

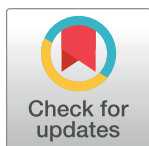
RESEARCH ARTICLE

Sensitivity analysis of bi-metal stacked-gate-oxide hetero-juncture tunnel fet with Si_{0.6}Ge_{0.4} source biosensor considering non-ideal factors

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Abstract

This article provides insights in designing a dielectrically modulated biosensor by adopting high-k stacked gate oxide proposition in a bi-metal hetero-juncture Tunnel Field Effect Transistor (BM-SO-HTFET) with Si_{0.6}Ge_{0.4} source. The integrated effect of heterojunction and stacked gate oxide leads to enhanced electrical performance of the proposed device in terms of carrier mobility and suppressed leakage current. Nano-cavity engraved beneath the bi-metal gate structure across the source/channel end acts the binding site of the biomolecules to be detected. This Configuration leads to improved control of biomolecules over source/channel tunnelling rate and the same is reflected in the sensing ability of the device while extracting the ON current sensitivity (SON) of the sensor. The reported biosensor is simulated using Silvaco ATLAS calibrated simulation framework. The analysis of the device sensitivity is carried out varying dielectric constants (k) of various biomolecules, both neutral as well as charged. Our study reveals that BM-SO-HTFET with Ge mole fraction composition $x = 0.4$ exhibits sensitivity as high as 4.1×10^{10} for neutral biomolecules and 3.2×10^{11} for positively charged biomolecules with $k = 12$. Furthermore, a transient response profile for the drain current with various biomolecules is explored to determine the varying settling time. From the simulation results, it is noted that BM-SO-HTFET exhibits ON current sensitivity of 4.1×10^{10} and 3.2×10^{11} for neutral and charged biomolecules respectively. In addition to this, for highly sensitive and real time detection of biomolecules, the impact of temperature and certain non-ideal factors drifting from ideal case of fully filled cavity have also been considered to analyze its optimum sensing performance.

1. Introduction

Present day microbiological progress has steered the researchers to a focused and streamlined path in biosensing performance investigations. Biological molecules or biomolecules or bio-

species are fundamental ecological components. DNA (Deoxyribonucleic acid), Biotin, Streptavidin, Gluten, Zenin, Keratin, Gelatin play critical roles in lifeforms. Field Effect Transistors (FET) based lab-on-chip biosensors for efficient and accurate label free detection of biomolecules have emerged as a major interest in the research arena for both ideal and non-ideal issues [1,2]. The complex lab based expensive sensors can be substituted by FET based biosensors which have easy fabrication steps, higher sensitivity, higher lifetime, high reliability, low power consumption and low cost [3]. To obtain the best performance of a FET based biosensor it should be highly sensitive. Ion sensing FET (ISFET) had become a prime focus for researchers in 1970s for sensing biomolecules with charge density [4]. But as reported in [5], ISFET could not detect neutral biomolecules. The above problem has been solved with the introduction of dielectrically modulated FET based biosensors with the potential of sensing neutral biomolecules as well as biomolecules with charge density. In dielectrically modulated FET based biosensors, nanogap engineering is implemented under the gate metal by wet etching the gate oxide [6]. The biomolecules are selectively captured with the help of receptors in the engineered nanogap. With the applied gate bias, the effectual gate-channel capacitance varies with different dielectric constant values of different biomolecules localized inside the engineered nanogap giving rise to readable signals in the form of drain characteristics, transfer characteristics, channel conductance, threshold voltage characteristics. The dielectric constant values vary with varying biomolecules such as Streptavidin, Biotin, 3-Aminopropyl Triethoxysilane (APTES), Gluten, Zenin, Keratin, Gelatin having $k = 2.1, 2.63, 3.57, 5, 7, 10, 12$ respectively [7]. The integration of dielectrically modulated n-FET and p-FET based biosensors with Complementary Metal Oxide Semiconductor (CMOS) architecture provides satisfactory compatibility for further logic applications. Bulk Metal Oxide Semiconductor Field Effect Transistor (MOSFET) emerged as a suitable candidate for dielectrically modulated biosensing [8]. But in accordance with Moore's Law, the downscaling of technology nodes causes MOSFETs to pose several problems. Its limitation to 60 mV/dec Subthreshold Swing (SS) at ambient conditions, giving rise to Short Channel Effects (SCEs), KT/q limit, increase in leakage current, high static power consumption makes MOSFET based biosensors not suitable for efficient sensing of biomolecules as well as long response time [9,10]. Dielectrically modulated Tunnel Field Effect transistors (DM-TFETs) based biosensors in recent times are under extensive research due to their capability of overcoming the above-mentioned limitations with MOSFET based biosensors [11].

TFET is also ideal for low power Very Large-Scale Integration (VLSI) utilities because of their significantly low OFF current therefore having reduced static power consumption [12]. DM-TFET based biosensors provides sub-60 mV/dec SS and faster response time. The Band-to-Band Tunnelling (BTBT) phenomenon of TFET based biosensors makes them essentially important candidates for biosensing operations with dielectric modulation approach [13,14]. Recently, Covid-19 illness causing virus, SARS-CoV-2 has come under tremendous attention due to the pandemic break-out that has taken countless lives and continues as a threat and demands fast and accurate detection [15]. It is reported in [3] that SARS-CoV-2 virus can be detected by TFET based biosensors. Besides the advantages of TFET based biosensors over MOSFETs, TFETs have extremely low ON current (I_{ON}) and ambipolar behaviour for conductivity which can lead to poor performance and even circuit failure [16]. Researchers are working to find out the best possible architecture that can increase the I_{ON} as well as reduce the ambipolar current behaviour. As reported in [17], asymmetric doping profiles of source and drain can suppress ambipolar current behaviour and the I_{ON} can be improved by sharp source doping, thin silicon body and a double gate architecture that will improve the gate controllability on the channel charge. The Z-shaped gate hetero dielectric horizontal source pocket TFET (ZHP-DM-TFET) based biosensor [18], Gate All Around TFET (GAA-TFET) [19],

SiGe Source and Pocket-Doped Channel [1], N+ Pocket Doped Vertical TFET Based Dielectric-Modulated Bio-sensor [20], Dielectric Modulated Dual Channel Trench Gate TFET-Based Bio-sensor [21], Back-Gate Bias and Front-Gate Engineering DMTFET-Based Bio-sensors [22] focuses on improving the ON current sensitivity by improving the carrier mobility. Lately, tunnel FETs with integrated hetero-junction architecture have grabbed attention [23]. The mindful selection of bandgap modulating materials at the source side allows improvement in ON-state current as well as the sub-threshold slope (SS) by improving the tunnelling rate. Therefore, in terms of considering ON-state current and SS as a sensitivity parameter, hetero-junction architecture in TFETs is of real advantage. However, hetero-junction architecture also leads to an increase in the sub-threshold current which is an issue in terms of power consumption [24]. Therefore, further research is needed to improve the hetero-junction architecture in TFETs.

