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Designing of Tunnel FET and FinFET using Sentaurus TCAD and Finding their Characteristics

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ABSTRACT- In this paper, a FinFET and Tunnel FET (TFET) are designed and implemented using Sentaurus TCAD. Due to numerous advantages, the TFET and FinFET have been proposed as a possible alternative to the conventional metal oxide semiconductor FET (MOSFET). A phenomenal performance-has been achieved using FinFET technology up to a 7 nm feature size. A detailed observation is made on FinFET and TFET regarding various effects such as short channel effects, quantum tunneling effect and characteristics like electric field, voltage and current, on-current, doping concentrations, energy band diagrams etc. FinFET technology can be used for designing different low power CMOS digital circuits and memory-based circuits. On the contrary, TFET based synthesized circuits are known for their high sensitivity, for which they are suitable for sensing applications, especially biosensors.

Keywords: Trigate Fin-FET, Tunnel FET, Doping concentrations, Energy band Diagram, Electric field.

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1. INTRODUCTION

There are a lot of new technologies booming in the recent years. The MOSFET's are now slowly replaced by other FET devices, such as Tunnel-FET (TFET) and FinFET [1] [2]. TFET and FinFET have better performance than MOSFET in low power supply devices in most cases. FinFET is basically a Multi-gate MOSFET structure. On scaling the MOS-FET, the size is reduced to 100 nm variation, due to which subthreshold-Swing has increased, and I-off current has also increased. Which is why, we are approaching alternate technologies. In MOSFET, limiting the subthreshold swing to 60mV/decade due to thermal Boltzmann tail of carries, whereas it does not affect the TFET devices [3] [4].

On restricting the Size of the MOSFET, it results in the increase of large Short Channel effects. Whereas, TFET works well in this scenario and shows better performance using Quantum Tunneling effect. There are many different types of devices in FinFET and TFET, including single-gate FinFET, double-gate FinFET, triple-gate FinFET, and many more [6]. A planar TFET has higher electric field effect, has better ON current and decreased subthreshold-swing than other TFET devices. There are many drawbacks to this device's also, In TFET, the ON current is very less and there are ambipolar effects. Whereas in FinFET, it has high parasitic capacitances, it's hard to manage the varying Threshold voltage (V_{th}). Both of them put to gather, have high fabricating cost compared to that of MOSFET.

While modelling the device, the structures are placed on Silicon on Insulator (SOI) to avoid any sort of leakage. There are two different types of device modelling such as 2D and 3D, which will result in analyzing the various structures. These devices are modelled in Sentaurus TCAD software for further analyzes. TCAD allows to study the device structure and various other parameter in the Software.

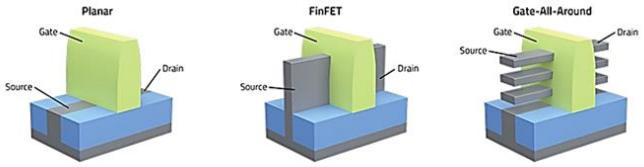

Figure 1. Types of FET devices [4]

FinFET has vertical channel which looks like a fin, whereas, MOSFET has a horizontal channel. In FIN-FET the channel is covered with a Silicon layer. The TFET device has P-I-N-junction, and works on-the band to band Tunneling. On giving some bias to drain, the conduction band of the channel is shoved below the valence band of the source part.

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For Device modelling, Sentaurus TCAD is used to implement both TFET and FinFET structures in device level. Sentaurus TCAD is a workbench which has a complete graphical arrangement for creating, executing, and visualizing the Simulations and various other Data [5].

In this paper, Both SDE and S-device is being used. In SDE (Synopsys Sentaurus structure editor), the device is being modelled where the structure is built with different doping concentrations and different types of materials. After the device is built, it is meshed with certain number, which helps to study the device in a better way. According to the SDE, all the required parameters are considered to that of the SDE and with a set of instructions or coding the needed physics of the device and math, the wanted graphs are plotted and observed. Then the output or the results are analyzed to match with the better performance of the device.

