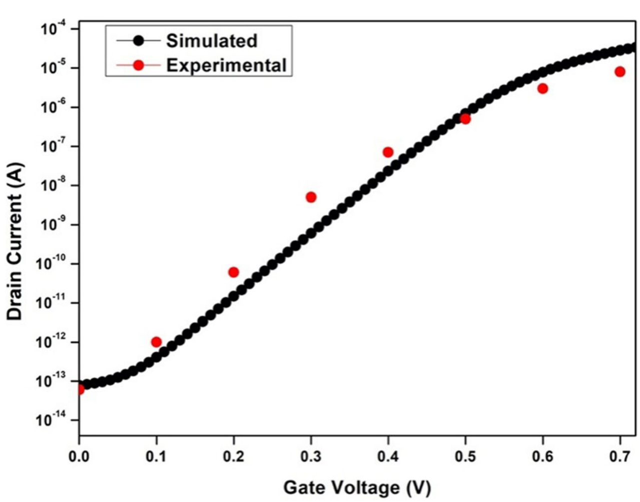

Fig. 2 Calibration of simulation models by reproducing the results from ref [21]

Table 2 Thickness and permittivity of Biomolecules [24]

Biomolecules	Bio Thickness (Tbio)	Bio Permitivity (€bio)
Aptes	0.9nm	3.57
Biotin	0.6nm	2.63
Streptavidin	6.1nm	2.1
Zein		5–7
Gluten		7
Keratin		8–10

gets altered and thus biosensors shows their effectiveness to detect the biomolecules [25].

3.1 Variation in Drain Characteristics of Proposed Biosensor

Figure 3 shows drain characteristics of the proposed biosensors for neutral and charge analytes interacting in the locale region respectively. It is observed from Fig. 3 that after immobilization of the neutral biomolecules as air whose K = 1 to K > 1 for the case of streptavidin, biotin, APTES, protein, enzymes, cell and DNA, the OFF current reduces drastically from 10^{-12} A/um to 10^{-15} A/um along with minor change in the ON current. The ON current is of the order 10^{-4} A and OFF current is observed as $6.78\,X\,10^{-15}$ A/um for K = 10. The ON current is found at V_{gs}=1 V and OFF current is calculated at V_{gs}=0 V at V_{ds}=1 V. The length of the cavity is kept at 15nm. The reduction in the OFF current is due to the effective control of the gate over the channel along with huge depletion the carriers in the channel. Similarly, Fig. 3 shows the I_d-V_{gs} characteristics of proposed biosensor with the charge analytes in the cavity region. The positive charge is varied from 10^{12} C/cm^2 to 4 × 10^{12} C/cm^2. The positive charge molecules when immobilized in the cavity region of n-type proposed biosensor increases, the OFF current found to be increasing. This is due to decrease in the width of space charge region inside the channel and thus decreasing the control of the gate over the channel. For the negative charge molecules which are varied from − 4 × 10^{12} C/cm^2 to -10^{12} C/cm^2 at fixed dielectric constant of 10, the OFF current also increases. The value of OFF current at different biomolecule charge is listed in Table 3.

3.2 Performance Parameters of Proposed Biosensor

Figure 4 shows the ON current and ON/OFF current ratio for proposed DM-DGJLT biosensor as the variation of charge of biomolecules. The sensitivity of the biosensor is an important parameter to be studied for analyzing the device performance. It is observed from the figure that ON current kept on increasing as the charges of biomolecules changes from negative to

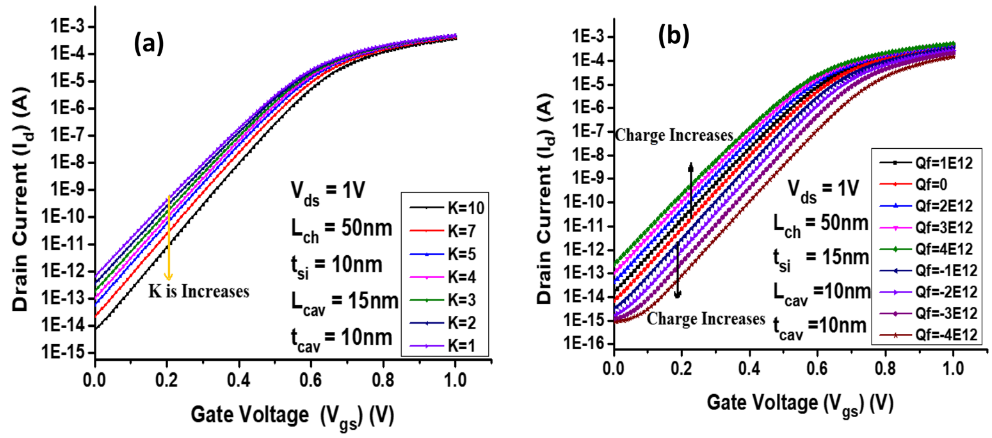

Fig. 3 I_d-V_{GS} characteristics with different biomolecules of DM-DGJLT-based biosensor **a)** For neural biomolecules **b)** For both positive and negative charged biomolecules

