



Detection of biomolecules in dielectric modulated double metal below ferroelectric layer FET with improved sensitivity

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Received: 31 December 2021

Accepted: 16 April 2022

Published online:

7 May 2022

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ABSTRACT

In this work, we examined the double metal below ferroelectric layer FET that is double metal below negative capacitance field-effect transistor (DM-below-NCFET) for biosensing application and change in nanocavity gap with biomolecules as protein, ChO_x (cholesterol oxidase), streptavidin, and uricase. For measuring the electrical characteristic and neutral biosensing such as threshold voltage, switching ratio (I_{on}/I_{off}) of the device which is higher than one without molecules by 1.52 times, sensitivity of protein enhanced by 1.11 over without biomolecule, limit of detection of protein is higher by 1.012 times over without molecule, shift in potential have been researched for cavity length 10 nm. The biosensor indicated improved sensitivity for biomolecules with the rise in their dielectric parameter. Moreover, modulation of the length of the gap of cavity was too examined, exposing that its increment (from 8 to 12 nm) altogether upgraded the sensitivity of the proposed biosensor. Visual TCAD (Technology Computer-Aided Design) software is used for simulating all results. In general, the consequences of this examination represent that such DM-below-NCFET biosensors can display extreme sensitivity (1.11) at small drain voltage (0.4 V), empowering their utilization for biosensor applications to analyze different infections which involve low power, extreme density, and enhanced speed.

1 Introduction

The new COVID-19 epidemic has once more gained a bleeding edge on the impact of microelectronic biosensors in recognition of biomolecules and biological fighting specialists. The applications might be discovered by electronic biosensors uninterruptedly

observing inflight biomolecules in conveyance contexts like airplanes and metro rail and midway cooled structures like hospitals, schools, clinics, and so forth. Consequently, the requirement of great importance is to plan and foster quick and precise biosensors. Biosensors utilize chemical responses to distinguish the biochemical mixtures like antibodies,

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enzymes, nucleic acids, proteins, and so forth. So they are broadly utilized in numerous applications like checking of infections, food investigation, crime detection, ecological field observing, and for the investigation of biomolecules cooperation [1, 2].

Various strategies have been created for recognizing of biomolecules such that the chemical connected immunosorbent measure [3], for Alzheimer's illness, coronary vein infection, and ovarian cancer. In any case, numerous of these methodologies are convoluted and tedious caused by the necessity for modeling procedures [4]. Field-effect transistor (FET) constructed biosensors have drawn in much consideration from late years inferable from their great versatility, extreme sensitivity, quick electrical identification, small force utilization, straight electrical display, and minimal expense large-scale manufacturing in correlation with different strategies, for example, surface plasmon resonance [5], microcantilevers [5], and varieties of fluorescence devices [6, 7]. Minimal expense, profoundly touchy, dependable, easy to use, and speedy symptomatic biosensing gadgets are fundamental for various organic and biomedical applications [8]. For biosensing functions, the main component of key for a MOSFET is sensitivity [9].

Ferroelectric FETs (Fe-FETs) have pulled in improved consideration because of their guarantee in both memory and exchanging applications [10]. Size and power consumption are the main figures of value of any advanced electronic device and the objective of past and present research endeavors is to devise forcefully scaled devices that consume ultralow power [11]. The effect of channel length scaling was excluded by NCFET. Additionally, the last utilizes the Landau model just in the outside-of-plane polarization part, which is not reasonable for huge ferroelectric thicknesses [12]. In our previous works, we examined and analyzed the execution of the double NCFETs with lengthy channels, utilizing logical displaying [13]. The Landau's parameters for the FE material is $\alpha = -1.0 \times 10^{-7}$ and $\beta = 8.9 \times 10^{-8}$ [14]. Double metal below negative capacitance FET (DM-below-NCFET) for protein biomolecule gives a higher ON-state flow contrasted to other biomolecule; be that as it may, we discover this not to be the case for all the ferroelectric materials. Moreover, a

definite actual understanding of the conduct of the dual constructions and general execution analysis is yet disappeared in the writing [15–20].

In this article, double metal below negative capacitance FETs (DM-below-NCFETs) for protein biomolecule enhanced the performance of the device in comparison with uricase, streptavidin, ChO_x (Cholesterol oxidase), without biomolecules such as higher sensitivity, lower leakage current, low input power consumption, and control over gate channel device. A new concept of a ferroelectric layer with a dielectric constant ($K = 33.5$) has been introduced. The matrix of device performance has been extracted by using visual TCAD (Technology Computer-Aided Design) software. In this DM-below-NCFET, the I_{off} is lying in the request for 10^{-12} A and thus has less releasing capacity from a battery point of view, which is useful for superior performance. The DM-below-NCFET has upgraded the sum of I_{on} and great depletion channel at off-state (i.e., at $V_{\text{gs}} = 0$). From this examination, we become more acquainted with the device that has phenomenal execution of analog and power amplification at the point when having an analogy and electrical stimulation between various biomolecules.