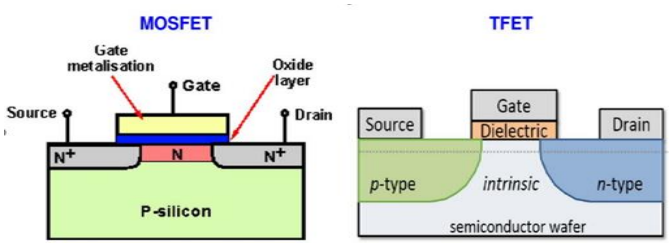

Figure 2. MOSFET vs TFET

2. MATERIALS AND METHODS

2.1 Tunnel-FET and it's Working Methodology

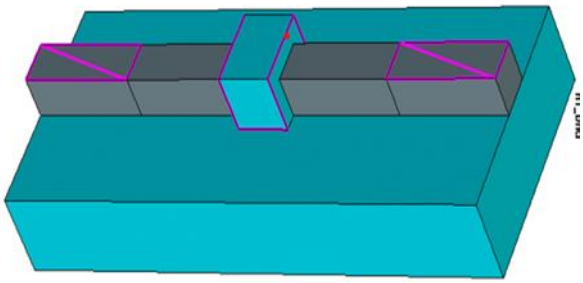

Figure 3. A Sentaurus made TFET

TFET has different switching mechanism than that of MOSFET. TFET works well for lower power devices. TFET works on the principle quantum tunneling effect which is also known as Band to Band tunneling. TFET works by tunneling the source to drain barrier instead of diffusing over the barrier. Thus, there are two conditions for the Quantum Tunneling to occur which is, the barrier should be thin over a larger area and there should enough density states on either side of the transmission and receiving ends to supply energy locations for those carriers [6].

TFET has MOSFET like structure but has reverse doping in both drain and source. In MOSFET, the diffusion happens over the barrier, whereas, in the TFET the tunneling happens through the barrier. There are two types of junctions based on the doping in P-I-N junction which are homojunction and heterojunction. In Homojunction same kind of doping is between the contact that is silicon to silicon, whereas, in heterojunction p-typed is doped with Ge (Germanium) and n-type is doped with silicon (Si) and intrinsic type remains silicon. There are different modeling methods used in TFET which are Kane's Model and Atomistic quantum modeling [7].

When the source's valence band and the channel's conduction band overlap, the tunnelling current in a TFET sub-threshold slope abruptly changes. TFET has higher control over the gate for which it produces better performance and has improves characteristics over the MOSFET. On comparing the thin body size for the Single Gate and Double Gate, thin body is said to have lower subthreshold-swing and high drive. The effect of having a thin body does not show any visible change in the single and double gates [8]-[9].

2.2 Principle of Operation of TFET

The TFET follows quantum Tunnelling Effect in ultra-low power devices. Quantum Tunnelling or Band to Band Tunnelling, simply explains barrier penetration, which is an atom passing through potential energy barrier. The Probability of penetration of an atom decreases exponentially with barrier height and width and mass of the particle. The Potential energy barrier has high energy than that of the atoms or particle's kinetic energy. A particle has a probability of penetrating through the barrier if the barrier thickness is thin without sufficient energy [10].

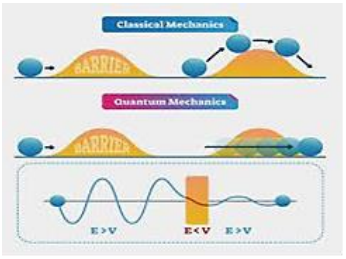

Figure 4. Quantum Tunneling Effect

2.3 Characteristics of TFET

TFET has less OFF-current as well as ON current and subthreshold slope compared to that of MOSFET. Thus, there is a cutting of supply voltage, which in turn increases the speed and performance of the device.

The Tunnel-FET is a P-I-N type junction, where both the drain and source are densely doped but the intrinsic layer is very sparsely doped [11].

