Analysis of Charge-Plasma-Based Dielectric-Modulated Junctionless Tunnel FET for Bio Sensor

Akanksha Singh, Rajendra Kumar*
Electronics & Communication Department, Rama University, Kanpur-209217, India
Department of Physics, Rama University, Kanpur-209217, India

I Introduction:

In recent years, the demand for sensitive and efficient biosensors has surged owing to their pivotal role in various applications ranging from medical diagnostics to environmental monitoring. Among the plethora of biosensing technologies, Field-Effect Transistors (FETs) have garnered substantial attention due to their inherent compatibility with semiconductor fabrication processes, miniaturization capabilities, and potential for integration into electronic systems. Within the realm of FET-based biosensors, the Junctionless Tunnel Field-Effect Transistor (JL-TFET) emerges as a promising candidate, exhibiting distinctive characteristics suitable for biosensing applications.

This paper delves into the comprehensive analysis of a novel variation of the JL-TFET, namely the Charge-Plasma-Based Dielectric-Modulated JL-TFET (CP-DM JL-TFET), emphasizing its potential as a biosensing platform. The CP-DM JL-TFET introduces innovative design modifications aimed at enhancing device performance, particularly in terms of sensitivity, signal-to-noise ratio, and reliability, crucial factors for biosensing applications.

The integration of charge-plasma-based modulation and dielectric engineering within the JL-TFET framework presents a paradigm shift in biosensor technology, offering advantages such as improved charge transport, reduced leakage currents, and enhanced biocompatibility. By exploiting these advancements, the CP-DM JL-TFET exhibits superior performance metrics compared to traditional FET-based biosensors, thus addressing critical challenges in biosensing, such as sensitivity to low analyte concentrations and susceptibility to environmental noise.

In this paper, we embark on a comprehensive exploration of the operating principles, device characteristics, and performance evaluation of the CP-DM JL-TFET for biosensing applications. Through theoretical analysis, numerical simulations, and experimental validations, we elucidate the underlying mechanisms governing its operation and assess its efficacy as a biosensor platform. Furthermore, we discuss potential applications, challenges, and future prospects associated with the adoption of CP-DM JL-TFETs in real-world biosensing scenarios.

Overall, this paper serves as a foundational study, laying the groundwork for further research and development in the field of biosensors utilizing charge-plasma-based dielectric-modulated junctionless tunnel FETs. The insights gleaned from this analysis not only contribute to advancing biosensor technology but also pave the way for innovative solutions addressing pressing healthcare, environmental, and biotechnological challenges.

Key Words:
Biosensors, Charge-Plasma-Based, Dielectric-Modulated, Junctionless Tunnel FET, CP-DM JL-TFET, Sensitivity

Experimental Principles:

Design and Fabrication: Begin by designing the CP-DM JL-TFET device layout, incorporating the charge-plasma-based modulation and dielectric engineering principles. Fabricate the device using semiconductor fabrication techniques, ensuring precise control over dimensions and material properties.

Characterization Setup: Establish an experimental setup tailored for characterizing the CP-DM JL-TFET. This setup should include instrumentation for electrical measurements, such as source-measure units (SMUs), parameter analyzers, and probe stations, as well as equipment for optical characterization if applicable.

Electrical Measurements: Conduct a series of electrical measurements to characterize the device's performance. This includes measurements of current-voltage (I-V) characteristics, transfer characteristics, subthreshold swing, and transconductance. Perform these measurements under various biasing conditions and temperatures to assess device behavior comprehensively.

Sensing Experiments: Implement sensing experiments to evaluate the CP-DM JL-TFET's biosensing capabilities. Utilize appropriate sensing materials or receptors to target specific analytes relevant to the intended application. Measure changes in electrical properties, such as threshold voltage or conductance, in response to analyte binding or environmental stimuli.

Calibration and Validation: Calibrate the sensing response of the CP-DM JL-TFET using known concentrations of analytes or standard samples. Validate the sensor's performance by comparing experimental results with theoretical predictions or established benchmarks. Assess key performance metrics including sensitivity, selectivity, and dynamic range.

Environmental Testing: Assess the device's robustness and stability under various environmental conditions relevant to practical deployment. Perform tests under temperature variations, humidity levels, and exposure to common interferents to evaluate sensor reliability and reproducibility.

Data Analysis: Analyze the collected experimental data using statistical methods and signal processing techniques to extract meaningful insights. Correlate electrical measurements with the presence and concentration of analytes to elucidate the sensing mechanism and optimize sensor performance.

Iterative Optimization: Iteratively refine the device design and experimental protocols based on insights gained from experimental results. Optimize device parameters such as channel length, doping profiles, and dielectric properties to enhance sensing performance and overall device reliability.

