Simulation-based Analysis of Ultra Thin-body Double Gate Ferroelectric TFET for an Enhanced Electric Performance

GIRDHAR GOPAL (✉ 2019rec9550@mnit.ac.in)

Malaviya National Institute of Technology <https://orcid.org/0000-0001-6212-6563>

Tarun varma

MNIT Jaipur: Malaviya National Institute of Technology

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Simulation-based analysis of ultra thin-body double gate ferroelectric TFET for an enhanced electric performance

Girdhar Gopal · Tarun Varma

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Abstract The Ultrathin body double gate FE layer TFET(UTB-DG-FE-TFET) is proposed and investigated in this work. Electrical performance parameters such as surface potential $\psi(x)$, electrical field, drain current, sub-threshold swing, threshold voltage, and I_{on}/I_{off} ratio are further analyzed using simulation-based analysis. Integration of Si: HfO_2 ferroelectric layer on top and bottom surfaces make the structure that provides negative capacitance, higher on current, enormous surface potential, peak electric field, and improvement in SS with degradation in off Current. The suggested design is evaluated in comparison with FE-TFET and standard TFET structures. Finally, the impact of device geometry variants like ferroelectric layer thickness (t_{fe}), intrinsic channel thickness t_{si} , interfacial layer types, interfacial layer thickness (t_{ox}) and channel length L_c on transfer characteristics are investigated through 2D TCAD Sentaurus Simulator for a clear validation of its optimization. The recommended work demonstrates that it is a suitable device enabling superior performance and helpful in ultra-low-power applications.

Keywords BTBT · Memory Window · Subthreshold Swing · Threshold Voltage · UTB-DG-FE-TFET

Girdhar Gopal
Electronics and Communication Engineering Department,
Malaviya National Institute of Technology Jaipur,
Jaipur, Rajasthan 302017, India
E-mail: 2019rec9550@mnit.ac.in

Tarun Varma
Electronics and Communication Engineering Department,
Malaviya National Institute of Technology Jaipur, Jaipur,
Rajasthan 302017, India

1 Introduction

Short channel effects (SCEs) and an increase in leakage current are the main issues with downscaling the CMOS technology node [1–4]. Moreover, at room temperature $T=300K$, the scalability of threshold voltage V_T is also limited due to Boltzmann tyranny ($SS \equiv \frac{KT}{q} \cdot \ln 10 \approx 60$ mV/decade) that decides the steepest nature of the transition between on and off state [5–9]. In short, there is a need for in-depth research on steep subthreshold swing devices (< 60 mV/decade) like Tunnel field-effect transistors (TFETs) [10, 11], Impact ionization MOSFETs (I-MOS-FETs) [12], Nanoelectromechanical FETs (NEMFETs) [13] and Negative capacitance FETs [14]. These Emerging devices have been seriously explored in recent years due to impending physical constraints of conventional CMOS devices. Thereby TFETs or commonly called the green transistors, are the most promising contenders that operate on the quantum mechanical band-to-band tunneling (B2BT) principle [15–17]. A most claiming obstacle for TFET being low on-drive-current (I_{on}) because of less transmission probability T_{WKB} of the interband tunneling barrier [18]. T_{WKB} is estimated using Wentzel-Kramer-Brillouin (WKB) approximation. WKB approximation defines it as exponential function of effective mass m^* , energy band gap E_g , tunneling length λ , and the difference in energy between both the source's conduction band and the channel's valence band $\delta\phi$. That is tunneling barrier approximation is estimated by $T_{WKB} \approx \exp \left[\frac{-4\lambda \cdot \sqrt{2m^*} \cdot \sqrt{E_g^3}}{3q \cdot \hbar (E_g + \delta\phi)} \right]$. I_{on} is obtained by integration of T_{WKB} over depth of source-channel junction. Moreover, at fixed drain voltage, a rise in gate voltage V_g changes the surface potential, minimizing λ and raising $\delta\phi$. Thereby, maximum transmission probability T_{WKB}