The quantum tunnelling propagation is expressed as –

$$T_t = exp[-2\int|k(x)|dx - \ x_2x_1] \quad (1)$$

Tunnelling current can be expressed as:

$$I = a \times V_{eff} \times E \times e^{b/E} \quad (2)$$

Sub-threshold swing can be expressed as:

$$Sunthreshold\ Swing(SS) = dV_{gs}/d\ (\log I_{ds}) \quad (3)$$

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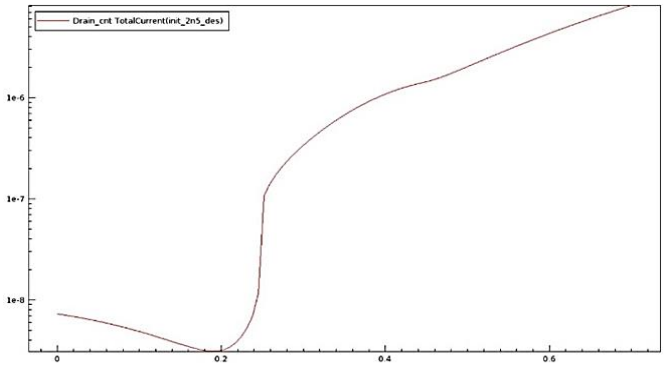

Figure 5. I_d vs V_{gs}

3. FinFET AND IT'S WORKING

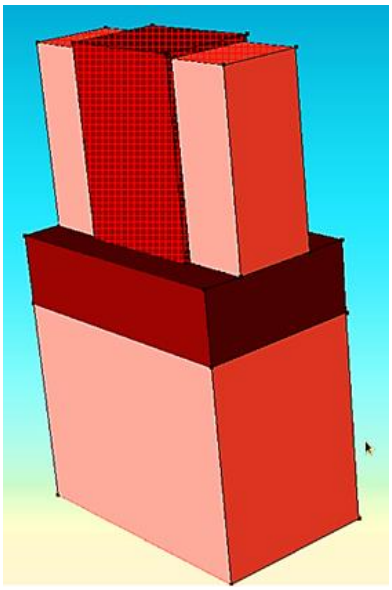

Figure 6. A Sentaurus made FinFET

FinFET is a multi-gate MOSFET device with a channel which looks a FIN. A thin or slight silicon film is covered over the channel. There are two kinds of FinFETs formations such as SOI (Si on insulator) and Bulk.

Due to depletion of channel-length in MOSFET, there is an elevation in the short channel effects. These SCE (short-channel effects), depends on limiting the e- (electron) drift and changing the threshold voltage [12].

The FinFET is made up of substrate (made up of silicon material), Oxide layer, Channel (silicon material), Gate-Oxide (SiO_2), source is made up of Silicon and drain as well is made up of silicon material. There are different types of FinFET such as double gate, tri-gate, Shorted gate and insulated or isolated gate FinFETS. FinFETS has better performance, operates at low voltage, less leakage currents and power.

In FinFET, the drain current escalates as bias is given drain terminal. FinFET has very less power consumption, better performance, and has a high operating speed. The main drawback of FinFET is that it very expensive to fabricate compared to Mos-FET. It is mostly used in microprocessors and other electronic components [3].

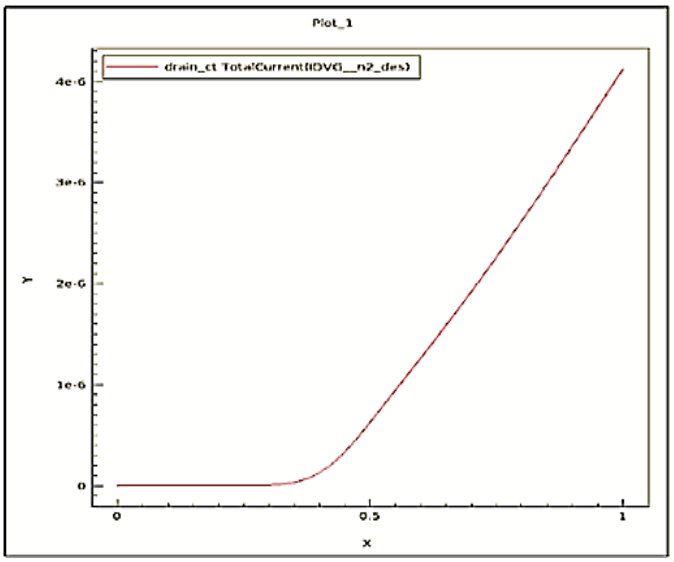

Figure 7. I_d vs V_{gs}

3.1 Principle of Operation of FinFET

The working principle of FinFET is same to that of MOS transistor. A regular MOSFET has conducting channel on the surface whereas the FinFET has conducting channel on three sides. The MOSFET has less control over device as channel is decreased. The FinFET produces less leakage and has higher potential for larger increases in power [2] [4].

