A Novel RFET Sensor for Label-Free Biomolecule Detection

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Abstract

In the current scenario, COVID-19 has created a havoc negative impact on the lives of the people, which have triggered the research interest on the design and development of sensitive, low cost and power-efficient sensors for detecting a wide variety of biomolecules. Here, a novel hetero dielectric (HD) hetero material (HM) Bio-RFET based sensor is proposed which works as n or p MOSFET and n or p TFET and hence, is capable to sense the biomolecules through label-free dielectric modulation technique. Without labelling expenses, this biosensor detects a number of biomolecules present in human body as and when kept in a nano cavity. The dielectric polarization within the nanocavity due to the presence of foreign biomolecules under the influence of an electric field causes a variation in drain current. In this paper (SiO₂ + TiO₂) and AlGaAs/Si based HD-HM-RFET is explored for biosensing applications and mole fraction optimization of AlGaAs is done to obtain better results for four FETs. Work function of 4.5 eV is used in over drain and source electrodes, while metal work function of 4.7 eV is used for gate electrode. Finally, we found that the proposed device possesses better sensing capability for varying dielectric constant ($K=20$ to 80) and charge (-5×10^{11} to 1×10^{13} C/cm²) as compared to a (SiO₂ + HfO₂)-HM-RFET and Si based (SiO₂ + TiO₂)-RFET. Further, it is observed that n-(SiO₂ + TiO₂)-HM-TFET is the best among all FETs and has highest I_d - V_{gs} sensitivity = 5.09×10^{13} , $I_{ON}/I_{OFF} = 1.23 \times 10^9$, lowest SS = 20.3 mV/dec and $V_{th} = 1.48$ V.

Keywords RFET · Biosensor · Heterodielectric · Biomolecules · Sensitivity

1 Introduction

Diagnostics and prevention have gained utmost importance since the outbreak of pandemics like Covid-19 [1]. Undoubtedly, it has become the need of the hour that we should be prepared with biomedical equipment that can handle any situation [2]. In this list, biosensors hold the first position as detecting an infected person and isolating him is the primitive solution for treatment of such contagious diseases [3]. However, preparation of infection specific biosensor is time-consuming process as it needs detailed research and analysis, which slows down detection and recovery rate. In addition, labelling biosensor is another limitation as

it is cost-consuming procedure to label and dye mark for detecting specific biomolecule [4]. Alternatively, if we have label-free biosensors for detection of wide variety of biomolecules, then it would be a boon to biomedical industry [5]. Therefore, in the paper a novel dielectric modulated (DM) reconfigurable field effect transistor (RFET) based biosensor is presented that would detect a large number of charged or neutral biomolecules using label-free methods.

RFET is a junctionless device in which an over drain and source electrodes attract holes/electrons depending on the negative/positive applied potential [6]. Therefore, unlike a conventional transistor, RFET can behave as either n or p MOSFET/Tunnel FET (TFET) based on electrically doped (ED) mechanism rather than physically doped (PD) separation [7]. Though Silicon RFET mimics conventional MOSFET behaviour faithfully, it suffers from basic TFET limitations such as low ON current and high ambipolarity [8–10]. Also, it is well explained in literature that the DM MOSFET biosensors are less sensitive and consumes more power as compared to the TFET biosensors which have low subthreshold swing (<60 mV/decade) and low OFF current [11]. However, MOSFET biosensors produce more current