positive whereas ON/OFF current ratio shows an interesting behavior when charges of the biomolecules changes from negative to positive. The ON/OFF current ratio is larger for negative charge biomolecules and lesser for positive charge. This is due to lesser OFF current for negative charge biomolecules. This can be understood by the fact that for negative charge biomolecules, the negative charges repel the electrons from the surface and thus widen the space charge region of the channel reducing the OFF current. For positive charge biomolecules, ON/OFF current ratio undoubtedly increases on increasing the charge of biomolecule from 10^{12} C/cm^2 to 4 × 10^{12} C/cm^2, but to the lower extent. For positive charge biomolecules, the positive charge attracts the electrons to the surface thus reducing the space charge region which results into the more carriers in the channel reducing the resistance and thus increasing the ON current which in turn increases ON/OFF current ratio to the lower extent. It can be concluded that for negative charge biomolecules, the ON/OFF current ratio is higher due to dominancy of reduced OFF current whereas for positive charge biomolecules, the ON/OFF current ratio is lesser than negative charge biomolecules due to dominancy of increased ON current. Another performance parameters includes subthreshold swing (SS) and drain induced barrier lowering (DIBL). The turn ON characteristics of the device is measured by SS and expressed as mV/decade. The lower value of SS indicates the better channel control and hence improved ON/OFF current ratio. The SS is calculated as 63.80mV/decade. The DIBL is calculated as 31.25mV for the proposed biosensor [26].

3.3 Variation of Threshold Voltage of Proposed Biosensor

Threshold voltage is an important parameter which is the minimum gate-source voltage required to create a conduction path between source and drain [27]. The threshold voltage changes the mode of operation from depleted region to partial depletion region in JLT. The threshold voltage is calculated for the proposed device using constant current method. The deviation of the threshold voltage is observed on varying the dielectric constant (K > 1). This results in the detection of analytes when the charge is zero. Figure 5 shows the threshold voltage variations with respect to different dielectric constant for neutral biomolecules and Fig. 5 shows the threshold voltage variation with respect to charged biomolecules. The threshold voltage found to be increasing with increase in the dielectric constant. The deviation in the threshold voltage found to beΔV_{th}=0.34 V and ΔV_{th}=0.23 V for K = 10 and K = 1 respectively. Thus, sensitivity is found to be 110mV for the device cavity of 15 × 10nm. It has been observed that in reference [21], the sensitivity found to be 90mV for cavity size of 25 × 10nm for K = 10. This clearly shows that the enhancement in threshold voltage of proposed biosensor with smaller dimensions found to be approximately 20 % for neutral biomolecules and 66 % increase in case of positive charge biomolecules. The sensitivity at fixed neutral biomolecules at K = 10 is 90mV for positive charged biomolecules and 130mV for negative charged biomolecules which can be obtained as

Table 3 OFF current with varying charge at constant Dielectric constant K = 10

Biomolecules charge (Q_f) [C/cm^2]		4	3	2	1
OFF current (A/um)	Positive charge Biomolecules	2.32×10^{-13}	1.01×10^{-13}	4.19×10^{-14}	1.67×10^{-14}
	Negative charge Biomolecules	8.42×10^{-16}	1.13×10^{-15}	1.68×10^{-15}	3.06×10^{-15}