A proposed device has been utilized as a biosensor for detecting different biomolecules. The main use of the device is to comprehend different biomolecules, which is done when biomolecule ties to the gate of the device and modifies its surface charge. In the proposed DM-below-NCFET device (biosensor), the device's channel limit gets improved with the electrical curve of biomolecules from which they can be distinguished. In the traditional MOSFET, the current through channel flow when the gate voltage transcends the threshold voltage (V_{TH}) [2, 21, 22]. With a general high doping concentration, the DM-below-NCFET acts as a resistor. At the point when the quantity of charged analyte changes on the sensor surface, the conductance of the resistor changes likewise. Following recently talked about detecting instruments, the charges from analytes influence the conductivity of the device channel due to attractive or repulsion electrostatic force. All in all, the level of depletion inside channel changes because of charges from analytes in the arrangement [23].

2 Structure of device and method of simulation

Figure 1a reveals the structure of Double Metal below ferroelectric layer FET that is double metal below negative capacitance FET and Fig. 1b represent the spacer has biomolecules. For immobilization of biomolecules in the area of Bio1 and Bio2, the region between area source and gate (L_{bio1}) or drain and gate (L_{bio2}) is the same as cavity gap. Since the determining region is the most important characteristic and behavior of DM-below-NCFET, the channel's length (L_c) is 20 nm, body's length (L_b) is 60 nm, drain's/source's length ($L_{\text{d/s}}$) is 10 nm, the Bio1/Bio2 length ($L_{\text{bio1/bio2}}$) is 10 nm, body's thickness (T_b) is 50 nm, drain's/source's thickness ($T_{\text{d/s}}$) is 3 nm, oxide's thickness (T_o) is 1 nm, Ferroelectric's thickness (T_f) is 1 nm, Metal1's (T_{m1}) thickness is 2 nm, insulator's thickness (T_i) is 2.3 nm, Metal2's thickness (T_{m2}) is 1.7 nm, the thickness of Bio1/Bio2 is 2 nm, and the thickness of gate is 2 nm. The total gate thickness (T_{gt}) is the addition of thickness oxide, Metal2, insulator, Metal1, ferroelectric layer, and gate. The material of the body is Si (silicon), the material of drain/source/substrate/gate is Al (aluminum), the material of Insulator is nitrite, the material of oxide is

SiO_2 (silicon dioxide), the material of Metal1 is Au and Material of ferroelectric is $\text{HfO}_{2\text{FE}}$ (an innovative idea of a ferroelectric layer with hafnium dioxide). A proposed device DM-below-NCFET contains metal, insulator, metal, ferroelectric, intermediate gate, silicon dioxide, and silicon from top to bottom. The doping concentration of body (N_b) is $1 \times 10^{16} \text{ cm}^{-3}$ with uniform profile and acceptor type, the doping concentration of drain/source ($N_{\text{d/s}}$) is $1 \times 10^{20} \text{ cm}^{-3}$ with Gaussian profile and type of donor and the doping concentration of threshold voltage (N_{vt}) is $1 \times 10^{18} \text{ cm}^{-3}$ with Gaussian profile and acceptor type. The work function is very high kept at 5.4 eV for a Metal1 gate.

3 Simulation methodology

Visual TCAD system is used for simulating all results. This region is confined to Bio1 and Bio2 to introduce and identify biomolecules. In this work, impartial(neutral) biomolecules, for example, streptavidin, protein, uricase, and ChO_x are created in the gap of the cavity. Drain voltage, V_d (V) is fixed in the entire process at 0.4 V. Gate voltage, V_{gs} is different from 0 to 4 V. temperature (T) is fixed during the entire device simulation at 300 K (room temperature). So, the existence of impartial biomolecules can be patterned by initiating substance with a dielectric constant related to impartial biomolecules. This method has been calibrated with the outcomes of the experiments [6, 21].

The design is used in concentration-dependent mobility (CONMOB), field-dependent drift velocity (FLDMOB) model, Shockley–Read–Hall (SRH) recombination model, and polarization model. We utilize visual TCAD multiphysics to play out every single mathematical reproduction. Bioelectronics is focused on straightforwardly coupling biomolecular work units of high-atomic weight and incredibly confounded subatomic construction (chemicals, receptors, or entire, cells, and so on just as tissues, cell clusters, and organisms) with electronic or optical transducer device. Elective and new ideas are constantly emerged and proposed for future data advancements to address, control, read, and use data, requiring the improvement of constructions for signal take-up, transduction, enhancement, handling, and change [24, 25].