In this work, a Bi-Metal Stacked-oxide Hetero-junction Tunnel Field Effect Transistor (BM-SO-HTFET) dielectrically modulated biosensor device has been utilized with an incorporated $\text{Si}_{0.6}\text{Ge}_{0.4}$ source. The engineered gate oxide architecture facilitates the carrier mobility by mitigating the leakage current. Bi-gate metal structure improves tunnelling at the source-channel interface thereby improving the ON current and higher control over the channel charge [14]. This delves deeper into the sensing abilities of the BM-SO-HTFET dielectrically modulated biosensor with various biomolecules consisting of dielectric constant values ranging from 5 to 12. The biosensor device exhibits ON current sensitivity for neutral biomolecules ($\text{SON} = 4.1 \times 10^{10}$ at $k = 12$), charged biomolecules ($\text{SON} = 3.2 \times 10^{11}$ at $k = 12$) for fully filled nanogap at ambient temperature. Furthermore, real-time bio-sensing performance considering non-ideal nanogap filling is extensively investigated in terms of ON current sensitivity.

1.1. Device architecture and simulation framework

Fig 1(A) presents the 2-D illustration of BM-SO-HTFET dielectrically modulated biosensor. $\text{Si}_{0.6}\text{Ge}_{0.4}$ has been incorporated in the source with a highly P-type doping profile over the mildly (intrinsic) doped silicon channel forming a hetero junction. A 40 nm channel length is considered. The SiO_2 (low- κ insulator) depth is 1 nm whereas HfO_2 depth is 2 nm. A nanogap of 30 nm distance and body depth of 10 nm is considered. The $\text{Si}_{0.6}\text{Ge}_{0.4}$ source is 1×10^{20} cm⁻³ doped; silicon drain is 1×10^{18} cm⁻³ doped. The silicon channel is 1×10^{15} cm⁻³ lightly

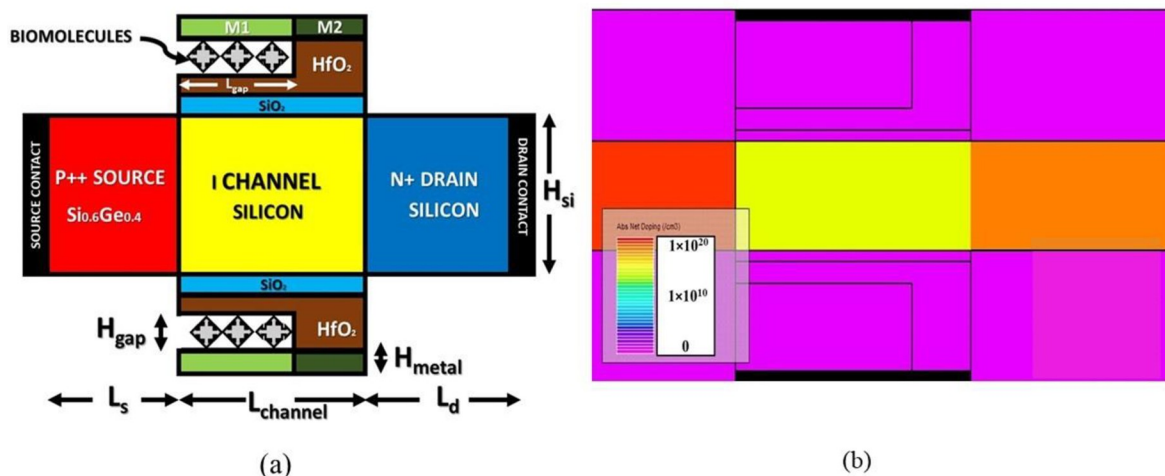


Fig 1. (a) 2D illustrative (b) TCAD Contour doping profile of BM-SO-HTFET biosensor with $\text{Si}_{0.6}\text{Ge}_{0.4}$ source.

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doped shown in simulated contour doping profile in Fig 1(B). The simulated BM-SO-HTFET has a high- k gate stack that mitigates the leakage current subsequently improving I_{ON} , while also being thermodynamically stable [25,26]. Bi-metal with work-function of tunnelling gate, $\phi_{tg} = 3.8\text{eV}$ and work-function of auxiliary gate, $\phi_{ax} = 4.8\text{eV}$ is utilized for constructing the gate architecture [2]. To emulate biosensing, the nanogap is considered air-padded at $k = 1$. At air-padded nanogap ($k = 1$), the effective gate-channel capacitance becomes less influential as compared to biomolecules padded nanogap thereby mitigating effective tunnelling. Therefore, a metal with lesser work-function ($\phi_{tg} = 3.8\text{ eV}$) positioned over the nanogap to overcome this is-sue. It is known that a filled nanogap will enhance the tunnelling vertical electric field leading to acute band bending and increased tunnelling. Metal with increased work-function ($\phi_{ax} = 4.8\text{ eV}$) utilized over high- κ insulator, HfO_2 to accurately facilitate charge carrier tunnelling for padded nanogap. Therefore, tunnelling gate controls subthreshold swing (SS) while auxiliary gate governs the leakage current [2]. From reported articles it is known that mono nanogap biosensors exhibit improved outputs in comparison to mirrored nanogap biosensors due to their ability to impregnate acute band-bending at the tunnelling interface for various biomolecules simultaneously providing improved coverage area of the nanogap. The split nanogap architecture in mirrored nanogap devices reduces the coverage area of the nanogap thereby degrading effective gate to channel capacitance [2].