4. RESULTS AND DISCUSSION

After Device modelling in the Sentaurus SDE, the code is being run and then it produces a modelled structure. It can be done vice versa also. Thus, after we analyse various parameters.

The data provided represents the characteristics of two different transistors: FinFET and TFET. Starting with the FinFET, it has a threshold voltage (V_{TH}) of 0.458075 Volts, indicating the minimum voltage required to activate the transistor. The maximum transconductance ($g_{m_{max}}$) of the FinFET is 7.61e-6 Siemens (S), which represents its ability to amplify signals. The saturation current (I_{dsat}) of the FinFET is 4.122e-6 amperes, indicating the maximum current it can handle when fully conducting. Moving on to the TFET, it has a lower threshold voltage of 0.205 volts, suggesting it can operate at a lower power supply. The TFET's maximum transconductance ($g_{m_{max}}$) is significantly lower at 5.06E-15 S, implying that it may provide lower signal amplification compared to the FinFET. However, the TFET demonstrates a saturation current (I_{dsat}) of 8.122e-7 A, which is higher than that of the FinFET. This suggests that the TFET can handle a greater current flow when fully activated.

In terms of resistance, the ON resistance (Ron) of the FinFET is 131.2 Ohms, while the TFET exhibits a higher ON resistance of 272.6 Ohms. A lower ON resistance allows for better conduction and less power loss in the transistor. Additionally,

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the output resistance (Rout) of the FinFET is 2.9e+9 ohms, while the TFET's output resistance is significantly higher at 9.25e+16 ohms. A higher output resistance may result in reduced signal degradation at the output.

Table 1. Comparison of FINFET and TFET

Device	V_{TH}	$g_{m_{max}}$	*Id sat*	*Ron*	*Rout*
FINFET	0.458	7.61E-6	4.122E-6	131.2	2.9×10^{9}
TFET	0.205	5.06E-15	8.122E-7	272.6	9.25×10^{16}

The TFET device is modelled using P-I-N based model, where the P type is doped with Boron (Source), intrinsic channel is doped as a channel and N type is doped with Arsenic (Drain). Masking is done for the device and high masking is done for the channel region. After masking the device the analysis is performed in Sentaurus device (S- device). Then analysis is performed on the device and I-V characteristics, electric Field and energy band diagram is extracted.

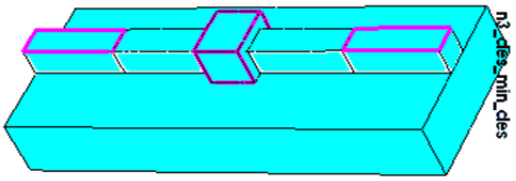
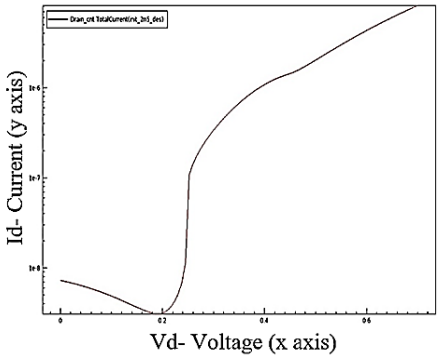
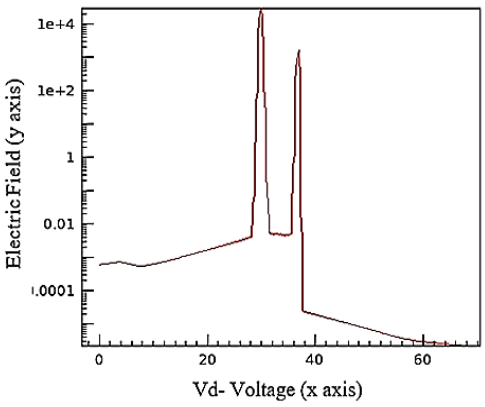