of tunneling barrier implies a greater on-current I_{on} . Accordingly, there are many possible causes to increase I_{on} : (i) The usage of high-K gate material, for example, is a type of gate dielectric engineering technology, service of multi-gate structures for controlling channel potential perfectly, selection of the optimum value of spacer to enhance on-current I_{on} , asymmetric gate design by the use of different work functions and different gate dielectric materials, and ferroelectric gate oxide [19] (ii) Tunneling junction engineering such as by use of the optimum value of source doping, by increasing effective tunneling area and heterojunction structure by use of low-bandgap materials [11] (iii) Material engineering techniques by use of unique materials like Ge and III-V semiconductors [20] (iv) by use of strained-silicon [21]. However, the ferroelectric gate oxide technique is the best example of negative capacitance that can provide high I_{on} and sub-60 mV/decade at a modest voltage value [22]. Integration of FE layer on TFET has drawn much attention in boosting the performance, i.e., possible structures for negative capacitance TFETs are metal-ferroelectric-insulator-semiconductor (MFIS), metal-ferro-electric-metal-insulator-semiconductor (MFMIS), metal-ferro-electric-semiconductor (MFS) and metal-ferroelectric-insulator-semiconductor-insulator-ferroelectric-metal (MFISIFM) [23]. It is well known that a combination of FE layers in the gate will provide internal voltage gain, which ultimately enhances tunneling probability T_{WKB} and improves on-current [24]. Thus on-current is obtained by integrating tunneling probability T_{WKB} over the source-channel junction. The proposed negative capacitance structure is MFISIFM, i.e., Ultra-thin body double gate FE layer TFET (UTB-DG-FE-TFET). The paper's organization follows with theory in part 2, followed by device construction and simulation setup in part 3, following with results and discussion in part 4. Lastly, part 5 concludes the paper.

2 Theory

The main reason for using the FE layer of $Si : HfO_2$ in UTB-DG-FE-TFET is to rectify the lattice mismatch problem. Thus, It is the most compatible with the flow of the CMOS manufacturing process [25]. The enticing characteristic of FE material is negative capacitance, which acts as a voltage step-up transformer. Therefore, SS and drain current are improved. Any CMOS device's subthreshold swing is generally calculated as the ratio of variation of gate bias potential (V_g) to variation of

subthreshold drain current by unity decade. Mathematically it can be expressed as:

$$SS = \frac{\partial V_g}{\partial (\log_{10} I_d)} = \underbrace{\frac{\partial V_g}{\partial \psi_s}}_m \cdot \underbrace{\frac{\partial \psi_s}{\partial (\log_{10} I_d)}}_n \quad (1)$$

Where m is the body factor used to calculate the effective twisting of surface potential at a specific bias, and n is the transport factor that tells how much current flows along the channel by lowering the potential. From Fig. 1, it is evident that the capacitor voltage divider rule clearly shows that V_g and ψ_s are correlated. that is

$$m = \frac{\partial V_g}{\partial \psi_s} = 1 + \frac{C_s}{C_{eq}} \quad (2)$$

where $\frac{1}{C_{eq}} = \frac{1}{C_{ox}} + \frac{1}{C_{fe}}$ is equivalent gate inter-facial capacitance, C_{ox} is inter-facial layer capacitance, C_s is semiconductor or intrinsic channel capacitance and C_{fe} is ferroelectric layer negative capacitance. If Q is total charge observed by total capacitance across gate C_g then equivalent gate inter-facial capacitance C_{eq} is calculated by following expression: $C_{eq} = \frac{C_{ox} \cdot C_{fe}}{C_{ox} + C_{fe}} = \frac{Q}{V_g - \psi_s}$. Effective voltage ($V_g - \psi_s$) is seen across C_{eq} and voltage in proportional with total charge Q also observed by C_g being expressed by ($\beta \cdot Q$) where β is internal amplification factor having value greater than unity. Therefore,

$$\begin{aligned} Q &= C_g [(V_g - \psi_s) + \beta \cdot Q] \\ \Rightarrow Q &= C_g (V_g - \psi_s) + C_g \beta \cdot Q \\ \Rightarrow Q(1 - \beta \cdot C_g) &= C_g (V_g - \psi_s) \\ \Rightarrow C_{eq} &= \frac{Q}{(V_g - \psi_s)} = \frac{C_g}{(1 - \beta \cdot C_g)} = \frac{C_g}{(1 - V_{fb})} \end{aligned}$$