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and are useful in driving rest of the circuitry. Therefore, in this paper our focus is to upgrade both MOSFET and TFET device characteristics of RFET for which a hetero material (HM), hetero dielectric (HD) oxide ($\text{SiO}_2 + \text{TiO}_2$) based RFET has been proposed. Further, performance of the proposed biosensor is compared with a Silicon RFET and a relatively low dielectric oxide combination ($\text{SiO}_2 + \text{HfO}_2$)-HM-RFET which demonstrates that the ($\text{SiO}_2 + \text{TiO}_2$)-HM-RFET provides better reconfigurability and sensing capability. When we say wide variety of biomolecules and their dielectric constant (K) and charge values, it includes K for SARS-CoV-2 (1–4), RNA transformed to C-DNA (1–64), Uricase (1.54), Uricase (1.64), Streptavidin (2.1), Biotin (2.63), ChO_x (3.30), GO_x (3.46), 3-aminopropyltriethoxysilane (APTES) (3.57), Ferro-cytochrome c (4.7), Bacteriophage T7 (6.3), Keratin (8) and Gelatine (12) [12]. This list is never-ending as human body comprises of water, proteins, minerals, fats, carbohydrates and vitamins and hence, each human tissue possesses a distinct dielectric property. Under the influence of electromagnetic wave, the wide dielectric spectroscopy of human blood or tissue are always a subject of disease detection through the chemical and mechanical examination of their protein structures or DNA/RNA strands. Therefore, proposed RFET biosensor holds an extensive potential in the area of biomedical applications.

2 RFET Based Biosensor

In this section, HD-HM-RFET based biosensor has been introduced and its working principle is elaborated. Later, the sensitivity analysis of each FET is discussed separately.

2.1 Device Structure and Simulation Setup

The proposed device structure of biosensor is shown in Fig. 1. The HM AlGaAs/Si used here improves ON current

as it consists of a high band gap material (AlGaAs) in source/channel and a low band gap material (Si) in the drain region. In addition, a high-K dielectric (TiO_2) near source/channel junction further improves ON current where as a low-K dielectric (SiO_2) in rest of the region helps to reduce ambipolarity [13]. Entire simulation has been carried out in Silvaco Atlas tool. The models used in device simulation are Universal Schottky Tunneling model (UST), Auger model, Shockley Read Hall (SRH) model, non-local band-to-band tunneling (BTBT) model, bandgap narrowing (BGN) model, Fermi Dirac statistics and Klaassen's Unified Low Field Mobility (KLA) models. Models are calibrated with the experimental device and Fig. 1(b) shows that the simulation results are closely matched to the experimental values [18].

AlGaAs grown on Si substrate is an important optoelectronic candidate, and a number of methods are proposed in literature to fabricate AlGaAs on Si substrate as there is large lattice constant mismatch (4%) between two materials [14]. In [15], an experimental procedure to grow AlGaAs films on Si substrates by atomic hydrogen assisted molecular beam epitaxy (MBE) is demonstrated. Liquid phase deposition (LPD) of TiO_2 on AlGaAs is done at room temperature experimentally [16]. Therefore, the fabrication of proposed biosensor is feasible and the fabrication steps for the proposed biosensor are depicted in Fig. 2(a). Further, an electrically doped (ED) concept is used here which not only prohibits the random dopant issues but also permits reconfigurable nature of the biosensor [17, 18]. Potentials (± 1.2) applied over the drain (V_{ODS}) and source (V_{OSS}) electrodes allow device to configure into either MOSFET or TFET. nMOSFET ($V_{\text{ODS}} = 1.2$ and $V_{\text{OSS}} = 1.2$), pMOSFET ($V_{\text{ODS}} = -1.2$ and $V_{\text{OSS}} = -1.2$), nTFET ($V_{\text{ODS}} = 1.2$ and $V_{\text{OSS}} = -1.2$) and pTFET ($V_{\text{ODS}} = -1.2$ and $V_{\text{OSS}} = 1.2$) are the four different configurations studied in this article. Two nanocavities are constructed below gate electrode where biomolecules are introduced into the biosensor. The device dimensions are listed in Table 1.

Fig. 1 ($\text{SiO}_2 + \text{TiO}_2$)-HM-RFET biosensor structure and (b) Calibration results

Fig. 2 (a)–(h) Steps involved in the fabrication of the proposed biosensor **Table 1** Design parameters of (SiO₂ + TiO₂)-HM-RFET