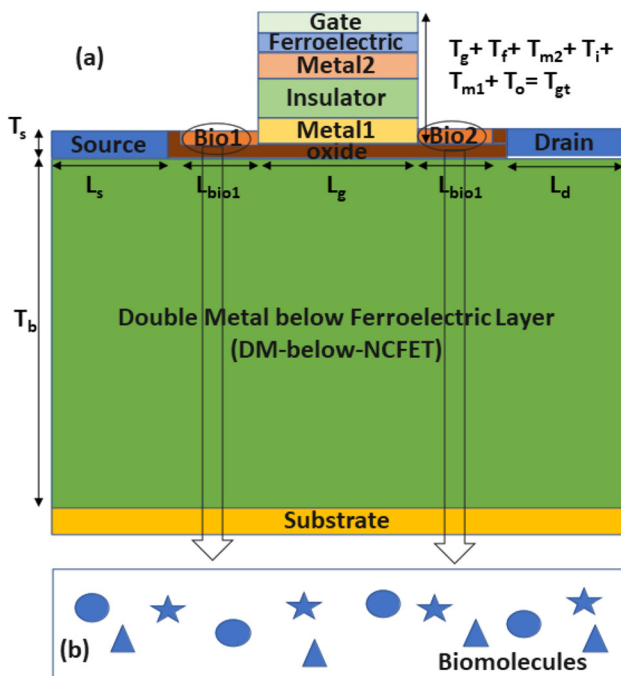


Fig. 1 Schematic diagram of double metal below ferroelectric layer FET (DM-below-NCFET) for biomolecules

The absorption of various biomolecules is patterned by the initiation of a non-conductor having the identical dielectric constant such as a specific biomolecule into the cavity's gap. The void cavity (i.e., without biomolecules present) is demonstrated by applying an insulator with dielectric constant ($K = 1$), although the dielectric constant of the diverse studied biomolecules is like this as shown in Table 1: protein ($K = 8$) [26], uricase ($K = 1.5$), ChO_x ($K = 3.5$), and streptavidin ($K = 2.1$) [27]. Streptavidin is utilized to distinguish Marek's disease virus (MDV) applying an enzyme-linked immunosorbent assay (ELISA) method [28, 29].

The essential thought behind a MD simulation is clear. Given the places of the multitude of atom in a biomolecular framework (e.g., a protein encompassed by water and maybe a liquid bilayer), one can compute the force applied on every particle by the wide range of various molecules. One can hence utilize Newton's laws of movement to foresee the spatial place of every molecule as an element of time. Specifically, one stages through time, more than once ascertaining the force on every iota and afterward utilizing those force to refresh the position and speed of every particle. The subsequent direction is, basically, a three-layered film that depicts the nuclear level setup of the framework at each point during the simulated time interval [30].

4 Results and discussion

4.1 Impact of dielectric modulation for cavity gap 10 nm

Figure 2 shows the curve between drain current, I_d (A) in linear scale and log scale vs gate voltage, V_{gs} (V) of different biomolecules for double metal below negative capacitance field-effect transistor (DM-below-NCFET) at $V_d = 0.4$ V, channel length, $L_c = 20$

Table 1 The value of dielectric constant for biomolecule

Biomolecules	Dielectric constant
Uricase	1.5
Streptavidin	2.1
ChO_x	3.5
Protein	8

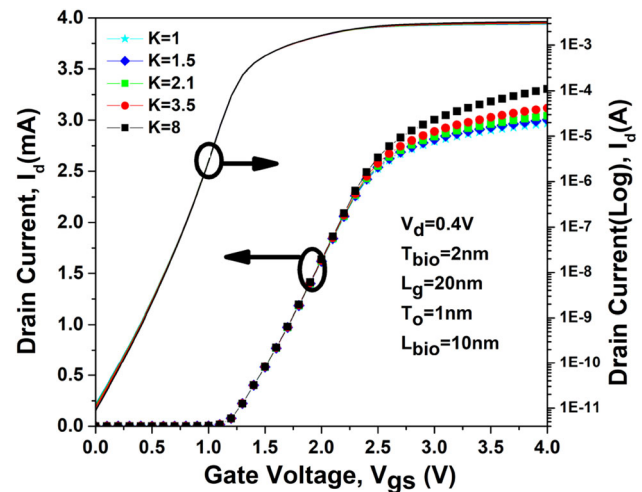


Fig. 2 Transfer characteristic of DM-below-NCFET for different biomolecules at drain voltage 0.4 V

nm, and oxide thickness $T_o = 1$ nm. The drain current of protein ($K = 8$) is higher than the others biomolecules, as enhanced drain current with an increase in dielectric constant that reflects the improved gate coupling capacitance and lowered leakage current I_{off} in the left side of the graph.