If $V_{fb} = \beta \cdot C_g \gg 1$ then equivalent gate-inter-facial capacitance C_{eq} attain negative value; hence it is called negative capacitance TFET. In other sense, the feedback voltage ($V_{fb} \gg 1$) must be positive to behave as negative capacitance TFET. It also implies amplifying internal voltage and reducing body factor m as clear from equation (2). Overall, SS is significantly decreased, as evident from equation (1). Moreover, equation (1) suggests that $\psi_s \gg V_g$, i.e., acts as a step-voltage transformer which ultimately results in an improved electric field and enhanced on-current. In case of MOSFET, body factor $m = 1$ results into a lower limit of $SS = 60 \text{ mV/decade}$ i.e., equation (1) results into $SS \equiv \frac{\partial \psi_s}{\partial (\log_{10} I_d)} = \frac{KT}{q} \cdot \ln 10 \approx 60 \text{ mV/decade}$. Moreover, ferroelectric polarization results in getting body factor $m < 1$ in the proposed device structure. The benefits of using FE material on the top and bottom surface of the intrinsic channel over perovskite material like PZT and SBT is the best scaling in the nanometer range. Voltage across the MOS (V_{MOS}) and voltage across the FE material (V_{FE}) is related by $V_g = V_{MOS} + V_{FE}$. Voltage amplification is given by [26] :

$A_v = \frac{V_{MOS}}{V_g} = \frac{|C_{fe}|}{|C_{fe}| + |C_{MOS}|}$. With $|C_{fe}|$ is less than $|C_{MOS}|$, voltage amplification factor yields into negative voltage gain.

3 Device construction and simulation set up

The cross-section perspective of the UTB-DG-FE-TFET is shown in Fig. 1, including its capacitive modeling. The channel is enclosed by an interfacial layer (SiO_2) to reduce inter-diffusion. In a stacking having dielectric (SiO_2) on sidewalls, a ferroelectric sheet of silicon doped hafnium oxide ($Si:HfO_2$) is utilized.

Fig. 1: UTB-DG-TFET Device Structure

Because of the lower value of the dielectric constant (32.5), $Si:HfO_2$ is preferred over Strontium Bismuth Tantalate (SBT) and Lead Zirconate Titanate (PZT) to lessen the impacts of fringing [27,28]. It enables thinner ferroelectric layers. As a result, the gate stack ratio is better for scaling. Furthermore, $Si:HfO_2$ is compatible with the CMOS manufacturing process flow [17]. Design must always utilize an interfacial layer with the substrate to minimize lattice mismatch and enhance SS. However, the memory window is restricted owing to a voltage drop throughout the interfacial layer [29]. As a result, the best value of $t_{ox} = 0.5$ nm is chosen. The source is highly doped, via an impurity concentration of 10^{20} cm^{-3} , compared to a weakly doped drain with an impurity concentration of $5 \times 10^{18} \text{ cm}^{-3}$, to diminish ambipolar conduction. The channel is weakly doped, while not being entirely intrinsic, with a trivalent impurity concentration of 10^{16} cm^{-3} . Table 1 lists the device variables used in the simulation. On the 2D TCAD Sentaurus Simulator, the device construction is simulated and tested [30]. Applying Fermi-Dirac statistics and the impact of band-gap narrowing, heavy doping at the drain, and source concerning channel is studied. Concentration-dependent mobility model, electric field-dependent mobility, band-gap narrowing model, Shockley-Read-Hall(SRH) recombination model, auger recombination model, and non-local band to band tunneling(BTBT) model are some of the models that are

Table 1: Experimental device parameters for the simulation

Parameter	Symbol	Value	Parameter	Symbol	value
Gate length	L_g	15 nm	Gate Thickness	t_g	40 nm
Source length	L_s	20 nm	Source Thickness	t_s	30 nm
Drain length	L_d	20 nm	Drain Thickness	t_d	30 nm
Channel length	L_c	30 nm	Interfacial layer thickness	t_{ox}	0.5 nm
Ferroelectric layer thickness	t_{fe}	2 nm	Intrinsic channel thickness	t_{si}	10 nm

employed throughout computations. Ideal ferroelectric sheet having remanent polarisation P_r , coercive field E_c , and saturation polarisation P_s are $10.75 \mu \text{ C/cm}^2$, 1.15 MV/Cm , and $11.37 \mu \text{ C/cm}^2$, respectively, to eliminate hysteresis loss difficulties such as dc breakdown, retention, as well as fatigue [31]. For gate material, the proper work function ($\psi_m = 4.6\text{eV}$) is used.