Parameter Name and Unit	Symbol	(SiO ₂ + TiO ₂)-HM-RFET
Substrate doping (cm ⁻³)	n _i	1 × 10 ¹⁵
Overdrive source length (nm)	L _{OS}	50
Overdrive drain length (nm)	L _{OD}	50
Spacer length, gate to source (nm)	L _{GS}	5
Spacer length, gate to drain (nm)	L _{GD}	5
Source length (nm)	L _S	55
Drain length (nm)	L _D	55
Gate length (nm)	L _G	50
Overdrive source work function (eV)	Φ _{OS}	4.5
Overdrive drain work function (eV)	Φ _{OD}	4.5
Gate work function (eV)	Φ _G	4.7
Silicon thickness (nm)	t _{Si}	10
Oxide thickness (nm)	t _{ox}	2
Cavity length (nm)	L _{Cavity}	27.5
Cavity thickness (nm)	t _{Cavity}	5.5
Drain and Source contact		NiSi

2.2 Operation of (SiO₂ + TiO₂)-HM-RFET Based Biosensor for Different Dielectric Values

Figure 4 shows the drain current variation of the proposed device in four configurations for varying neutral biomolecule dielectric constant (*K*) values. Figure 3(a) shows that as *K* value increases the drain current prominently rises in p-(SiO₂ + TiO₂)-HM-MOSFET while there

is slight improvement in n-(SiO₂ + TiO₂)-HM-MOSFET. Figure 3(b) shows that the drain current improves with the increasing *K* values for n and p (SiO₂ + TiO₂)-HM-TFET. Figure 3(c–d) shows the energy band diagram (EBD) and surface potential variation for n-(SiO₂ + TiO₂)-HM-RFET and p-type EBDs are deliberately avoided to prevent repeated explanation. In n-(SiO₂ + TiO₂)-HM-MOSFET the gate region band bends more downwards with increasing *K* value (Fig. 3(c)) resulting into higher potential (Fig. 3(d)) and better drain current. Similar results are obtained for n-(SiO₂ + TiO₂)-HM-TFET. Therefore, it is obvious that all the four FETs offer good sensing capability for various biomolecules.

2.3 Operation of (SiO₂ + TiO₂)-HM-RFET Based Biosensor for Varying Charge Values

Figure 4 depicts the drain current variation of the proposed device in the four configurations for varying positive and negative charged biomolecule values, where *K* = 80 is kept constant. Figure 4(a) shows that as positive charge value increases the drain current increases for n-(SiO₂ + TiO₂)-HM-MOSFET while current reduces for p-(SiO₂ + TiO₂)-HM-MOSFET in linear region specifically. It indicates that the threshold voltage reduces for n-type MOSFET while it rises for p-type MOSFET. Similar, effect has been observed for (SiO₂ + TiO₂)-HM-TFET with increasing positive charge of the biomolecules as shown in Fig. 4(b). Considering negatively charged biomolecule and constant *K* = 80, opposite characteristics are observed. Figure 4(c–d) shows that as the negative charge increases, the n-type drain current decreases, while the p-type drain current

Fig. 3 I_d - V_{gs} characteristics of (a) $(\text{SiO}_2 + \text{TiO}_2)$ -HM-MOSFET, (b) $(\text{SiO}_2 + \text{TiO}_2)$ -HM-TFET, and (c) Energy Band Diagram, (d) Surface Potential of $(\text{SiO}_2 + \text{TiO}_2)$ -HM-RFET biosensor for different dielectric constant (K)

Fig. 4 I_d - V_{gs} characteristics of (a) $(\text{SiO}_2 + \text{TiO}_2)$ -HM-MOSFET, (b) $(\text{SiO}_2 + \text{TiO}_2)$ -HM-TFET for positive charge density and, (c) $(\text{SiO}_2 + \text{TiO}_2)$ -HM-MOSFET, (d) $(\text{SiO}_2 + \text{TiO}_2)$ -HM-TFET biosensor for negative charge density

increases in linear region. Therefore, the threshold voltage increases for n-type while it reduces for p-type. Since, most of the drain current variation is concentrated near OFF state

($V_{gs} = 0$), hence, variation in OFF-state EBD and surface potential is observed for negatively charged biomolecule in Fig. 5.