BM-SO-HTFET biosensor measurements are presented in Table 1. The simulation of the BM-SO-HTFET is carried out with SILVACO ATLAS commercial TCAD tool [27]. The Wentzel-Kramer-Brillouin (WKB) approximation based non-local BTBT model has been implemented to incorporate effective tunnelling due to band-bending at the tunnelling junction. CONMOB and FLDMOB models are used for mobility degradation. Furthermore, the classical Drift Diffusion model along with Shockley-Read-Hall (SRH) model and Auger model has been incorporated for facilitation of carrier generation and recombination. The Band Gap Narrowing model (BGN) and Fermi-Dirac statistics were further included to procure accurate band-to-band tunnelling. The calibration of the mole fraction parameter (x) has been done with the experimental results reported in [28] and implemented in the SILVACO ATLAS TCAD tool. The experimental results of the device transfer characteristics of SiGe PIN TFET [29] are fitted with the simulation results in terms of physical models and device specifications. The calibration results are highlighted in Fig 2.

2. Simulation results and discussions

A $\text{Si}_{1-x}\text{Ge}_x$, a bandgap tuneable alloy semiconductor, is incorporated in the P^{++} type source of BM-SO-HTFET dielectrically modulated biosensor. The mole fraction composition of Ge is

Table 1. Measurements of the simulated BM-SO-HTFET biosensor.

S. No.	FET specifications	Measurements
1.	Channel length (L_{channel})	40 nm
2.	Silicon channel depth (H_{si})	10 nm
3.	Source length (L_s)	25 nm
4.	Drain length (L_d)	35nm
5.	Nano-gap length (L_{gap})	30nm
6.	Nano-gap depth (H_{gap})	8 nm
7.	Gate metal depth (H_{metal})	1nm
8.	Low- k (SiO_2) and High- κ (HfO_2) dielectric depth	1nm and 2nm respectively
9.	High- k (HfO_2) dielectric depth below M_2	nm

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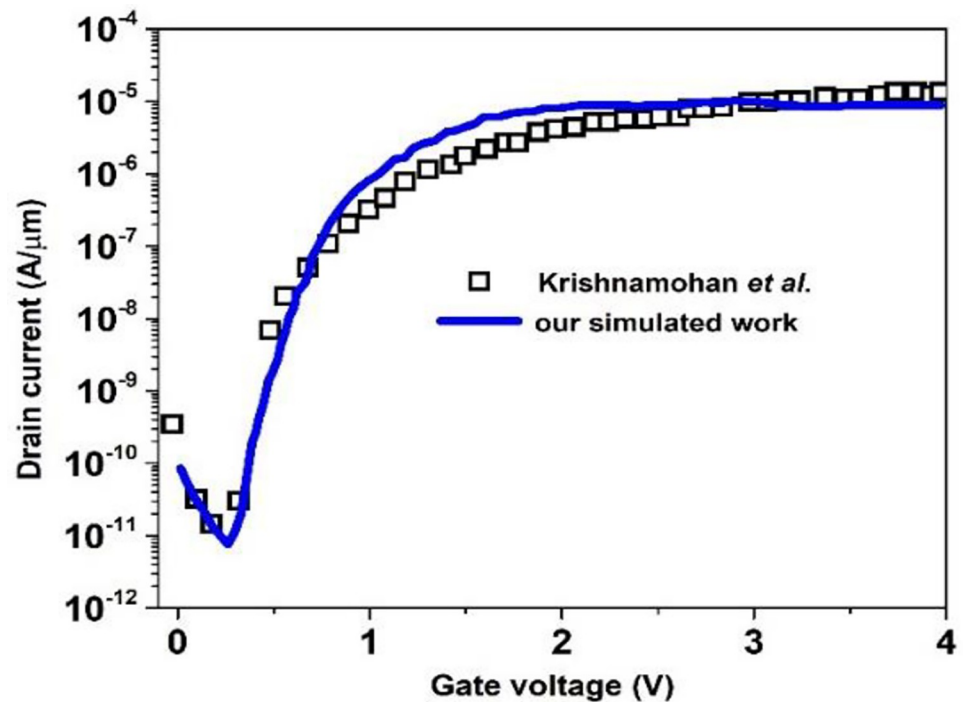


Fig 2. Calibration of transfer characteristics of SiGe PIN TFET [26].

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determined by mole fraction (x) values. From Fig 3, it is noted that as the value of x increases, it is observed that the bandgap of $\text{Si}_{1-x}\text{Ge}_x$ narrows till $x = 0.4$ for both empty and filled nano-gap, thereby boosting the band-to-band tunnelling rate, GBTBT [29]. However, the GBTBT doesn't improve at $x = 0.6$ and $x = 0.8$ values thereby making $x = 0.4$ a suitable choice for the simulation of BM-SO-HTFET.

Fig 4A highlights increment of the tunnelling vertical electrical field profile. It is observed that vertical electric field is greatest at $k = 12$ (2.4×10^6 V/cm) that can be attributed by the increased gate coupling effect. Fig 4B represents that the Band-to-band tunnelling generation rate (GBTBT) that increments at greater k values (28×10^{30} cm⁻³s⁻¹ at $k = 12$). The non-local Band-to-band tunnelling model activates the BTBT dynamics at the tunnelling juncture of the biosensor device [30].

The Energy Band diagram profile shown in Fig 5A highlights the acute band-bending at the tunnelling interface for increasing dielectric constants of the biomolecules that is mainly attributed by the ϕ_{tg} whereas, OFF current (I_{OFF}) is governed by ϕ_{ax} . Thereby, enhancing the BTBT generation rate (G_{BTBT}) resulting in enhanced Ion values. Fig 5B represents the biosensor device threshold voltage profile for increasing dielectric constants of the biomolecules. As observed from the energy band diagram profile that the band gap narrowing with increasing dielectric constant of the biomolecules leads to increased vertical electric field thereby increasing ON current resulting in the decreased threshold voltage at greater dielectric constants.

$$G_{BTBT} = CE^\sigma \exp\left(\frac{-B}{E}\right) \quad (1)$$

Here, C is a factor which is a function of electron effective mass, B representing tunnelling possibilities. Transition constant is represented by σ . Electric field is represented by E . The tunnelling possibility in tunnel FET devices are mainly governed by the Wentzel-Kramer-

