In-silico Investigation of Cyl. Gate all Around (GAA) Tunnel Field Effect Transistor (TFET) Biosensor

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Abstract. For some time now, the advancement of low power and high sensitivity biosensors has been the center of attention for in-situ detection and monitoring which form an integral part of portable health monitoring systems. This paper elucidates the design-optimization of a cylindrical (cyl.) gate all around (GAA) tunnel field effect transistor (TFET) biosensor with retrograde doping using numerical modeling. The device consists of n⁺ heavily doped SiGe substrate and two insulated gates i.e. primary gate (PrG) and biasing gate (BG) with suitable work functions. Sensitivity of the biosensor is investigated by varying dielectric constant (k) and charge density (ρ) in the active region of device. TFET biosensor design and simulation is performed using TCAD Synopsys software. Computations are carried out for various conditions of dielectric constant (k) and charge density (ρ) for analyzing the sensor sensitivity. Simulation results show that for k=10 and ρ = 3.0x10¹² cm⁻², there is low leakage current (\(I_{OFF}\)) = 1.0x10⁻¹⁶ A/µm, and high ON current (\(I_{ON}\)) = 1.0x10⁻⁶ A/µm. Results obtained in this work as useful as it will act as a design guideline for developing TFET biosensors for various biological applications.

Keywords. Biosensor, TFET, Gate all around (GAA), short channel effect, leakage current

1. INTRODUCTION

Presently, the center of attention have been the enhancement of biosensors due to a surge in new strains of bacteria and virus induced diseases like COVID 19. For in-situ detection of bio-molecules, the desired characteristics of a biosensor includes increase in susceptibility, rapid latency, immense span of measurement, real time detection, portability, low power consumption, to cite a few. Literature encompasses examples of devices for detecting bio-molecules with various technologies [1-9].

One of the solutions that has been highly explored in recent times is field effect transistor (FET) based biosensor. Even though, FET biosensors depict desired characteristics, performance of such sensors is limited due to the short channel effects(SCEs). In contrast to a conventional FET device, a Tunnel Field Effect Transistor (TFET) with gate all around (GAA) structure depicts lower subthreshold swing (SS) with reduced SCEs. Some innovational solutions for the performance improvement of GAA TFET include source pocket Silicon (Si) TFET [10], 2-D tunneling FET with localized charges [11], double gate TFET with drain underlap [12-14], cylindrical TFET with reliability issues [15], hetero gate dielectric TFET [16], asymmetrical underlap 3D-cylindrical GAA-TFET with low spacer width [17]. Although Si based GAA TFET depicts high performances, it has limitations such as low thermal stability, high OFF current (\(I_{OFF}\)) and high SS due to ambipolar behaviour.
In this paper, we have performed the design-optimization of a cylindrical (cyl.) gate all around (GAA) tunnel field effect transistor (TFET) biosensor. Furthermore, detailed investigation is performed to comprehend the impact of multiple specification on sensor performance i.e. sensitivity. The paper has the following sections: the device details and modelling-simulation environment are explained in section 2. Subsequently, results obtained through numerical simulation are summarized in section 3, and the conclusion of the computations is detailed in segment 4.

2. DEVICE DETAILS AND MODELLING PARAMETERS

The device under study is a cyl. GAA TFET with retrograde doping. 3D structure and the transversal view of the proferred structure are shown in Figure 1(a) and (b) respectively. Retrograde doping is incorporated in subsidiary band gap substrate (SiGe) at the source to channel edge. Parameters of device and simulations environment are as follows: p-channel doping concentration in the core region=10^{15} cm^{-3} and outer region=10^{14} cm^{-3}, source-region doping concentration (p-type)=1\times10^{18} cm^{-3}, drain-region doping concentration (n-type) = 5\times10^{20} cm^{-3}, oxide thickness (t_{oxide}) = 5nm , channel length (L_{channel}) = 20nm , gate work function of control gate (CG) = 4.1eV , gate work function of polarity gate (PG) =4.53eV, extended source length (L_{extss}) and drain length (L_{extdd}) = 40nm. The device modelling and simulation has been performed using TCAD Synopsys software.