4 Simulation results and discussion

The effect of ferroelectric thickness on electric parameters in UTB-DG-FE-TFET is discussed. The paper investigates a comparison of UTB-DG-FE-TFET with FE-TFET [32] and conventional TFET [33,34]. Simulated data of UTB-DG-FE-TFET is compared with reference data of FE-TFET and conventional TFET, which shows proposed UTB-DG-FE-TFET, which indicates the high value of on current I_{on} and significant change in off current I_{off} . In addition, it must be noted that due to the negative capacitance but the double gate construction, the drain current level rises. The drain current I_{ds} rises as the gate voltage V_{gs} increases. Memory window is key deciding parameter for description of total dipoles and can be expressed as $MW \equiv 2E_c \times t_{fe}$, here E_c as well as t_{fe} denote coercive field or coercivity and ferroelectric material thickness, respectively [25]. In Table 2, the proposed work's electrical parameters have been compared to those of previously reported devices.

4.1 Comparison of TCAD model physics with referenced data

Transfer characteristics of UTB-DG-FE-TFET are examined and simulated using experimental parameters shown in Table. 1 and also compared with FE-TFET

[32] and conventional TFET [33], respectively in Fig. 2. Proposed UTB-DG-FE-TFET almost provides two times improvement in I_{on} and 20 times improvement in I_{on} in comparison with FE-TFET and conventional TFET, respectively. One can observe that the proposed structure also gives 10^1 times reduction in I_{off} and 10^2 times reduction in I_{off} as compared to FE-TFET and conventional TFET, respectively. Internal voltage amplification, such as that provided by a voltage step-up transformer, is the cause of this occurrence, which finally yields into increment in I_{on} and reduction in I_{off} , i.e., it leads to enhancement in the current level.

Fig. 2: Simulated and referenced data comparison [Under forward sweep at $V_{ds} = 0.5$ V for quantitative comparison]

Due to the particular hysteresis behavior of FE materials, forward and reverse sweeps for voltage are introduced in transfer characteristics for the proposed structure in Fig. 3.

Comparison of output characteristics of UTB-DG-FE-TFET with FE-TFET and conventional TFET at $V_{gs} = 1$ V is illustrated in Fig. 4. In triode region up to $V_{ds} = 0.2$ V, a channel is formed due to the availability of large charge carriers, and when the V_{ds} is increased beyond 0.2 V, the large numbers of charge carriers starts to tunnel. Thus, I_{ds} shows a growing exponential curve due to the lowering of drain induced barrier. The lateral electrical field from the drain is halted through the channel. That's why a perfect saturation is also seen in output characteristics [35].

Moreover, incomplete charge compensation and decrease in polarization also happened due to depolarization field in FE materials. Fig. 5 illustrates that approximately the same window is granted for two different structures of 15 nm gate length UTB-DG-FE-TFET and 30 nm gate length FE-TFET by sweeping

Fig. 3: Transfer characteristics of UTB-DG-FE-TFET under forward and reverse sweep at $V_{ds} = 0.5$ V keeping all parameters same

Fig. 4: Comparison of output characteristics of UTB-DG-FE-TFET with FE-TFET and conventional TFET at $V_{gs} = 1$ V keeping all parameters same

the gate voltage. Comparison results confirm that approximately the same memory window (0.32 V for 15 nm gate length UTB-DG-FE-TFET and 0.32 V for 40 nm gate length FE-TFET) is obtained. Moreover, One can observe an enhancement in I_{on} and also a reduction in I_{off} . Thereby 15 nm gate length UTB-DG-FE-TFET structure could be the best alternative for enriched electric performance. Apart from data storage properties of FE materials, the surface potential is boosted, and the output current level is amplified [24]. For this purpose, the variation in the channel surface potential of UTB-DG-FE-TFET, FE-TFET, and conventional TFET to the varied value of V_{gs} is presented in Fig. 6. Fig. 7 demonstrates the comparison of UTB-DG-FE-TFET electrical fields with FE-TFET and conventional TFET [27]. Under the bias conditions having