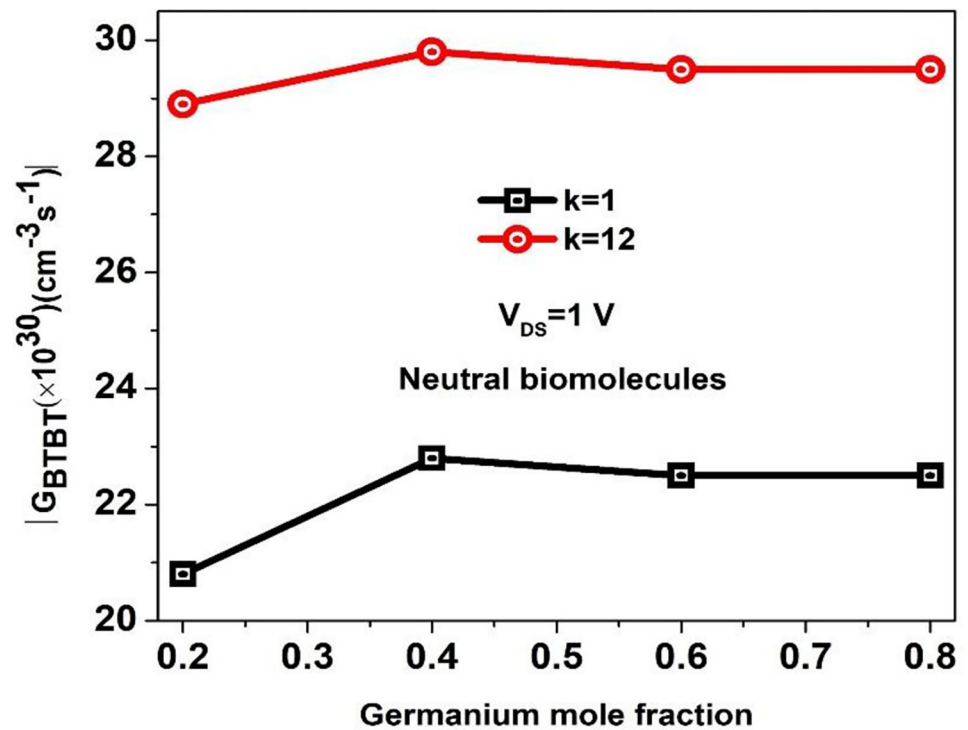


Fig 3. Band to Band tunnelling rate for empty and filled nanogap for different Ge mole fraction values of BM-SO-HTFET.

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Brillouin approximation (WKB) [21].

$$T_{\text{WKB}} \approx \exp \left(\frac{-4\lambda \sqrt{2m^*} \sqrt{E_g^3}}{3q\hbar(E_g + \Delta\phi)} \right) \quad (2)$$

Here, λ and m^* represents the screening tunnelling span and the electron effective mass respectively. The semiconductor forbidden gap (bandgap) is represented by E_g , $\Delta\phi$ represents

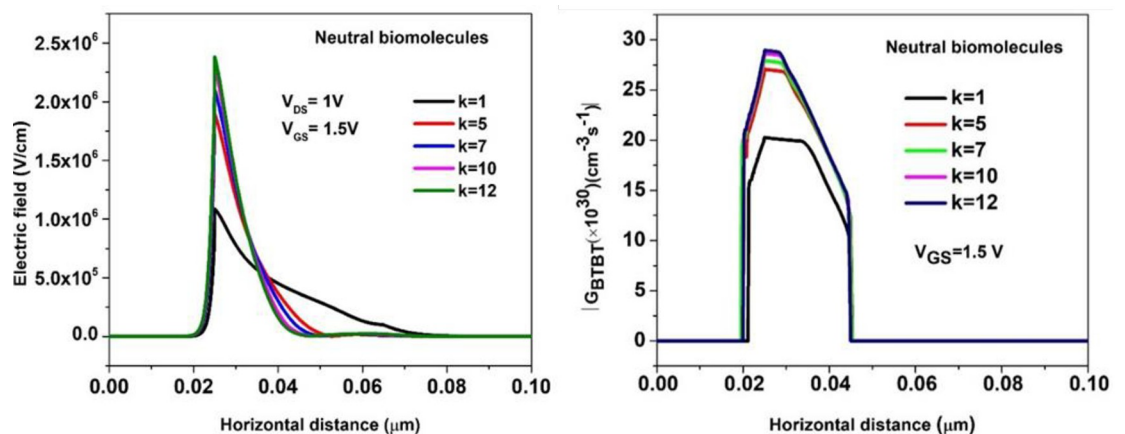


Fig 4. (a) Electric field profile (b) BTBT generation rate of the BM-SO-HTFET with increasing dielectric constant (k) values of the biomolecules.

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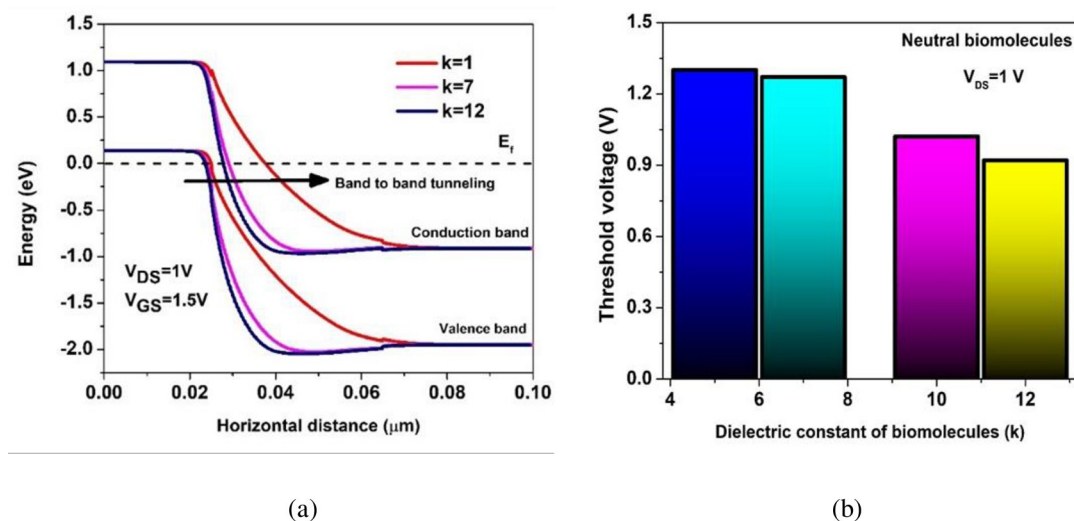


Fig 5. (a) Energy band diagram profile (b) Threshold voltage profile of the BM-SO-HTFET with increasing dielectric constant (k) values of the biomolecules.