The device substrate material is Silicon-Germanium (Si-Ge) which has better SS due to narrow bandgap. The RD doping used exemplify a high doping region (inner-region) that incorporates 25% of the channel region with remaining portion relatively less than the inner region [18]. Premise results in reduced SCEs, and improves I_{OFF} along with SS. The primary gate (PrG) and biasing gate (BG) have been modeled with appropriate work function as well as polarity controlled voltage. By etching an adequate segment of PrG dielectric section Nano gap cavity is incorporated inside the CG dielectric about the BG edge. This region acts as the active site for biomolecule sensing. As a effect of low-k dielectric (SiO_{2}) a reduction in the influence of fringing field is observed. Simulation models like band-to-band tunneling (BTBT) model, trap assisted tunnelling (TAT) which represents the supremacy of the I_{OFF}, Shockley Read Hall (SRH) for creation and rebinding of the hole-electron pairs in the semiconductors, Wentzel Kramer's Brillouin (WKB) approximation and Kane’s models have been incorporated for device modeling and simulation [19].
3. RESULTS AND DISCUSSION

This segment, analyzes the influence of various parameters on the receptiveness of the retrograde doping based TFET biosensor. The target biomolecule concentration variation is mimicked as change in dielectric constant \((k)\). The condition \(k=1\) depicts inadequacy of biomolecules, whereas \(k>1\) represents the occurrence of biomolecules in the active region of the biosensor. The tunnel barrier reduces as a result of increasing \(k\) which intensifies band bending. Rising barrier width results in elevated negative charge concentration. A lower measure of surface potential is observed beneath the cavity sector when biomolecules are inadequate \((k=1)\). On the other hand, for the availability of biomolecules \((k>1)\), the surface potential attains a greater value beneath the cavity sector. In this work, dielectric constants are varied as \(k=1, 5\) and \(10\), and charge densities are imparted as \(\rho = -5\times10^{-11}, -1\times10^{-12}\) and \(-3\times10^{-12}\) cm\(^{-2}\) depicting the variation in the biomolecules [20]. The highly doped pocket placed at the source edge results in a tunnel gap which induces a restraint between conduction and valence bandwidth resulting in a tunneling event at source-channel interface as a result of low band gap substrate. Furthermore, tunnel barrier width at the drain-channel interface increases as a result of high band gap substrate at the drain side.

The variation in drain current relies on the parameters \(k\) and \(\rho\) for different gate source voltage \((V_{GS})\) is shown in Fig.2. With the rise in accumulation of biomolecules the switching current \((i.e I_{ON})\) of the device increases. Furthermore the inclusion of retrograde doping in the device results in lower leakage current \((I_{OFF})\). It also resolves the concern of a higher SS as in conventional MOSFET’s.

Figure 2: Drain current as a function of parameters \(k\) and \(\rho\) for different \(V_{GS}\)
The variation in electric field (EF) relies on the parameters k and \( \rho \) along the longitudinal direction (length of the device) is shown in Fig.3. With the rise in k the gate-channel coupling elevates the surface potential. On account of accumulation of the biomolecules which promotes to an improved flow of charges results in higher EF, and thereby higher tunneling across the valence and conduction bands. With increase in the parameter k values, at the source-channel intersection, the EF improves effectively, also EF reduces as the tunneling barrier increases.

![Electric field as a function of parameters k and \( \rho \) along sensor length](image1)

**Figure 3:** Electric field as a function of parameters k and \( \rho \) along sensor length

The variation in current density relies on the parameters k and \( \rho \) along side the longitudinal direction (length of the device) is shown in Fig.4. The current density depends on various parameters such as bandgap of the material, also the inclusion of the WKB approximation supports for higher current density. Furthermore it is witnessed that as the concentration of biomolecules rises, there is an enhancement in the density of charges resulting in a higher current density.

![Current density as a function of parameters k and \( \rho \) along sensor length](image2)

**Figure 4:** Current density as a function of parameters k and \( \rho \) along sensor length

Under the cavity region at source-channel intersection as the electric field reduces, an increase in charge concentration is observed leading to reduced \( I_{ON} \). As dielectric constant increases the \( I_{ON}/I_{OFF} \)
ratio tends to increase. Moreover it reduces as the negative charge density increases. Sensitivity is defined by eq.(1)

\[
S_{\text{drain}} = \left( \frac{i_{\text{drain}}^{\text{biomolecule}} - i_{\text{drain}}^{\text{air}}}{i_{\text{drain}}^{\text{air}}} \right)
\]  

\[ (1) \]

\(i_{\text{drain}}^{\text{air}}\) is the drain current with \(k=1\) representing biomolecules are absent and \(i_{\text{drain}}^{\text{biomolecule}}\) is the drain current with \(k > 1\) representing the occurrence of biomolecules in the cavity section and as the dielectric constant rises the sensitivity of the drain current also rises. Furthermore, the ability of sensing the biomolecular element in the cavity is represented by a significant repositioning in the drain current sensitivity across gate-to-source voltage (\(V_{\text{gs}}\)). With variations in the dielectric constant and charge density at low \(V_{\text{ds}}\) an enhancement of drain current sensitivity is observed, for a biosensor based application [21-24].