Fig. 5 Off state (a) Energy Band Diagram and, (b) Surface Potential of $(\text{SiO}_2 + \text{TiO}_2)$ -HM-RFET biosensor for negative charge density

Again, to avoid repeated information, EBD and potential of n- $(\text{SiO}_2 + \text{TiO}_2)$ -HM-RFET is included only for negative charge. Here, we found that for increasing negative charge the potential barrier increases for n- $(\text{SiO}_2 + \text{TiO}_2)$ -HM-MOSFET and less band bending in p- $(\text{SiO}_2 + \text{TiO}_2)$ -HM-TFET produces less current during OFF-state as shown in Fig. 5(a). Similarly, surface potential reduces with increasing negative charge in n-type devices as shown in Fig. 5(b).

2.4 Comparison between $(\text{SiO}_2 + \text{TiO}_2)$ -RFET and $(\text{SiO}_2 + \text{TiO}_2)$ -HM-RFET

This section compares the proposed device to the Si based $(\text{SiO}_2 + \text{TiO}_2)$ -RFET, to indicate the significance

of using a III-V semiconductor in label-free biosensor. We compared the drain current variation of two devices for idle situation (no biomolecule) and for $K = 80$ and charge $= 1 \times 10^{13} \text{ C/cm}^2$. Figure 6(a) shows that MOSFET drain current of the Si device is much higher as compared to the proposed one, both in the presence and absence of the biomolecule. However, our device drives less drain current as compared to the proposed device, which indicates that the $(\text{SiO}_2 + \text{TiO}_2)$ -HM-MOSFET is less sensitive towards air and hence, less power is consumed during idle situation. The reason behind this is explained through EBD of two devices. Figure 6(b) shows that the EBD of Si based MOSFET is more flat for both the presence and absence of the biomolecule as compared to the proposed device due to the presence of high band gap material in

Fig. 6 Comparison of (a) I_d - V_{gs} characteristics and (b) Energy Band Diagram in between $(\text{SiO}_2 + \text{TiO}_2)$ -HM-MOSFET, $(\text{SiO}_2 + \text{TiO}_2)$ -MOSFET and, Comparison of (c) I_d - V_{gs} characteristics and (d) Energy Band Diagram in between $(\text{SiO}_2 + \text{TiO}_2)$ -HM-TFET, $(\text{SiO}_2 + \text{TiO}_2)$ -TFET biosensors

the channel region. Therefore, the Si device provides better MOSFET drain current than the proposed device. Similarly, the TFET drain current of the two devices are compared at $K = 1$ and $K = 80$, and charge = 1×10^{13} C/cm² in Fig. 6(c). Here, we also found that the drain current of the proposed device is much below the Si device in TFET configuration, indicating that the (SiO₂ + TiO₂)-HM-TFET is insensitive towards the air (idle condition) as compared to the (SiO₂ + TiO₂)-TFET and hence, better sensitivity and power reduction can be achieved for this device. Again, EBD of the two devices in Fig. 6(d) shows that due to band gap difference the band bending of the proposed device at tunneling junction is less steep than the Si device.

2.5 Comparison between (SiO₂ + HfO₂)-HM-RFET and (SiO₂ + TiO₂)-HM-RFET

This section compares the proposed device to the (SiO₂ + HfO₂)-HM-RFET, to indicate the significance of using TiO₂ instead of HfO₂ in biosensor. We found that as we replace the gate source oxide with a higher dielectric it improves biosensor sensitivity. Figure 7(a–b) shows that as oxide dielectric increases it drastically reduces the drain current during idle ($K = 1$ and charge = 0) condition and hence, provides improved sensitivity. Figure 7(c–d) shows that TFET band bending at tunneling junction is

more for HfO₂ device as compared to the TiO₂ during idle condition. Hence, the (SiO₂ + HfO₂)-HM-TFET provides more current than SiO₂ + TiO₂-HM-TFET. Therefore, using a high dielectric oxide surely improves bio-FET sensitivity.

3 Mole Fraction Optimization

In this section mole fraction (X) optimisation of AlGaAs is discussed with x varying from 0.01 to 0.2. Figure 8(a) shows that for each FET drain current decreases as mole fraction increases and hence, a small value of x is the optimum solution for the proposed bio-RFET. Because, energy band gap increases with the increasing x value for n- (SiO₂ + TiO₂)-HM-MOSFET as shown in Fig. 8(b) during equilibrium condition, we opted x = 0.01 as the optimum value.