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the tunnelling range in terms of energy. From (1), it can be noticed that the acute band-bending can be achieved with increased electric field. From (2), it is deduced that as the k values rise, the tunnelling span narrows and T_{WKB} surges thereby increasing drive current/ON current [30].

Fig 6A demonstrates the device transfer characteristics ($I_{DS}-V_{GS}$) of the BM-SO-HTFET for increasing dielectric constant (k) values of the localized biomolecules in the nanogap. It is noted that air-filled nanogap yields poor $I_{ON} \sim 10^{-17}$ A/ μm [31]. However, I_{ON} increases significantly with rising k values whereas maintaining an appreciably low I_{OFF} which improves ON-OFF switching. SNR, signal-noise-ratio (SNR) gets hindered in real time for these FET based biosensors [32]. Low I_{OFF} current results in reduced consumption of static power in traditional Bi-Metal TFET biosensor. Furthermore, researchers are implementing a transient

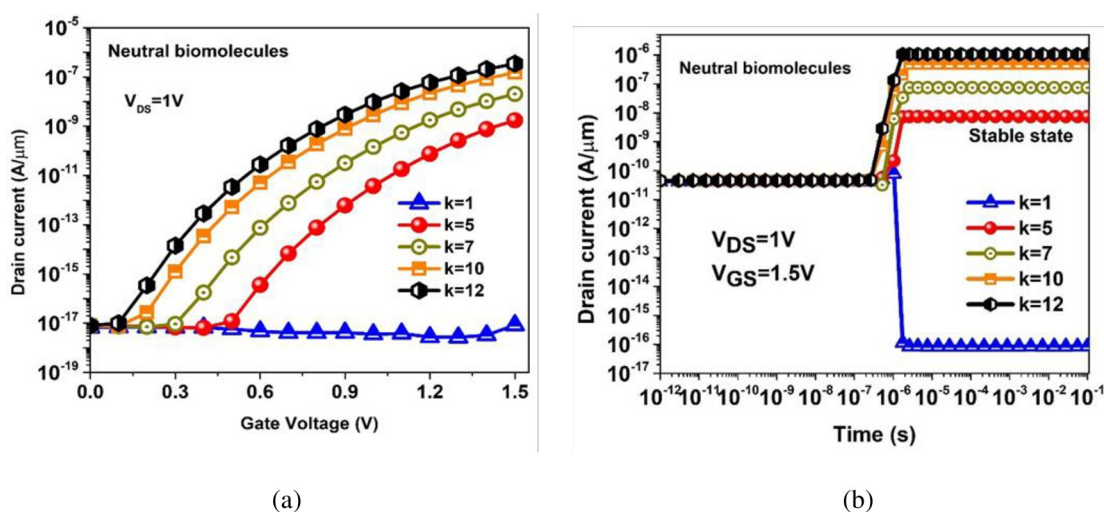


Fig 6. (a) DC Transfer characteristics (b) Transient response profile of the BM-SO-HTFET with increasing dielectric constant (k) values of the neutral biomolecules.

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response approach for exploiting the settling time of I_{ON} with different biomolecules inside the nanogap [32]. Biosensing parameters like sensitivity and selectivity for a certain applied gate voltage can be meticulously studied using transient response of a FET based biosensor device. Fig 6B shows the transient response of BM-SO-HTFET biosensor localizing different biomolecules inside the nanogap. It is evident from the analysis that as the k values for different biomolecules inside the nanogap increase, the I_{ON} increases and reaches a stable state at different settling times [30]. In the case of gelatin biomolecule ($k = 12$), I_{ON} takes the least settling time to reach transient stable state since vertical electric field induces acute band bending at the tunnelling junction due to higher dielectric constant of the biomolecule [30]. Whereas, for an empty nanogap ($k = 1$), prolonged settling time is observed to reach transient stable state as air-filled nanogap mitigates band bending at the tunnelling junction, thereby reducing BTBT rate.

2.1. Sensitivity of ON current (S_{ON})

$$S_{ON} = \left| \frac{I_{ON}(\text{biomolecules})}{I_{ON}(\text{air})} \right| \quad (3)$$

The sensitivity of the biosensor is one of its most important metrics to determine the biosensing functionality. Various sensitivity profiles like threshold voltage sensitivity, I_{ON}/I_{OFF} sensitivity, ON current sensitivity can be considered to analyse the performance of a biosensor. However, in this work, we consider sensitivity of ON current for BM-SO-HTFET biosensor as shown in (3). S_{ON} is defined by the fraction of ON current when the biomolecules are localized and absent in the nanogap. I_{ON} has been selectively considered to determine sensing performance since in TFETs I_{ON} depends on BTBT rate. BTBT however, is independent of temperature. Subthreshold Swing (SS), threshold voltage shift (ΔV_{th}) and I_{ON}/I_{OFF} ratio depend heavily on thermionic emission phenomenon [2]. Hence temperature dependence of these parameters might hamper the sensing functionality of the biosensor. The dependence of sensitivity on temperature is elaborated under section 3.2.

Asymmetrical doping of source ($1 \times 10^{20} \text{ cm}^{-3}$) and drain ($1 \times 10^{18} \text{ cm}^{-3}$) achieves better sensitivity of the TFET based biosensors [33]. Fig 7A highlights steep rise of S_{ON} for increasing k values and it can be noted the $k = 12$, gelatin yields the maximum sensitivity, $S_{ON} = 4.1 \times 10^{10}$. Fig 7B highlights the S_{ON} profile as a function of gate voltage. It is observed that peak S_{ON} (6.4×10^{10} at $k = 12$) for increasing dielectric constant of biomolecules is achieved at $\sim 1.35 \text{ V}$ gate voltage.

2.2. Impact of temperature on S_{ON}

The sensitivity profile of dielectrically modulated biosensors can be furthermore investigated considering its variation from ambient temperature. It is evident from Fig 8A that I_{OFF} increases with increase in temperature as recombination rate increases in BM-SO-HTFET biosensor for $k = 7$ and $k = 12$ [34]. Insignificant change in I_{ON} at higher gate voltages is observed. Sensitivity varies with gate voltage and temperature. The I_{OFF} keeps on increasing in the presence of air in the nanogap with varying temperature as a result the ON current sensitivity (S_{ON}) monotonically reduces as temperature rises, same can be observed in Fig 8B for biomolecules with dielectric constant ($k = 7$ & 12).