Figure 8. A simulation model of FinFET





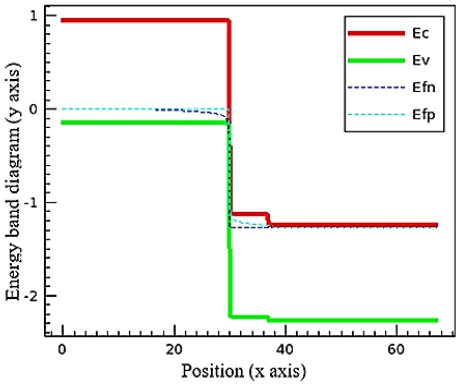
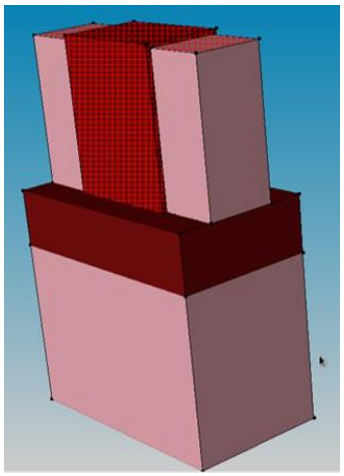
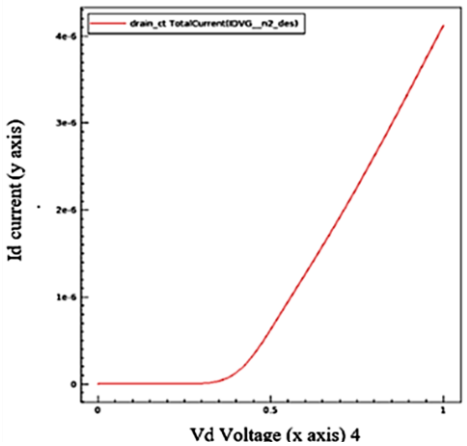


Figure 8.*a.* Device modelling of TFET device, ***b.*** I-V characteristics of the TFET device, ***c.*** Electric Field vs Drain Voltage graph, ***d.*** Energy band diagram of the TFET Modelled device.

The FinFET device is modelled using N-P-N type transistors where N type is doped with arsenic and P type is doped with boron. The FinFET is modelled in S-device and different characteristics like I-V characteristics, Electric field and Energy band diagram are extracted from the TCAD Sentaurus simulations.



a. Sentaurus made FinFET device structure



b. Extracted I-V characteristics of FinFET

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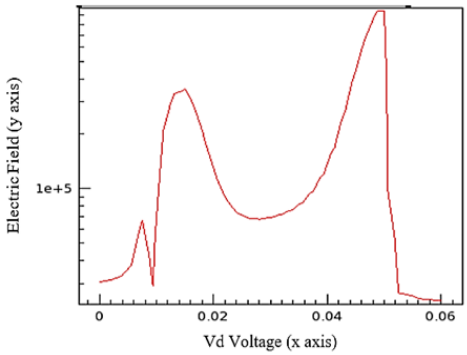
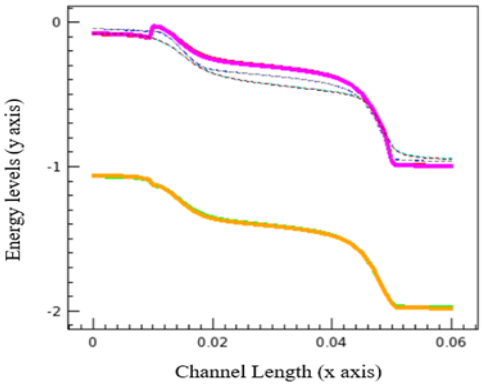


c. Electric field vs drain voltage



d. Energy band diagram of FinFET modelled device

Figure 9. ***a***. Device modelling of FINFET device, ***b.*** I-V characteristics of the FINFET device, ***c.*** Electric Field vs Drain Voltage graph, ***d.*** Energy Band diagram of the FinFET device.

5. CONCLUSIONS

The analysis of the TFET and FinFET models in Sentaurus TCAD provides insights into their respective characteristics. While the TFET offers a lower threshold voltage and higher saturation current, indicating potential energy efficiency benefits and current-handling capabilities, it may have limitations in terms of signal amplification and higher ON resistance. The FinFET, with a higher threshold voltage, exhibits superior signal amplification capabilities, lower ON resistance, and a moderate saturation current. The specific choice between the two transistors would depend on the application requirements and desired trade-offs between energy efficiency, signal amplification, and conduction properties.

6. ACKNOWLEDGMENTS

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