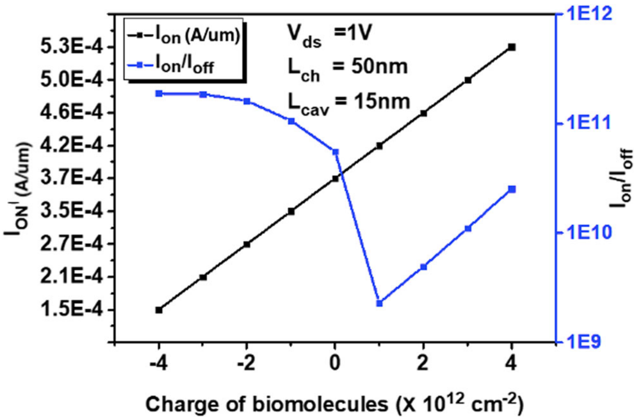

Fig. 4 Variation of ON current and ON/OFF current ratio of proposed DM-DGJLT based biosensor

$$V_{th}=\left(V_{th(NeutralBio)}-V_{th(ChargedBio)}\right)V$$

3.4 Variation of Central Potential of Proposed Biosensor

The variation of central potential of the proposed biosensor along the channel on varying the dielectric constant for neutral biomolecules and charged biomolecules are investigated in this section. Figure 6(a) shows the central potential varying along the channel when the cavity is made free from the biomolecules that indicates none of the analytes are immobilized in the cavity region. For such case the central potential increases by 0.5 and 1.5 V in source side and drain side of the channel respectively. When the analytes are made to interact in locale on increasing the dielectric constant (K), the central potential reaches at the minima of -0.58 V. The reason is increase in the gate capacitance on increasing the dielectric constant in the cavity region which leads to enhance the vertical electric field. This depicts the coupling enhancement between the gate and channel that leads to the increase in the gate voltage which further depletes the channel and hence more threshold voltage is acquired. Figure 6(b) shows the central potential along with the position of the channel for both positive and negative charged biomolecules. It is observed that when the cavity is filled up with charged analytes, the central potential decreases for negative charge analytes. The central potential is observed to be approximately −0.59 V for Q_f=0 C/cm^2 and −0.66 for Q_f=-4 × 10^{12} C/cm^2. The reason behind this is the increase in flat band voltage from qN_f/C_{eff}, that decreases the central potential. This also indicates more depletion in the channel region which in turn leads to greater control of the gate. For positive charge biomolecules, the central potential is highest at -0.48 V. This is due to the stronger attraction between the charges present in the cavity and channel. The higher central potential implies non-depletion of the charges in the channel and thus representing the weakening of the gate control. This further decreases the threshold voltage.

3.5 Effect of Variation of Cavity Length on Performance Parameters of Proposed Biosensor

The effect of length of the cavity of proposed biosensor on the ON/OFF Current ratio is investigated in this section. The length of the cavity is varied from 9nm to 20nm for channel length 50nm and thickness of the cavity is kept at 10nm. Figure 7 shows the variation of ON/OFF current ratio for different cavity length and varying dielectric constant. On decreasing the cavity length from 20nm to 9nm, the ON/OFF current ratio found to be increasing. For dielectric constant K = 10, the OFF current is found to be lowest for 9nm cavity length. This leads to increase in ON/OFF current ratio for lower cavity length for any value of dielectric constant. The reason of increase in ON/OFF current ratio for lower cavity length can be explained in a way that analytes become closer to the center of the channel and thus channel potential barrier gets more influenced over the capacitive effect of the analytes [28]. Also, for smaller cavity length for K = 10, the threshold voltage is also higher that leads to the improve in the performance parameters. The values of OFF current and

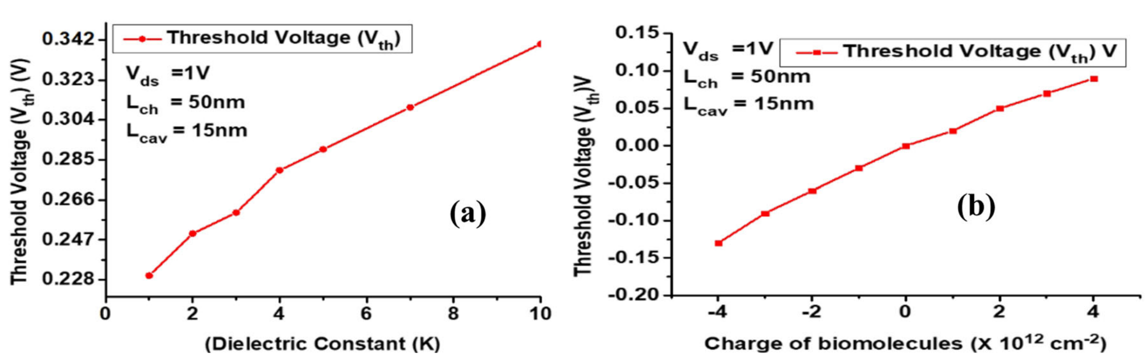

Fig. 5 Threshold Voltage (V_{th}) for n-type DM-DGJLT biosensor **a)** Neutral Biomolecules on varying dielectric constant K **b)** Threshold voltage for charged biomolecules