Fig. 9 compares maximum sensitivity of the three devices for varying K values of the biomolecules. It is clear that, with respect to K values the proposed device is a better bio-FET sensor as compared to other devices. Also, for all devices TFET provides better sensitivity as compared to MOSFET when K is varied from 20 to 80. p-MOSFETs are better biosensors as compared to the n-MOSFETs for all the three cases. However, both n and p TFETs are superior to MOSFETs and offer almost

Fig. 7 Comparison of (a) I_d - V_{gs} characteristics and (b) Energy Band Diagram in between (SiO₂ + TiO₂)-HM-MOSFET, (SiO₂ + HfO₂)-HM-MOSFET and, Comparison of (c) I_d - V_{gs} characteristics and (d) Energy Band Diagram in between (SiO₂ + TiO₂)-HM-TFET, (SiO₂ + TiO₂)-HM-TFET biosensors

Fig. 8 Mole fraction variation in (a) On state I_d - V_{gs} characteristics and, (b) Equilibrium Energy Band Diagram of (SiO₂+TiO₂)-HM-RFET bio-sensor

Fig. 9 I_d - V_{gs} sensitivity of (SiO₂+HfO₂)-HM-RFET, (SiO₂+TiO₂)-RFET and, (SiO₂+TiO₂)-HM-RFET bio-sensors for different dielectric constants (K)

same sensing capability. Further, replacement of HfO₂ by a higher dielectric oxide TiO₂ improves sensitivity of Silicon based device as compared to the (SiO₂+HfO₂)-HM-TFET. However, introduction of high band gap HM like AlGaAs in place of Si in source and channel regions are responsible for further sensitivity improvement of four FETs characteristics. Indeed, (SiO₂+TiO₂)-HM-TFET provides better sensitivity with respect to K values as compared to any other FET.

3.1 DC Comparison

Apart from sensitivity, comparing DC parameters like I_{ON}/I_{OFF} ratio, SS and V_{th} of these devices are important criteria. The DC parameters of (SiO₂+TiO₂)-HM-RFET and (SiO₂+TiO₂)-RFET devices for air and charged biomolecules ($K=80$, charge = $\pm 5 \times 10^{12}$ C/cm²) are included in Table 2 which shows that the proposed device achieved much improvement as compared to the Si device in

Table 2 DC parameter of (SiO₂ + TiO₂)-RFET and, (SiO₂ + TiO₂)-HM-RFET biosensors for positive, neutral and, negative charge densities

Device Name	Charge Density for $k = 80$ (C/cm ²)	DC parameter and unit	n-MOSFET	p-MOSFET	n-TFET	p-TFET
(SiO ₂ + TiO ₂)-RFET	-5×10^{12}	I_{ON}/I_{OFF}	6×10^8	5.2×10^4	8.6×10^4	1.2×10^8
		SS (mV/dec)	60.5	60.4	55.3	42.1
		V_{th} (V)	0.34	0.02	1.51	1.33
	0	I_{ON}/I_{OFF}	8.9×10^7	3.3×10^5	3.5×10^5	4.83×10^7
		SS (mV/dec)	60.4	60.5	55.6	41.5
		V_{th} (V)	0.28	0.05	1.49	1.35
	5×10^{12}	I_{ON}/I_{OFF}	1.43×10^7	2.35×10^6	9.5×10^5	5.96×10^7
		SS (mV/dec)	60.2	60.6	55.3	41.04
		V_{th} (V)	0.13	0.09	1.48	1.38
(SiO ₂ + TiO ₂)-HM-RFET	-5×10^{12}	I_{ON}/I_{OFF}	2.83×10^{11}	1.48×10^9	1.91×10^7	7.78×10^8
		SS (mV/dec)	60.4	60.2	20.3	43.7
		V_{th} (V)	0.38	0.23	1.51	1.32
	0	I_{ON}/I_{OFF}	4.47×10^{10}	9.56×10^9	1.23×10^9	2.45×10^8
		SS (mV/dec)	60.2	60.4	23.52	42.83
		V_{th} (V)	0.33	0.29	1.50	1.36
	5×10^{12}	I_{ON}/I_{OFF}	7.38×10^9	6.54×10^{10}	6.41×10^8	7.18×10^7
		SS (mV/dec)	60.1	60.6	24.29	41.84
		V_{th} (V)	0.28	0.34	1.48	1.37