2.3. Impact of charge biomolecules on S_{ON}

The relation between the gate voltage and the biomolecule charge density (N) given in (4) represents the field effect transistor voltage balance equation. Where, Ψ_s represents surface

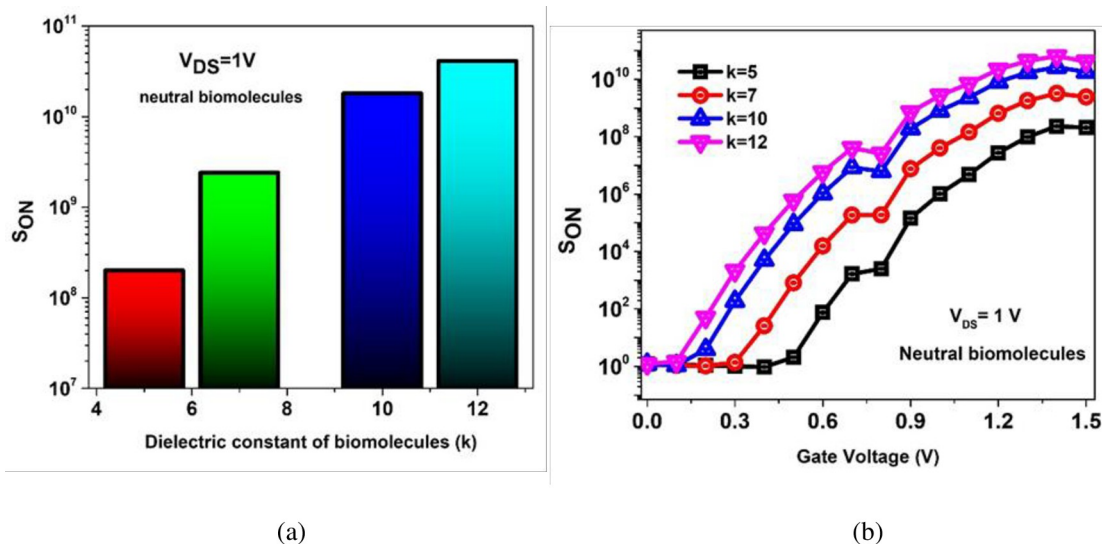


Fig 7. ON current sensitivity for (a) with increasing dielectric constant (k) values (b) gate voltage of the BM-SO-HTFET of the neutral biomolecules.

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potential, N represents biomolecules charge density, C_{eff} represents the effective capacitance per unit area, ϕ_{ms} represents the metal-semiconductor work function. There will be increased Ψ_s as $+N$ increments at fixed gate voltage (V_{GS}) as shown in (4). This will result in increased sensitivity of BM-SO-HTFET biosensor [21]. Increment in sensitivity takes place as the $\frac{+qN}{C_{eff}}$ component at HfO_2 increases depleting the intrinsic channel resulting in acute band bending at the tunnelling junction [33]. On the other hand, as $-N$ increases, Ψ_s reduces at fixed V_{GS} that results in hindered device sensitivity. The $\frac{-qN}{C_{eff}}$ component at HfO_2 increases thereby boosting the threshold voltage by broadening the tunnelling span [35,36]. In our work, the biomolecules charge density varies from $N = \pm 2 \times 10^{11} \text{ Ccm}^{-2}$ to $N = \pm 2 \times 10^{12} \text{ Ccm}^{-2}$. Fig 9A and 9B show

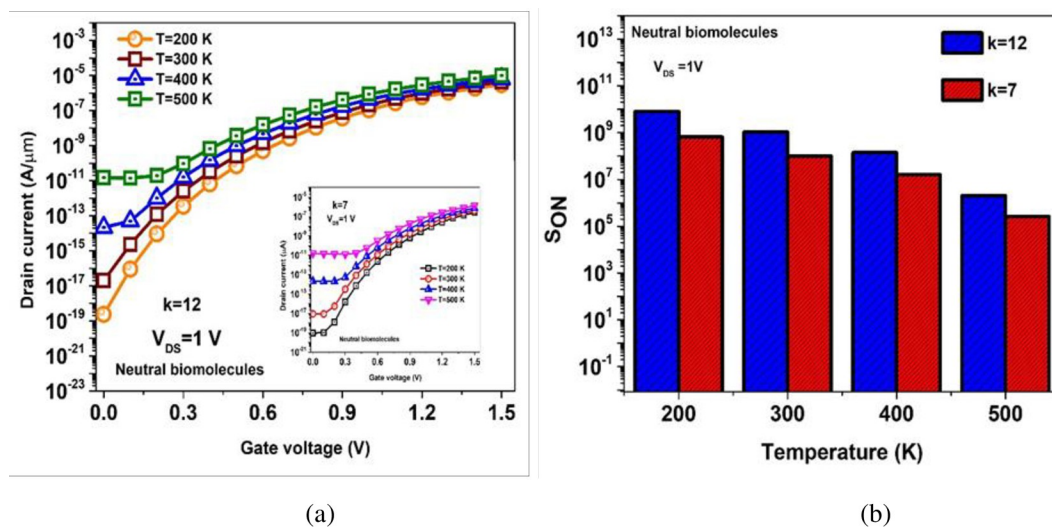


Fig 8. Drain current variation (b) ON current sensitivity (S_{ON}) of the proposed BM-SO-HTFET with different temperature at $k=7$, $k=12$.

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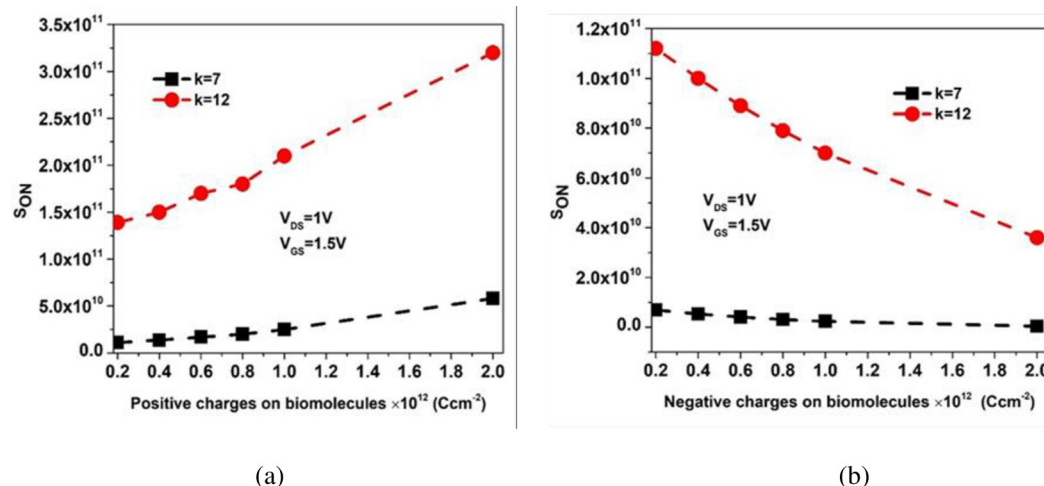


Fig 9. ON current sensitivity of the simulated BM-SO-HTFET biosensor at $k = 7, 12$ for (a) positive charge (b) negative charged biomolecules.