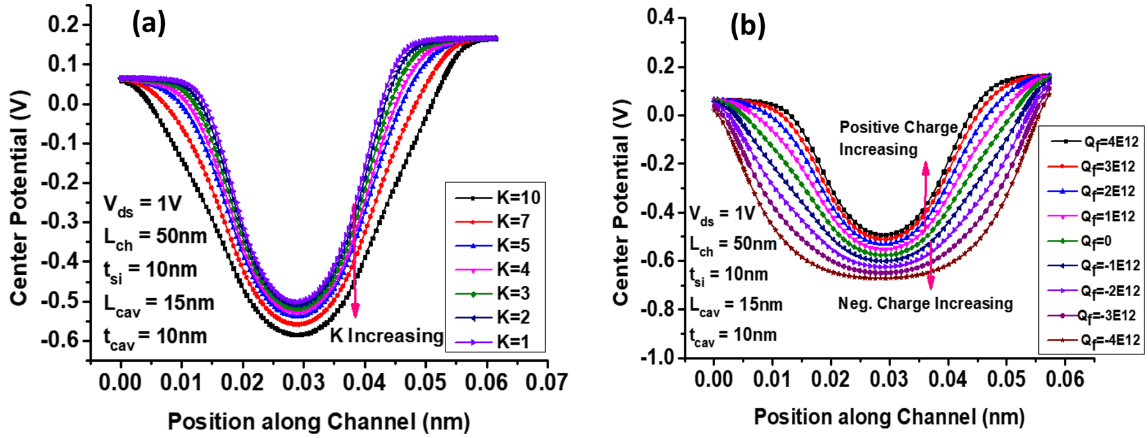

Fig. 6 Variation of Central Potential along with channel for **a** Neutral biomolecules in cavity with varying dielectric constant **b** For charged biomolecules

threshold voltage for different cavity lengths is given in Table 4.

3.6 Analysis of Partial Hybridization in Proposed Biosensor

The effect of steric hindrance causes immobilized bio-analytes to hinder the further entry of biomolecules. Therefore, it becomes equally important to consider the partial filling of nanogap cavities [29]. Hence, in this section, the impact of Partial Hybridization (PH) issue has been presented for double gate junctionless based bio-sensor. In the simulation, the non-uniform step arrangements of biomolecules (Aptes [K = 3.57]) such as increased, decreased profiles are considered. Figure 8 shows the structure of proposed bio-sensor with non-uniform step arrangements of biomolecules with increased and decreased profile respectively. The non-uniform step arrangements of biomolecules has been placed in all fours regions of nanogap cavities.

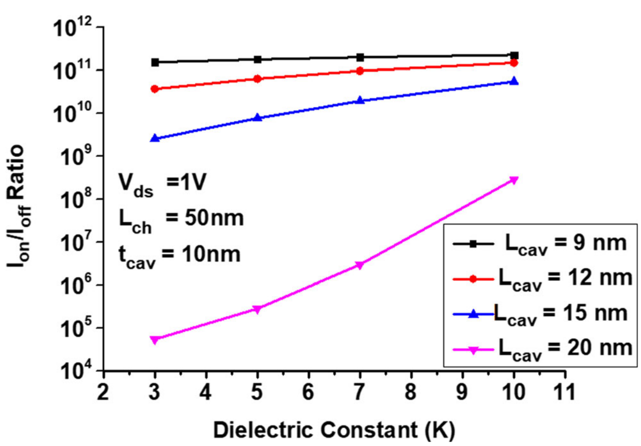

Fig. 7 ON/OFF current ratio vs. Dielectric Constant (K) for different cavity lengths

Figure 8 shows I_d-V_{gs} characteristics of proposed biosensor with and without PH. It has been observed that on introducing the partial hybridization with increased/decreased profile in the nanogap cavity, the OFF current increases compared to without PH. This is probably due to effective reduction in the control over the carriers in the device. A slight reduction in threshold voltage is also observed with PH effect in either increased/decreased non-uniform step profile.