Figure 3 reveals that transconductance is a factor of the shift in drain current (I_d) to shift in gate voltage (V_{gs}) at drain voltage (0.4 V). The transconductance curve of protein is higher than the streptavidin, uricase, ChO_x , without molecules. Thus, the g_m has taken from the curve drain current vs gate voltage that reflects enhanced gate control and lowered short channel effects (SCEs) and also increases average

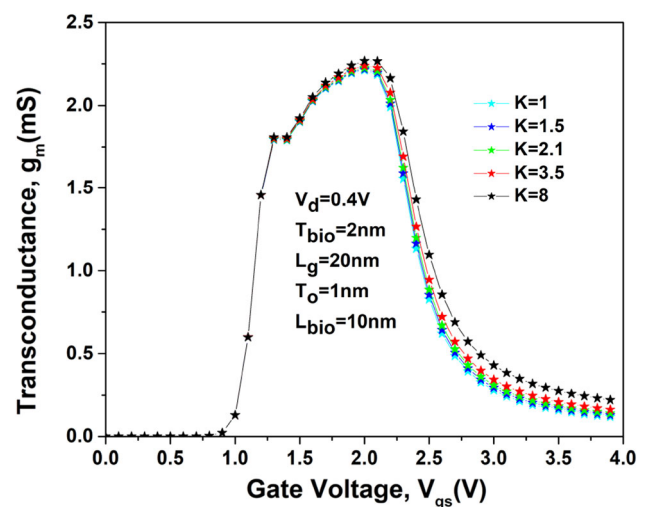


Fig. 3 Transconductance (g_m) of DM-below-NCFET for different biomolecules at V_d 0.4 V

carrier velocity, upgraded electron mobility with increase transconductance [31].

Figure 4 shows the threshold voltage, V_{th} (V) of protein is enhanced than other biomolecules configuration at drain voltage, $V_d = 0.4$ V because of enlarged gate control over the channel and biomolecule of protein is the better shield of drain-side potential so that improved the character of the threshold voltage. The threshold voltage is directly related to the dielectric constant was applied as a sensing application for recognition. Figure 5a shows the switching ratio, I_{on}/I_{off} of protein is higher than the different biomolecules at $L_g = 20$ nm, $T_o = 1$ nm, $L_{bio} = 10$ nm, and $V_d = 0.4$ V, decreased leakage current, I_{off} (A/um), and high switching speed for protein molecules ($K = 8$) is also obtained. Figure 5b implies the sensitivity of various biomolecules for instance protein, streptavidin, uricase, ChO_x , and without biomolecules at drain voltage 0.4 V as shown in Table 2. The cavity gap is completely filled with dielectric constant. The formula for sensitivity is given in Eq. (1).

$$S = \frac{I_{on}(K > 1)}{I_{on}(K = 1)} \quad (1)$$

Figure 6a–e represents the contour plot of electronic concentration of channel from source to drain for various dielectric constant Fig. 6a implies biomolecule is created, the extra charges become caused in the channel from source to drain in the region beneath the cavity. Charge quantity caused hangs on the various biomolecules. The electronic

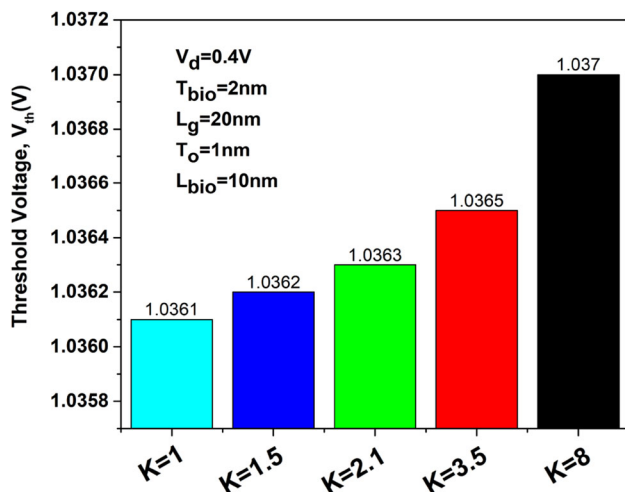


Fig. 4 The threshold voltage (V_{th}) of DM-below-NCFET for different biomolecules at $V_d = 0.4$ V

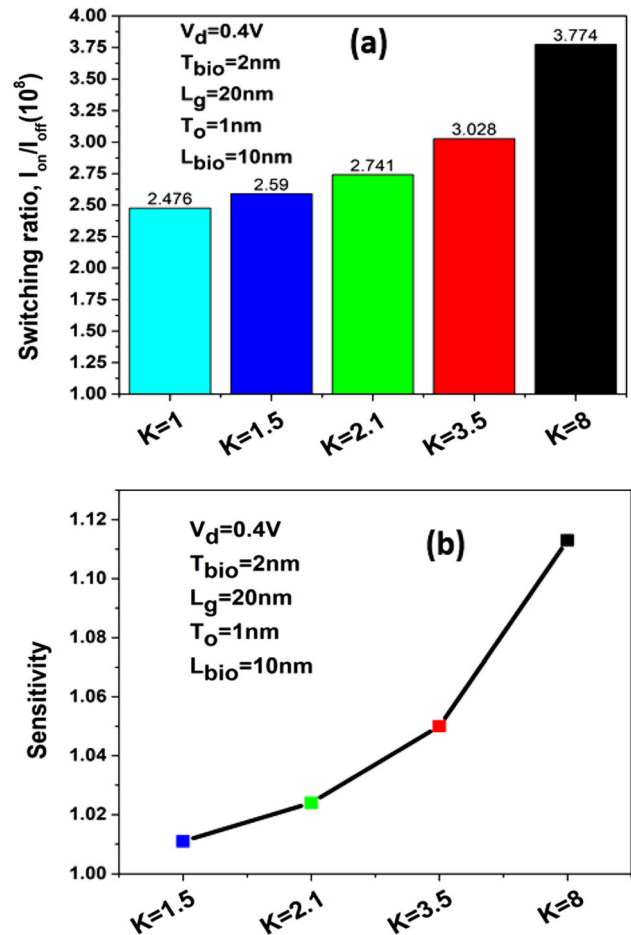


Fig. 5 **a** Switching ratio (I_{on}/I_{off}), **b** sensitivity of DM-below-NCFET for different biomolecules at drain voltage 0.4 V