Table 3 Comparison of the sensitivity of the proposed biosensor with other Biosensors for different K values

Reference no.	K	Sensitivity
[19]	17	2150
[20]	20	2
[11]	9	8.8×10^6
[13]	10	10^8
[12]	12	8.7×10^{10}
[10]	12	1.7×10^8
This work	20	3.36×10^{12}

terms of various DC characteristics. Therefore, the presented device is a power efficient solution for resource constraint applications. Also, sensitivity of the proposed biosensor (n-(SiO₂ + TiO₂)-HM-TFET) for ($K \leq 10$) has been compared to the other works published in literatures [10–13, 19, 20] as presented in Table 3, which indicates that the proposed bio-FET is a highly sensitive for sensing applications. Also, Table 4 shows that the proposed (SiO₂ + TiO₂)-HM-RFET provides better sensitivity as compared to other RFET biosensors available in the literature.

4 Conclusions

COVID-19 around the globe was a lesson to entire the community that we should be ready with the efficient and quality diagnostic equipment to save time and money. Among these equipments, biosensor is the foremost crucial equipment that needs to be improved to detect the infection first and timely quarantine the patient later. Therefore, in this paper, a novel HD-HM-RFET biosensor is proposed and analysed to investigate its potential for sensing a dynamic range of biomolecules through dielectric modulation label-independently. RFET devices operate either as n or as p MOSFET and n or p TFET. Therefore, four FETs are possible from single device. In this paper, we explored this configurable nature to produce a wide range biomolecule detection sensor by introducing a cavity within. However, TFET out of Si-RFET does not provide enough ON current and needs high amplification stages later. Therefore, in this paper (SiO₂ + TiO₂) as HD and AlGaAs/Si as HM are investigated and mole fraction optimization is done for the improvement of all FETs in the proposed RFET. The proposed bio-RFET sensor is compared with (SiO₂ + HfO₂)-HM-RFET and Si

Table 4 Sensitivity comparison of the proposed with RFET biosensors available in literature

Biosensors	Charge (C/cm ⁻²)	Sensitivity (p-TFET)	Sensitivity (n-TFET)
RFET-biosensor [6]	1×10^{13}	10^6	10^8
Dual polarity biosensor [21]	1×10^{12}	10^2	10^4
(SiO ₂ + TiO ₂)-HM-RFET [This work]	1×10^{13}	5.66×10^{12}	5.09×10^{13}

based ($\text{SiO}_2 + \text{TiO}_2$)-RFET devices for biomolecules with varying K (0 to 80) and charge values (-5×10^{11} to 1×10^{13} C/cm^2). We found that ($\text{SiO}_2 + \text{TiO}_2$)-HM-RFET possesses extremely better sensing capability as compared to other devices. Besides that, n-TFET configuration of the proposed device is the best among all FETs which along with better sensing capability contributes to ION/IOFF ratio, low SS and V_{th} . Therefore, n- $(\text{SiO}_2 + \text{TiO}_2)$ -HM-TFET can be a possible biosensor solution for the biomedical field.

Author Contributions All the authors have contributed to the design, investigation, conceptualization and formal analysis. and design. Author Arpita Biswas prepared the first draft of the manuscript after performing the simulation study and validation. Author Chithraja Rajan edited the manuscript after data analysis and validation. D P Samajdar commented on the manuscript and supervised the entire work. All the authors read and approved the final version of the manuscript.

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Code Availability Not Applicable.

Declarations

Ethics Approval Not Applicable.

Consent to Participate All the authors contributed voluntarily to this work.

Consent for Publication In accordance with the copyright transfer or open access rules.

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

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