The variation in device performance relies on the parameters \(k\) and \(\rho\) for different \(V_{\text{GS}}\) values are summarized in Table 1. Device capacitances (\(C_{\text{gs}}\)) and (\(C_{\text{gd}}\)) as a function of parameters \(k\) and \(\rho\) for various \(V_{\text{GS}}\) is shown in Figure 5 and Figure 6 respectively. The parasitic capacitances play a crucial role in sensor’s switching capability as well as leakage current. The parameter \(C_{\text{gd}}\) is calculated by eq.(2)

\[
C_{\text{gd}} = C_{\text{of}} + C_{\text{dif}} + C_{\text{gdinv}}
\]  

\[ (2) \]

where the symbol \(C_{\text{of}}\) represents outer fringing capacitance and \(C_{\text{dif}}\) represents drain region inner fringing field capacitance. The symbol \(C_{\text{gdinv}}\) represents inverted gate-drain capacitance [17].

In TFET, the parameter \(C_{\text{gd}}\) should be less for better performance. As depicted in Figure 5 the steepest \(C_{\text{gd}}\) is observed for \(k=1\) and \(\rho = -3.0 \times 10^{-12}\text{ cm}^{-2}\). As mentioned earlier \(k=1\) signifies absence of biomolecules in the cavity section under gate due to which the barrier width increases hindering the tunneling channel-to-drain section.

![Figure 5: Capacitance (C_{gd}) as a function of parameters k and \rho for various V_{GS} values](image)

The parameter \(C_{\text{gs}}\) can be obtained by eq.(3)

\[
C_{\text{gs}} = C_{\text{of}} + C_{\text{sif}}
\]  

\[ (3) \]

where, \(C_{\text{of}}\) represents outer fringing capacitance and \(C_{\text{sif}}\) depicts source region inner fringing field capacitance [17]. Due to the presence of SiGe HDF layer it results in a higher \(C_{\text{gs}}\) value.
Table 1. Change in device performance as a function of parameters k and ρ

| Parameters | ρ = -5.0x10^{-11} cm⁻² | ρ = -1.0x10^{-12} cm⁻² | ρ = -3.0x10^{-12} cm⁻² |
|------------|------------------------|------------------------|------------------------|
|            | K=1 K=5 K=10          | K=1 K=5 K=10          | K=1 K=5 K=10          |
| I_ON (A)   | 3.68n 90n 216n        | 1.5n 57n 150n         | 1200n 3.21n 18.3n     |
| I_OFF (A)  | 81.9a 93.5a 63.8a     | 71.7a 58.4a 33.7a     | .093a .858a .786a    |
| I_ON/ I_OFF| .0449G .963G 3.38G   | .021G .976G .445G    | .0128G 3.74G 23.3     |
| EF (V/µm)  | 1.65M 1.96M .586M    | 1.08M 1.59M 1.66M    | 1.77M 2.31M 2.28M    |
| ECD (A/cm²)| .216k 5730k 18.9k   | .184k 6.88k 15.4k    | .001k .824k 3.77k    |
| C_gn (F)   | 2.57a 3.79a 4.31a    | 2.66a 3.89a 4.41a    | 4.59a 6.41a 7.21a    |
| C_gd (F)   | 1.08a 1.17a 1.21a    | 1.0a 1.09a 1.12a     | .379a .428a .461a    |

Figure 6: Capacitance (C_{gs}) as a function of the parameter k and ρ for different V_{GS} values

4. CONCLUSION

This paper elucidates the numerical investigation of a cyl. gate all around (GAA) TFET biosensor. Sensitivity of the biosensor is analysed using device simulation software. The variation in the concentration of biomolecules in the active region of the biosensor is mimicked by varying the dielectric constant (k) and charge density (ρ). The sensor performance has been investigated through the DC and transient analyses. Parameters which have been observed in this study include I_{ON}, I_{OFF}, C_{gs}, C_{gd}, EF Intensity and electron current density for variation in dielectric constant and charge density depicting biomolecule concentration change. Simulation results show that in the cyl. GAA retrograde doped highly doped pocket TFET biosensor, for k=10 and ρ = 3.0x10^{12}cm⁻² the truncated OFF current (leakage current) is (I_{OFF} = 1.0x10^{-16}A/µm), and high ON current is (I_{ON} = 1.0x10^{-6} A/µm). In addition, it is observed that the presence of highly doped pocket between the source and source ended channel enhances the device efficacy due to reduced influence of fringing electric fields of gate towards the source. Premise is primarily due to tunnelling of barrier width. C_{gd} = 5.0x10^{-10}F and C_{gs} = 7.0x10^{-10}F at drain voltage of V_{ds} = 1V have been observed in numerical simulation.

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