Fig. 5: Comparative analysis of transfer characteristics for UTB-DG-FE-TFETs with 15 nm gate length and FE-TFETs with 30 nm gate length while keeping all other parameters constant

Fig. 6: Surface potential $\psi(x)$ variation across the channel positions of UTB-DG-FE-TFET, FE-TFET, and conventional TFET with channel length $L_c = 30$ nm at constant $V_{ds} = 0.5$ V and $V_{gs} = 1$ V. TCAD simulated data with the same variables as stated in Table 1 is depicted by symbols.

$V_{gs} = 1$ V and $V_{ds} = 0.5$ V, the maximum electric field for UTB-DG-FE-TFET at the interface of source and channel is 37.5 % greater than conventional TFET and 10 % greater than FE-TFET. This is owing to the excellent characteristics of positive feedback caused by FE materials.

4.2 Effect of ferrothickness on subthreshold swing, threshold voltage, electric field dependent polarization and I_{on}/I_{off}

Due to negative capacitance, voltage is amplified to a great extent but with negative potential gain. Sub-

Fig. 7: Comparison of electric fields for UTB-DG-FE-TFET with FE-TFET and conventional TFET

threshold swing is a crucial parameter for understanding any MOS switching behavior [4]. It is found that Polarization of ferroelectric layer improves the value of point subthreshold swing SS_{point} as shown in Fig. 8. Fig. 8. shows that as t_{fe} varies from 4 to 16 nm, SS_{point} value is reported below 36 mV/decade for a range of approximately ten orders of magnitude. Average subthreshold swing $SS_{average}$ is noticed around below 45 mV/decade in Fig. 9 for the various value of t_{fe} . Because the subthreshold properties are significantly improved, the device is appropriate for ultra-low energy switching applications.

Fig. 8: Impact of ferrothickness t_{fe} on SS_{point}

Fig. 10 demonstrates the relation between threshold voltage V_{th} and intrinsic channel thickness t_{si} for different values of t_{fe} . The figure reveals that as the intrinsic channel thickness t_{si} and the FE layer thickness

Fig. 9: Impact of ferrothickness t_{fe} on $SS_{average}$

Fig. 10: Threshold voltage V_{th} against intrinsic channel thickness t_{si} for different FE layer thickness t_{fe}

t_{fe} increases, so does V_{th} . This was primarily because the tunneling volume was reduced with a rise in t_{si} and the feedback charge lowered since t_{fe} increased [27,33]. A FE layer of $t_{fe} = 16$ nm shows a relatively thinner hysteresis curve having greater polarization on the application of the highest electric field to get deep saturation that is evident from Fig. 11. Therefore current level enhances in thinner FE layer with maximum negative capacitance. Due to spontaneous polarization in ferroelectric, a non-linear relationship exists between polarization and electric field, represented by a hysteresis loop. On increasing t_{fe} , magnetic polarization tries to become zero, as illustrated in Fig.11. Thereby Coercive field strength reduces in-considerably. Therefore, simulation results validate that characteristics governing parameter are t_{fe} and memory window value is raised dramatically. The primary concern in the design of the proposed device is to choose an optimum

value of FE layer thickness so that three key parameters SS, memory window, and drain current, are improved. Therefore former is reduced, and the latter is increased. Recently explored silicon doped hafnium oxide (Si:HfO₂) is selected not only to provide relatively coercive field E_c over PZT (Lead-Zirconate-Titanate) and SBT (Strontium-Barium-Titanate) but also to present a large memory window [25]. Fig. 12 depicts a summary

Fig. 11: Total electric field vs. Polarization for different FE layer thickness

of the impact of the ferroelectric device layer thickness on the I_{on}/I_{off} ratio of the ferroelectric device. Fig. 12 illustrates that the ON current rises as the thickness of the ferroelectric layer decreases due to polarisation trapped charges while the OFF current remains similar. This improves the ratio of I_{on}/I_{off} , as the ferroelectric layer's thickness decreases.