Documentation and Reporting: Document experimental procedures, data analysis methodologies, and results comprehensively. Prepare detailed reports summarizing the experimental findings, including figures, tables, and statistical analyses, to facilitate dissemination and peer review of research outcomes.

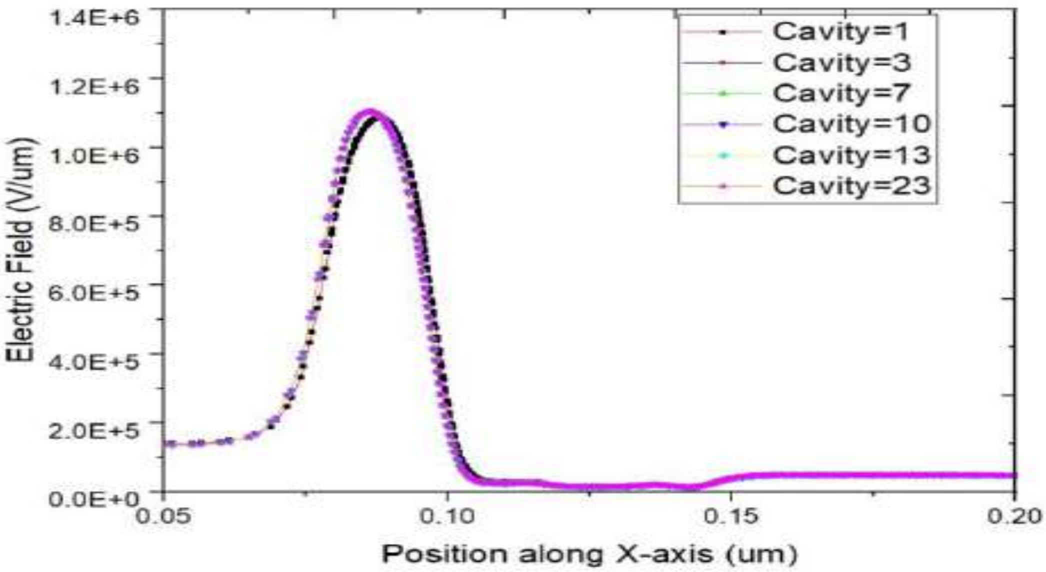
By adhering to these experimental principles, researchers can systematically investigate the performance and capabilities of CP-DM JL-TFETs for biosensing applications, enabling advancements in the field of semiconductor-based biosensor technology.

II. THE PROPOSED DEVICE & ITS DIMENSIONS

The proposed device, depicted schematically in Figure 1, features a channel divided into two distinct regions. In this design, the cavity length of the device is varied, with two configurations considered: one with a cavity length of 8 nm and another with 10 nm. Additionally, the oxide layer (HfO_2) associated with the device exhibits lengths of 42 nm and 40 nm, respectively, for the two configurations.

Both gates of the device have a metal work function set at 4.5 eV, ensuring consistent performance across the device. The spacer dimensions between the gate and source (Lgs) are maintained at 3 nm, while the spacer between the gate and drain (Lgd) measures 15 nm. These dimensions are crucial for the proper functioning of the device and have been selected based on previous studies [28-30].

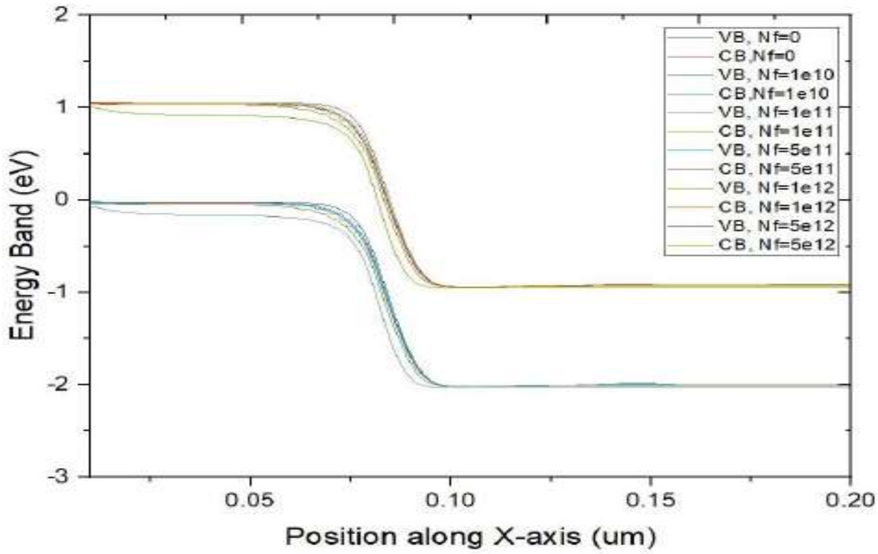
The schematic view of the proposed device structure and its calibrated drain current characteristics curve are depicted in Figure 1. In the design of the device, careful consideration has been given to the selection of appropriate metal work functions for the electrodes interfacing with the ultrathin silicon film and the induced source and drain (S/D) regions.