Table 2 Value and parameter of DM-Below-NCFET for different biomolecules at $T_o = 1$ nm and cavity length 10 nm

Parameter	$K = 8$	$K = 3.5$	$K = 2.1$	$K = 1.5$	$K = 1$
I_{on} (mA)	3.31	3.12	3.04	3.01	2.97
I_{off} (pA)	8.76	10.3	11.1	11.6	12
I_{on}/I_{off} (10^8)	3.77	3.03	2.74	2.59	2.48
V_{th} (V)	1.037	1.0365	1.0363	1.0362	1.0361
g_m (mS)	2.27	2.23	2.21	2.2	2.19
g_d (nS)	0.662	0.698	0.718	0.731	0.744

concentration of protein at drain is worked at lower concentration. Due to the smallest value of the dielectric constant of without molecules, extra charges are created in the channel as shown in Fig. 6f that is deducted from the increase of drain current.

Figure 7a–e reflects the contour plot of the potential of the channel for diverse biomolecules. It is also

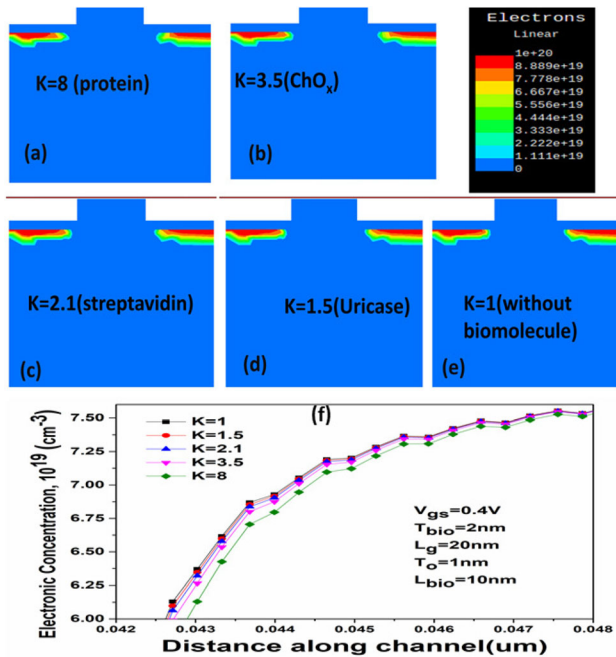


Fig. 6 a–e Electronic concentration contour plot of DM-below-NCFET at V_d 0.4 V for different biomolecules, for example, a $K = 8$, b $K = 3.5$, c $K = 2.1$, d $K = 1.5$, e $K = 1$, and f graph of electronic concentration vs distance along channel

the electrical performance of DM-below-NCFET. Changes of the potential occur (at the drain side) under the cavity region. When the cavity gap is immobilized by biomolecules [32], a deformation in potential is detected because of the shift in the dielectric constant caused by the biomolecules as shown in Fig. 7f. This change in potential can as well be applied to identify the existence of biomolecules in the cavity gap area.

Figure 8 signifies the plot of drain current, I_d (A) vs drain voltage, V_d (V) at gate voltage V_{gs} (0.4) oxide thickness of 1 nm, cavity gap of 10 nm, and channel length of 20 nm. Output conductance is the driving capacity of the device as characterized mirrors the locale of device activity as shown in Fig. 9. At first, a high-output conductance in the linear region is observed with increasing drain voltage beyond pinch-off voltage owing to drain-induced barrier lowering (DIBL) as well as channel length modulation (CLM) [33]. The g_d