Fig. 12: Change in I_{on}/I_{off} ratio with ferrothickness t_{fe}

Table 2: Comparison of electrical characteristics with previously published works [25,26,28,29]

Variation	Ferro thickness (nm)	I_{on}/I_{off} ratio	MW (V)	SS_{point} (mV/dec)
Proposed Work	2	7.117×10^{13}	0.32	23
	4	3.459×10^{11}	0.25	19.6
	6	1.165×10^{11}	0.21	17.3
[28]	10	5×10^{13}	1.8	-
	30	7×10^{12}	4	-
[25]	10	1×10^7	1.7	-
	15	9×10^6	2.05	-
	20	2×10^6	2.3	-
[29]	100	1×10^7	1.8	46
[26]	153	1×10^{10}	-	5

At $t_{fe} = 2$ nm, it was discovered that the proposed device had a better SS, a large ratio of I_{on}/I_{off} , and a larger memory window. Since the ferroelectric layer is placed on top and bottom of the gate dielectric. The ferroelectric layer thickness is controlled to get the best band to band tunneling (BTBT).

4.3 Effect of device geometry variants on transfer characteristics

Fig. 13 illustrates the logarithmic effect of ferroelectric layer thickness on drain current while changing gate voltage on a linear scale. Table 3 shows the ferroelectric characteristics for different Si:HfO₂ layer thicknesses. Table 4 displays the device's parameter value concerning different device geometry variations. Table 4 demonstrates that improved SS, large memory window and high on-off current ratio are regarded to be the most suitable value when compared with other variations at $t_{fe} = 2$ nm, $t_{ox} = 0.5$ nm, $t_{si} = 10$ nm, SiO₂ as interfacial layer type and $L_c = 30$ nm.

The ferroelectric layer thickness has a significant effect on device performance. Negative capacitance rises as t_{fe} decreases resulting in increased trapped charge density. These trapped charge densities within this ferroelectric sheet create a channel and start a tunneling process at low V_{gs} . It can be shown that when the thickness of ferroelectric oxide t_{fe} increases from 2 nm to 4 nm, 6 nm, etc., the drain current significantly reduces. With an increase in t_{fe} , this results in the creation of a low feedback charge. However, in the absence of the FE layer ($t_{fe} = 0$), the drain current is observed to be less because of the absence of positive feedback. For $t_{fe} > 0$, a high current is seen due to positive feedback introduced by negative capacitance. Yet the coercive field E_c hardly reduces on increasing t_{fe} . So it leads to an apparent dependency of t_{fe} on the memory window

Fig. 13: Impact of different FE layer thickness on transfer characteristics**Table 3:** Si:HfO₂ ferroelectric characteristics increasing t_{fe}

t_{fe} (nm)	ϵ_r	P_r ($\mu\text{C}/\text{cm}^2$)	P_s ($\mu\text{C}/\text{cm}^2$)	E_c (MV/cm)
2	37.2	13.5	13.7	1.52
4	35.8	12.1	12.2	1.48
6	33.1	10.65	10.7	1.44

(MW). For this reason, MW rises from 0.32 V to 0.45 V substantially.

Fig. 14: Influence of various intrinsic channel thickness on transfer characteristics

Fig. 14 illustrates the influence of the thickness of the channel of varying the intrinsic channel thickness t_{si} on the I_{ds} - V_{gs} curve. The drain current I_{ds} decreases with t_{si} , as shown in the figure. The reason for this is that when t_{si} rises, the tunneling volume decreases. Moreover, one can notice that the memory window (MW) falls with t_{si} due to a reduction in the

Table 4: EXTRACTED PARAMETER VALUE

Device geometry variants		MW (V)	V_{th} (V)	SS	I_{on}/I_{off}
t_{fe} (nm)	2	0.32	0.38	23	7.1×10^{13}
	4	0.25	0.59	19.6	3.4×10^{11}
	6	0.21	0.61	17.3	1.1×10^{11}
t_{si} (nm)	10	0.32	0.38	23	4.1×10^{12}
	12	0.22	0.50	26.5	2.3×10^{11}
	14	0.19	0.51	21.3	1.2×10^{10}
Interfacial layer types	HfO_2	0.56	0.31	20.6	3.1×10^{12}
	Si_3N_4	0.41	0.32	21.5	5.1×10^{11}
	SiO_2	0.32	0.38	23	2.4×10^{10}
t_{ox} (nm)	0.25	0.31	0.45	38.5	2.3×10^{12}
	0.5	0.41	0.42	31.3	4.6×10^{12}
	1	0.37	0.38	23	3.1×10^{11}
L_c (nm)	10	0.32	0.36	13.7	5.6×10^{11}
	20	0.41	0.51	21.4	4.8×10^{12}
	30	0.58	0.65	23	3.1×10^{13}
	70	0.58	0.75	37.6	6.8×10^{11}