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the sensitivity for positively and negatively charged biomolecules having dielectric constant ($k = 7, 12$). Maximum sensitivity of ON current reported for positively charged biomolecule is 3.2×10^{11} for gelatin biomolecule ($k = 12$).

2.4. Impact of non-ideal issues on S_{ON}

This section broadly discusses the real-time manifestation of the biomolecule localization inside the engineered nanogap of the BM-SO-HTFET biosensor, drifting from the ideal case of fully filled nanogap [30,37]. Fig 10A shows four different cases of gelatin ($k = 12$) localization inside the nanogap with fill factor (β) equal to 50%. Case A, B, C and D determine gelatin with $\beta = 50\%$ at the source-channel tunnelling junction, channel-drain junction, mid-nanogap and top air-filled nanogap respectively. It is observed from Fig 10B shows the device transfer characteristics for all the four cases. It is noted that Case A exhibits the highest ON current and almost provides similar behaviour for a $\beta = 100\%$ filled nanogap because of the presence of gelatin at the source-channel tunnelling junction that facilitates utmost BTBT thereby increased band bending resulting in enhanced ON current. However, for both Case B and Case C it is observed that low ON current is obtained since gelatin is located away from the tunnelling junction which reduces the gate control and thus hinders BTBT at the same. Even though there is 50% air filled from the top in Case D, the complete localization of gelatin from the tunnelling junction to the channel-drain interface leads to increased ON current than Case B and Case C. However, the air fill in Case D reduces its BTBT when compared to Case A. Subsequently, the ON current sensitivity is evaluated in Fig 10C. A maximum $S_{ON} = 3.8 \times 10^{11}$ is obtained at gelatin with $\beta = 50\%$ for Case A and a minimum $S_{ON} = 2.66 \times 10^6$ for Case C. Thus, it is understood that in real-time the presence of biomolecules at the source-channel tunnelling junction even at $\beta = 50\%$ can provide optimum sensing performance.

Furthermore, the real-time biosensor performance is even widely investigated by stacking the biomolecules inside the engineered nanogap [37] of the BM-SO-HTFET to determine gluten ($k = 5$) in Fig 11 for $\beta = 100\%$. From Fig 11A (i), an empty nanogap (air filled) is considered, (ii) a 4 nm thick keratin ($k = 10$) is bounded with the nanogap, (iii) a 2 nm thick zenin ($k = 7$) is stacked on the 4 nm thick keratin, (iv) another 2 nm thick gluten ($k = 5$) is stacked over the 2nm thick zenin and 4 nm thick keratin for $\beta = 100\%$ nanogap. From the transfer

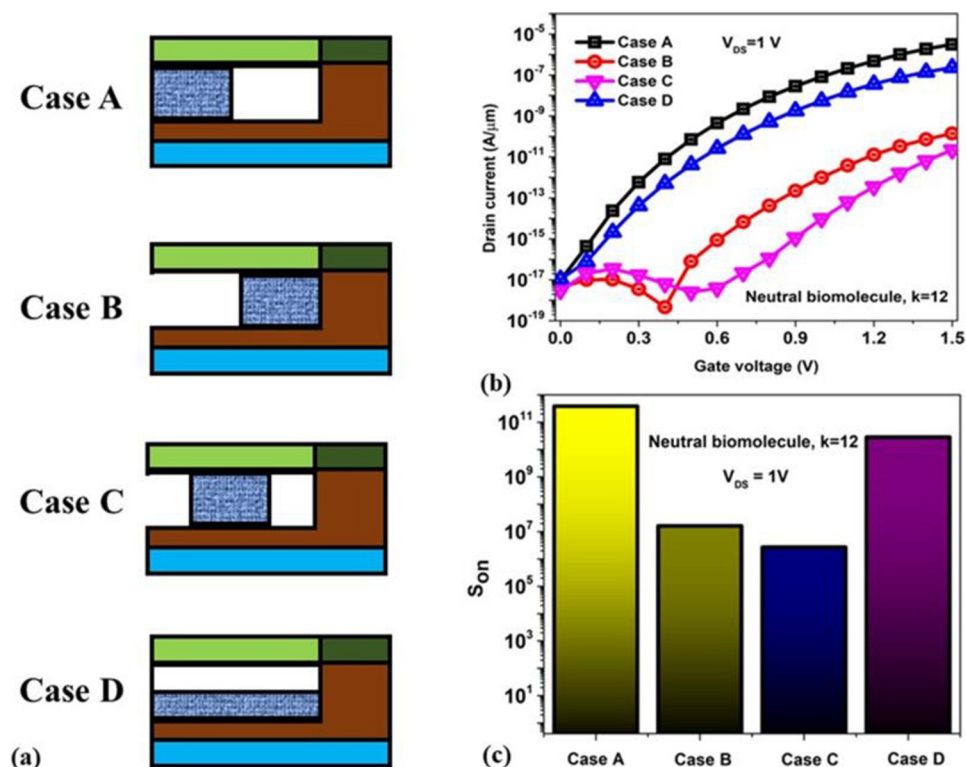


Fig 10. (a) 2D illustration of BM-SO-HTFET biosensor with four different cases of gelatin fill factor (b) transfer characteristics of four different cases (c) ON current sensitivity for four different cases of gelatin fill factor.

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characteristics in Fig 11B, it is observed that the completely stacked biomolecules ($k = 5+7+10$) inside the nanogap provides maximum ON current and thereby optimum ON current sensitivity of 7.8×10^{11} as shown in Fig 11C. Table 2 shows the benchmarking of the

Table 2. Performance standardization of BM-SO-HTFET biosensor considering current sensitivity.