4 Conclusions

In this work, a dielectric modulated double gate junctionless field effect transistor (DM-DGJLT) has been proposed for biosensing application. Using extensive simulations, various design parameters have been altered to achieve best performance parameters of the proposed device and hence higher

Table 4 Threshold voltage and OFF current at various cavity lengths

Cavity Length (L_{cav}) (nm)	Biomolecule Dielectric Constant (K)	Channel length (L_{ch}) (nm)	Threshold Voltage (V_{th}) (V)	OFF current (I_{off})
20	10	0.05	0.42	1.89×10^{-12}
15	10	0.05	0.0421	6.79×10^{-15}
12	10	0.05	0.42	2.15×10^{-15}
9	10	0.05	0.432	1.22×10^{-15}

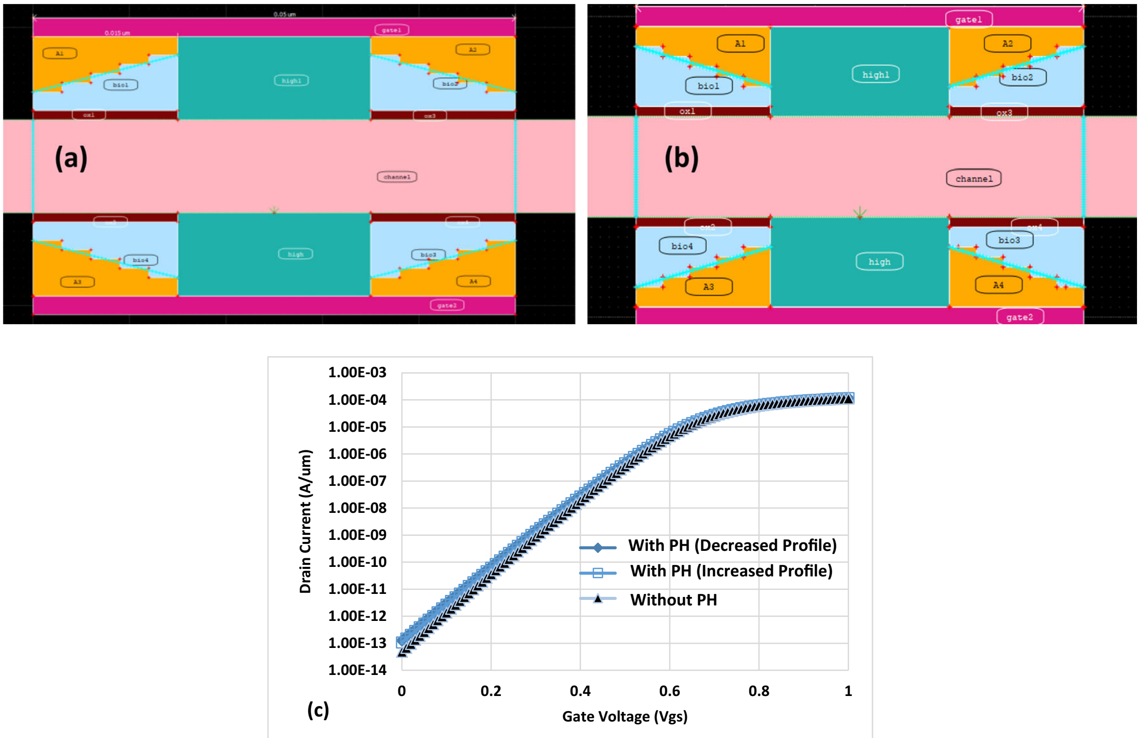

Fig. 8 (**a** & **b**) Structure of proposed bio-sensor with non-uniform step arrangements of biomolecules of in increased and decreased profile respectively **c**) I_d-V_{gs} characteristics of proposed biosensor with PH and without PH

sensitivity for biosensing application. The proposed device offers best ON current of order ~ 10^{-4} A/um, OFF current ~ 10^{-16} A/um and ON/OFF current ratio of 10^{12}.The deviation in the threshold voltage found to be ΔV_{th}=0.34 V and ΔV_{th}=0.23 V for K = 10 and K = 1 respectively. The central potential has been evaluated for both neutral biomolecule and charged biomolecule. The central potential is observed to be approximately − 0.59 V for Q_f=0 C/cm^{2}and − 0.66 for Q_f=-4 × 10^{12} C/cm^2. Also, The cavity length along with dielectric constant is also varied to study the performance of the biosensor. The OFF current reduces with the reduction in cavity length. It is also concluded that sensitivity for the biosensor is higher by the absorption of high-K protein biomolecules in the cavity region. Also, on introducing the PH effect in proposed biosensor with Aptes as biomolecule, the OFF current found to be on higher side.

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Author Contribution Author's have equally contributed to the work.

Data Availability No data was used for the research described in the article.

Declarations

Conflict of Interest The authors declare that they have no conflict of interests.

Consent of Participate Informed consent was obtained from all individual participant included in the study.

Consent of Publication Not applicable.

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