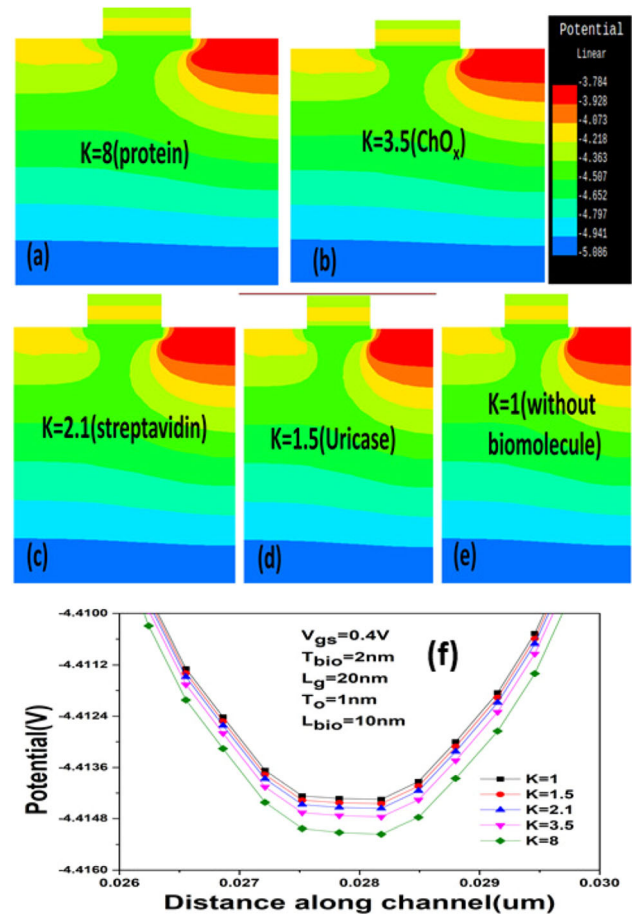


Fig. 7 Potential contour plot of DM-below-NCFET at V_d 0.4 V for different biomolecules for example a $K = 8$, b $K = 3.5$, c $K = 2.1$, d $K = 1.5$, e $K = 1$, f Potential graph of DM-below-NCFET at drain voltage 0.4V for different biomolecules

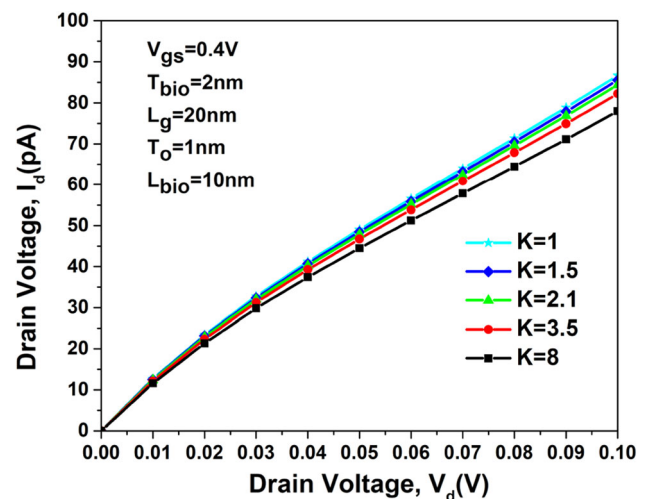


Fig. 8 Graph of drain current vs drain voltage of DM-below-NCFET at gate voltage 0.4 V for different biomolecules

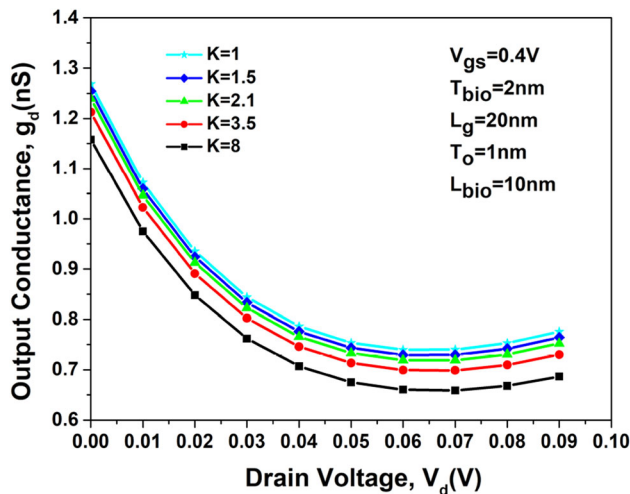


Fig. 9 Graph of output conductance vs drain voltage of DM-below-NCFET at gate voltage 0.4 V for different biomolecules

4.2 Effect of length modulation in cavity gap

Figure 10 shows graph of drain current vs gate voltage for various cavity length $L_{\text{bio}} = 8$ nm, 10 nm, and 12 nm with various biomolecules for instance ChO_x , protein, streptavidin, uricase, and without biomolecules. The drain current of protein with cavity length ($L_{\text{bio}} = 8$ nm) is enhanced over others as the dielectric constant increases with lower cavity reflects to improve drain current.