coercive field E_c . Fig. 15 shows the impact of various

Fig. 15: The effect of various interfacial layer types on transfer characteristics

inter-facial layer types, i.e., 0.5 nm SiO_2 layer is replaced by HfO_2 and then by Si_3N_4 . Detailed analysis is done by SiO_2 only because of two limitations of HfO_2 : (i) lattice mismatch problem between HfO_2 and silicon substrate during fabrication process (ii) deterioration of I_{on}/I_{off} , instead of large ON current and large memory window of 0.56 V. Impact of various interfacial layer thickness t_{ox} of SiO_2 interfacial layer on transfer curve $I_{ds}-V_{gs}$ is depicted in Fig. 16. For the moderate value of $t_{ox} = 0.5$ nm, the enormous electric field is induced by a more significant voltage drop in the substrate material at the tunneling interface. Thus on current increases with greater memory window as compared to a thicker layer of $t_{ox} = 1$ nm. Effective oxide thickness $t_{ox} = 0.5$ nm is one of optimum dimension

Fig. 16: The effect of various interfacial layer thicknesses upon transfer curve

over standard CMOS high dielectric/metal gate technique. In addition, for $t_{ox} = 0.25$ nm, on current is less with reduced memory window. Effect of different chan-

Fig. 17: Impact of different channel length on transfer characteristics

nel length L_c on $I_{ds}-V_{gs}$ transfer curve is depicted in Fig. 17. It is noticed from the figure that I_{on} remains the same for channel length up to 30 nm while the same I_{off} is obtained for channel length greater than 20 nm. The figure shows that on-current I_{on} decreases for channel length greater than 30 nm, and off-current I_{off} rises for channel length smaller than 20 nm. The best suitable channel length $L_c = 30$ nm is chosen because of the larger I_{on} and memory window.

5 Conclusions

UTB-DG-FE-TFET is experimentally demonstrated to investigate electrical characteristics like surface potential, drain current, threshold voltage, and subthreshold swing over conventional TFET and FE-TFET using Sentaurus TCAD 2D simulator. The results indicate that the current level is raised by increasing the gate voltage, with a drop in the off-current compared to other TFETs. It is also noticed that surface potential is boosted along with the channel position, and at the source-channel interface, there seems to be a maximum electrical field. In contrast, V_{th} rises with increment in t_{si} and t_{fe} and thinnest hysteresis loop is obtained for larger t_{fe} . It is also noticed that SS_{point} and $SS_{average}$ are improved against I_{ds} for different value of t_{fe} . Moreover, Effect of larger t_{fe} , t_{si} results into reduced tunneling current. While the type of interfacial layer, especially SiO_2 layer having $t_{ox}=0.5$ nm over HfO_2 and Si_3N_4 is found to be best suitable because of lattice mismatch problem faced by HfO_2 against silicon substrate. In addition, larger on-current as well as huge width of memory window is noted for $t_{ox}=0.5$ nm. Finally, channel length L_c also has a significant effect on transfer characteristics. Furthermore, a high I_{on} and a very little I_{off} was shown for the proposed design to produce outstanding I_{on}/I_{off} ($\approx 10^{13}$). Thus, Such TFETs may be appealing for ultra-low-power device operation while still providing high performance.

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The authors declare that they have no conflict of interest.

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Not applicable

Code availability

Not applicable

Compliance with ethical standards

In research involving human participants, all procedures were carried out in compliance with ethical guidelines.

Consent to participate

Not applicable

Consent for Publication

Not applicable

Author contributions

Girdhar Gopal

Conceptualization, TCAD Simulation, Writing and Editing.

Tarun Varma

Supervision, Reviewing, Investigation and Validation.

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