S.No	FET Based Biosensors	ON Current Sensitivity
1.	This work	4.1×10^{10}
2.	Biswas, A, et.al [2022] [34]	8×10^5
3.	Ghosh R, et.al [2022] [38]	8.11×10^9
4.	Reddy N. N, et.al [2022] [16]	6.15×10^3
5.	Vanlalawmpuia K, et. al [2021] [3]	3.61×10^8
6.	Vanlalawmpuia K, et. al [2021] [3]	2.48×10^7
7.	Mukhopadhyay S, et.al [2020][2]	1.7×10^8
8.	Wangkheirakpam V. D, et. al [2020] [20]	2×10^6
9.	Dwivedi P, et.al [2020] [39]	1.05×10^2
10.	Anand, S, et. al [2019] [40]	1×10^{10}
11.	Narang, R, et. al [2018] [19]	~ 0.6
12.	Kanungo S, et. al [2016] [1]	1×10^5
13.	Kanungo S, et. al [2015] [41]	3×10^6
14.	Cao W, et.al [2014] [33]	$\sim 10^{10}$
15.	Szymanski T. H, et.al [2014] [42]	9×10^3
16.	Sarkar D, et. al [2012] [43]	1×10^6

<https://doi.org/10.1371/journal.pone.0301479.t002>

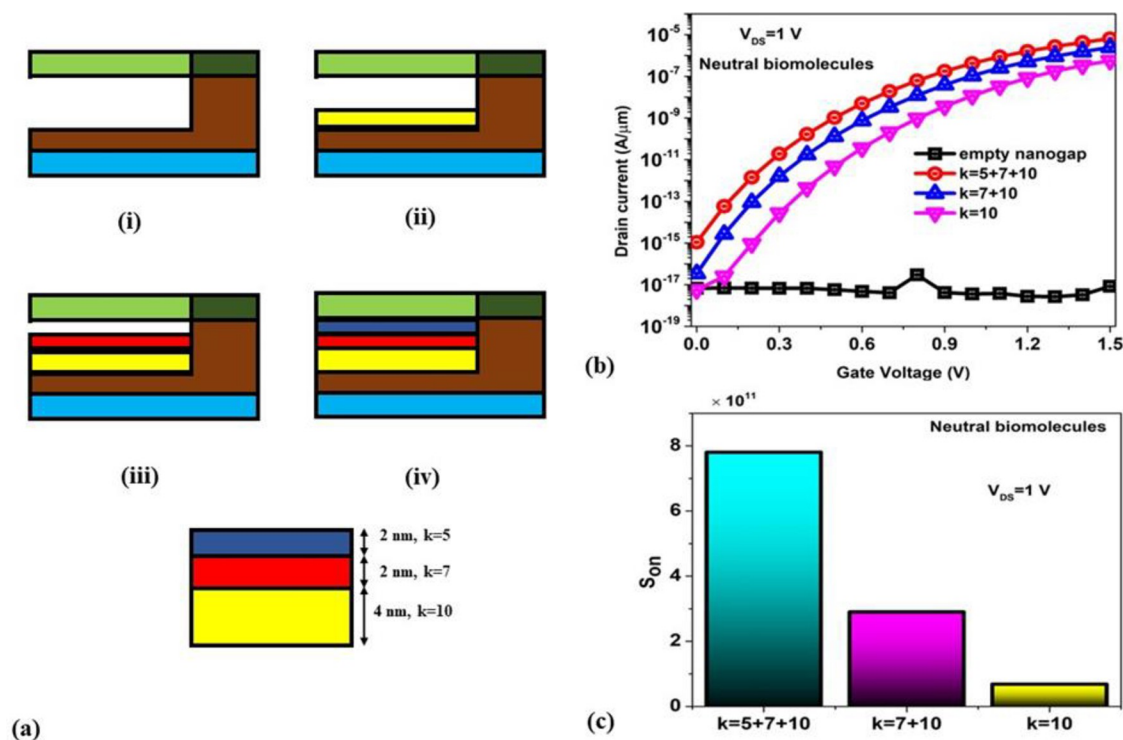


Fig 11. (a) 2D illustrative of BM-SO-HTFET biosensor with (i) air-filled (ii) 4 nm thick keratin filled (iii) 6 nm thick gluten+zenin+keratin filled (iv) 8 nm thick gluten+zenin+keratin filled nanogap (b) transfer characteristics of four different cases (c) ON current sensitivity for three stacking cases.

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BM-SO-HTFET biosensor considering its S_{ON} performance with the existing FET based biosensors. It is reported that the BM-SO-HTFET biosensor exhibits improved ON current sensitivity for neutral biomolecules than almost all the existing biosensors reported in the literature.

3. Conclusions

In this paper, a high- k stacked gate with bi-metal hetero-junction TFET is proposed for label free biosensing applications. This study considers the effect of dielectric modulation within the nanocavity beneath the bi-metal gate structure that acts as the sensing site for the biomolecules. The change in dielectric constant (k) and charge densities of the bio-species alter the gate capacitance modulating the device characteristic trend. Hence, the impact of biomolecule immobilization at the binding sites have been studied on band-to-band generation rate, electric field and drain current characteristics of the device. Finally, the ON current sensitivity (S_{ON}) of the device is extracted which is utilized as the major sensing metric throughout the work. A better sensitivity ($S_{ON} = 3.2 \times 10^{11}$) is reported with Ge content $x = 0.4$ for positively charged biomolecules in comparison to neutral ones ($S_{ON} = 4.1 \times 10^{10}$). The impact of temperature variation depicts a reduction in S_{ON} monotonically with rise in temperature. Moreover, some non-ideal cases are also considered to evaluate the detection limit of the device. From the results, it can be predicted that the reported structure can exhibit optimum sensitivity of $S_{ON} = 3.8 \times 10^{11}$ with biomolecules across the source-channel interface even with 50% fill factor. Finally, sensitivity is also determined for stacked biomolecules depicting $S_{ON} = 7.8 \times 10^{11}$ for completely stacked biomolecules ($k = 5+7+10$) inside the nanogap. Comparative analysis of the ON current sensitivity of BM-SO-HTFET biosensor with some of the reported FET

based sensors pledges for the potential of the proposed structure for future ultra-sensitive applications.

Supporting information

S1 Raw data.

(XLSX)

Author Contributions

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