Figure 11 implies that the switching ratio was obviously lowered due to a rise in the leakage current

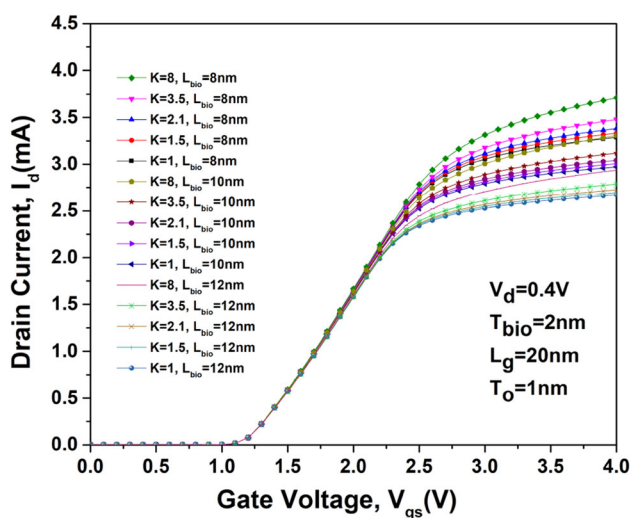


Fig. 10 Plot of drain current vs gate voltage of DM-below-NCFET at drain voltage 0.4 V for various biomolecules with different cavity length $L_{\text{bio}} = 8$ nm, 10 nm, and 12 nm

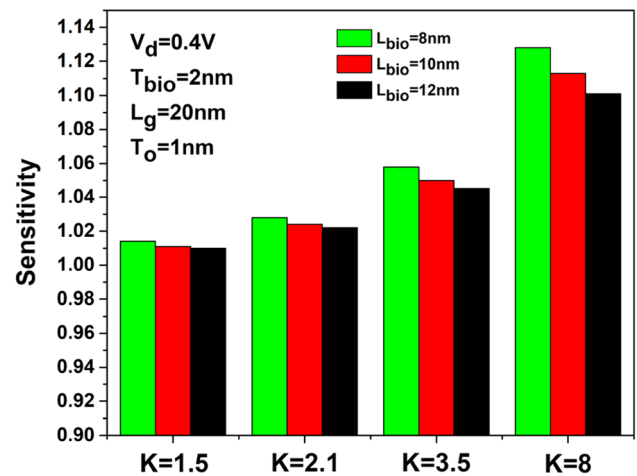


Fig. 11 Sensitivity of DM-below-NCFET at drain voltage 0.4 V for various biomolecules with different cavity length $L_{\text{bio}} = 8$ nm, 10 nm, and 12 nm

subsequent from greater capacitance with the rise in the cavity gap length. Furthermore, the sensitivity of the DM-below-NCFET biosensor with distinct cavity gap lengths was too calculated, exposing that it improved meaningfully with the rise in L_{bio} (Fig. 12). Since this figure, it is stated that the sensitivity enhanced with a dielectric constant for offered L_{bio} . Thus, for $L_{\text{bio}} = 12$ nm, the nanogap-inserted DM-below-NCFET biosensor indicated improved sensitivity for protein ($K = 8$) in analogy with the additional biomolecules.

Figure 13 gives the plot of limit of detection (LOD) vs different K values with standard deviation 0.000719 for $K = 1$, 0.000719 for $K = 1.5$, 0.00072 for $K =$

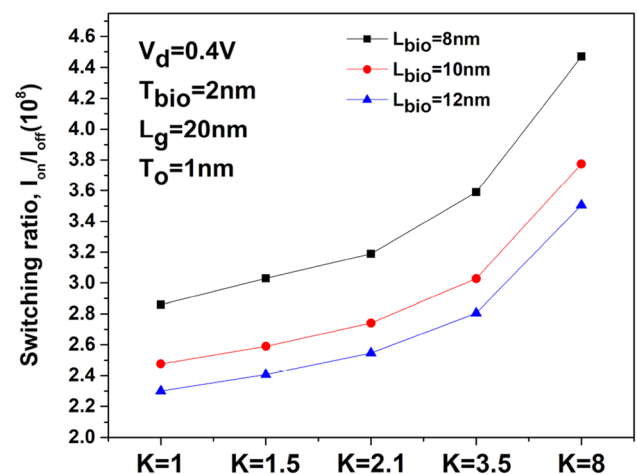


Fig. 12 Switching ratio of DM-below-NCFET at drain voltage 0.4 V for various biomolecules with various cavity length $L_{\text{bio}} = 8$ nm, 10 nm, and 12 nm

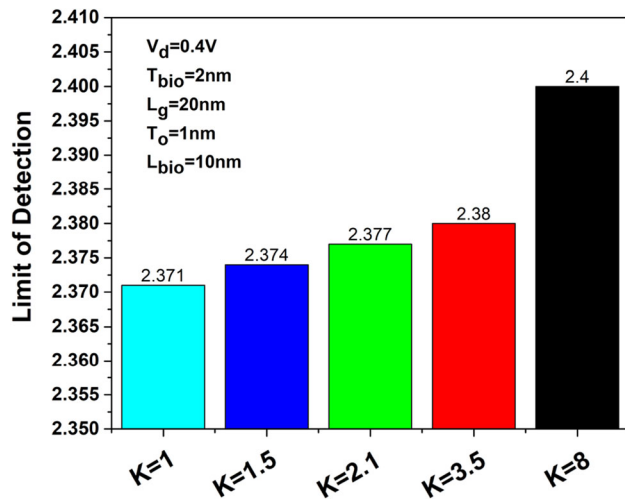


Fig. 13 Plot of limit of detection (LOD) vs different K values with standard deviation 0.000719 for $K = 1$, 0.000719 for $K = 1.5$, 0.00072 for $K = 2.1$, 0.000722 for $K = 3.5$, and 0.000727 for $K = 8$

2.1, 0.000722 for $K = 3.5$, and 0.000727 for $K = 8$. LOD of protein is higher than without molecule that indicating higher concentration of analyte in the sample that can be detected but not necessarily quantified [34]. It is determined by the response of standard deviation and slope. At the lower limit of detection in COVID-19 reflects it can miss more infected cases. These outcomes give understanding into the significance of controlling properties for amplifying sensitivity and limiting execution variety across device when planning and manufacturing nano-FET biosensors [35, 36].

Figure 14 shows the experimental data and simulated result with some parameters and reveals the

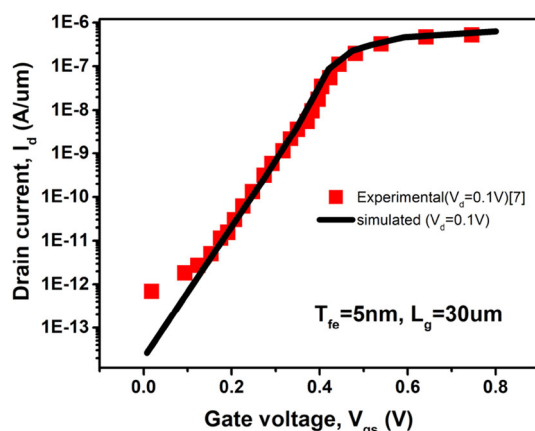


Fig. 14 Calibration results of experimental data and simulated data curve of drain current vs gate voltage at $V_d = 0.1$ and the channel length is 30 μm

curve of drain current and gate voltage at drain voltage is 0.1 V, ferroelectric thickness is 5 nm, and the channel length is 30 μm for negative capacitance field-effect transistor (NCFET), and data of experiment are taken from reference [7].

Organic FETs have formed into an astonishing area of examination and innovation to supplant exemplary inorganic semiconductors. Light-emitting diodes, organic photovoltaics, and thin-film transistors are as of now very much evolved and are at present being marketed an assortment of application for DM-below-NCFET. All the more as of late, organic FET has tracked down new applications in the field of biosensors [37, 38]. The FET-based biosensor turns into a promising contender for applications requiring ultra-sensitivity and fast reaction time. Moreover, new era complementary metal-oxide semiconductor (CMOS)-producing methods give advantages of scaling down, parallel detecting (for example, detecting clusters), and abilities to be coordinated with electronic circuits and frameworks. This would be a significant benefit for strong state-based biosensors to compete with other bio-detecting mechanism later on [23].

5 Conclusion

In this work, we examined the biosensing application of a double metal below negative capacitance FET (DM-below-NCFET). For the recognition of different biomolecules, the electrical performance was calculated in conditions of the shift of threshold voltage for protein enhanced by 0.09% over without biomolecule, the sensitivity of protein improved by 1.11 by times over $K = 1$, switching ratio of protein higher by 52% over to without biomolecule, the surface potential at cavity length of 10nm, as shown in Table 2, and measured higher limit of detection for protein by around 1.18% over without molecules. The DM-below-NCFET device was significantly improved, indicating better sensitivity for biomolecules with a large value of K . The proposed device realized that the sensitivity was greater for the recognition of protein ($K = 8$) in analogy with the various biomolecules. Moreover, the impacts of the gap of cavity length on the V_{th} , sensitivity, and switching ratio (I_{on}/I_{off}) of the DM-below-NCFET biosensor were too analyzed, exposing that the sensitivity enhanced with the rise in the gap size although the whole biosensor

operation was marginally reduced. So, the gap of cavity length is well improved for improved execution, which will authorize the utilization of such cavity length of 8 nm high sensitivity, high-speed biosensors for recognition of several associated diseases.

Acknowledgements

The authors would like to thank Microelectronics Lab and Nano Bioelectronics Lab, Delhi Technological University, for giving essential facilities.

Author contributions

All authors added to the study's understanding and design.

Funding

Yash is grateful to the Council of Scientific Industrial Research (C.S.I.R.) for an award of CSIR-JRF (08/133(0050)/2020-EMR-I). BDM thanks the Science & Engineering Research Board (DST-SERB), Govt. of India for the award of Distinguished Fellowship (SB/DF/011/2019).

Data availability

The creators expressed above have every one of the suitable data associated with this examination work and will be dedicated to uncovering that they will be addressed to do as such future.

Declarations

Conflict of interest The writers broadcast that they have no known dispute of individual connections or interests that might have arisen to impact the work depicted in this article.

Ethical standards The authors have found all the moral standards and will intended to follow them in future.

Consent to participate and publication Since the related research document is created on the 'no-life science journal.' Therefore, 'Non-Applicable' at this

point. Still, the authors have turned over all journal guidelines and consent to the agencies for additional processing.

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