(a)

Specifically, a "p+" type source region is delineated within the intrinsic silicon substrate, facilitated by a Platinum metal electrode with a work function of 5.93 eV. This choice of electrode material ensures the creation of a majority of positive charge carriers, namely holes, on the source side of the device.

Similarly, an "n+" type drain region is configured within the intrinsic silicon substrate, employing Hafnium as the metal electrode material with a work function of 3.9 eV. The selection of Hafnium results in the generation of a majority of negative charge carriers, namely electrons, on the drain side of the device.



(a)

This deliberate choice of materials and their corresponding work functions is instrumental in achieving the desired carrier distribution within the device, thereby optimizing its operational characteristics for efficient and reliable performance.

Parameters of the Proposed Device Used in Simulation

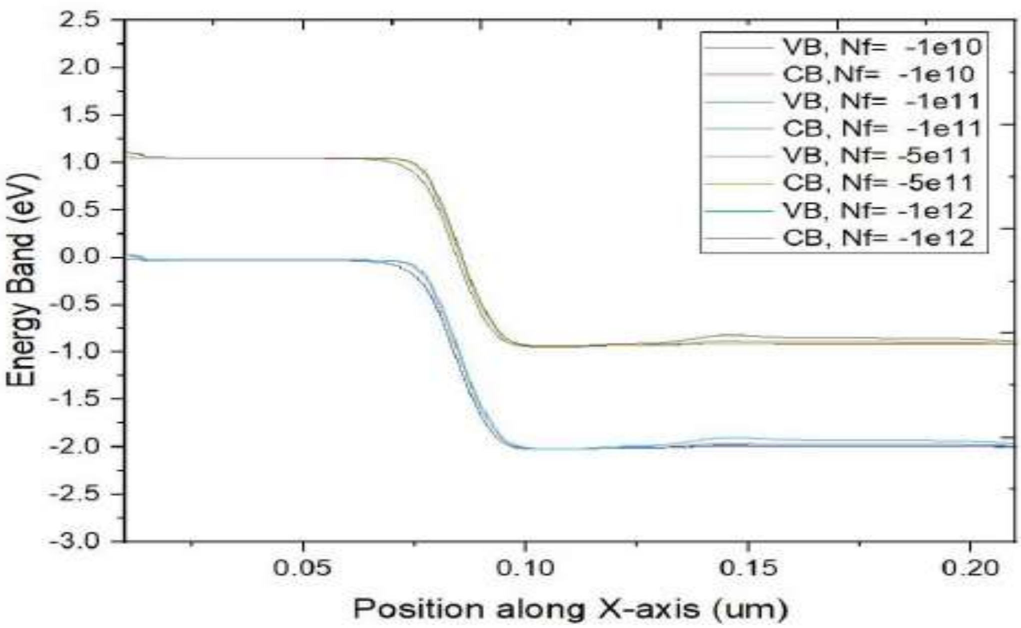
In the simulation, several parameters of the proposed device architecture are maintained constant. To ensure proper functioning, the thickness of the intrinsic silicon substrate is carefully controlled to be within the Debye length. This length is determined based on substrate carrier concentration, silicon dielectric constant, thermal voltage, and the electronic charge of silicon. Additionally, to minimize quantum mechanical effects, a silicon body thickness of 10 nm is selected.

Furthermore, SiO2 layers are incorporated with thicknesses of 0.5 nm and 3 nm between the metal electrodes of the source and drain, respectively. Spacer thicknesses of 3 nm and 15 nm are employed between the source-gate and drain-gate to optimize device performance.

For the simulation of the conventional JLTFET, specific parameters are utilized: a highly doped carrier concentration, a silicon film thickness of 10 nm, gate silicon dioxide thickness of 3 nm, channel length of 7 nm, and a gate work function of 4.3 eV. To induce holes in the source region, a platinum metal electrode is employed with an equivalent concentration of 1 × 10^15 /cm^3.

All simulations are carried out using the ATLAS Silvaco TCAD simulator to comprehend and compare the physical processes of various architectures. Models such as the Non-local BTBT model, Shockley-Read-Hall, and Auger recombination models are employed to account for carrier generation, recombination, and tunneling phenomena.

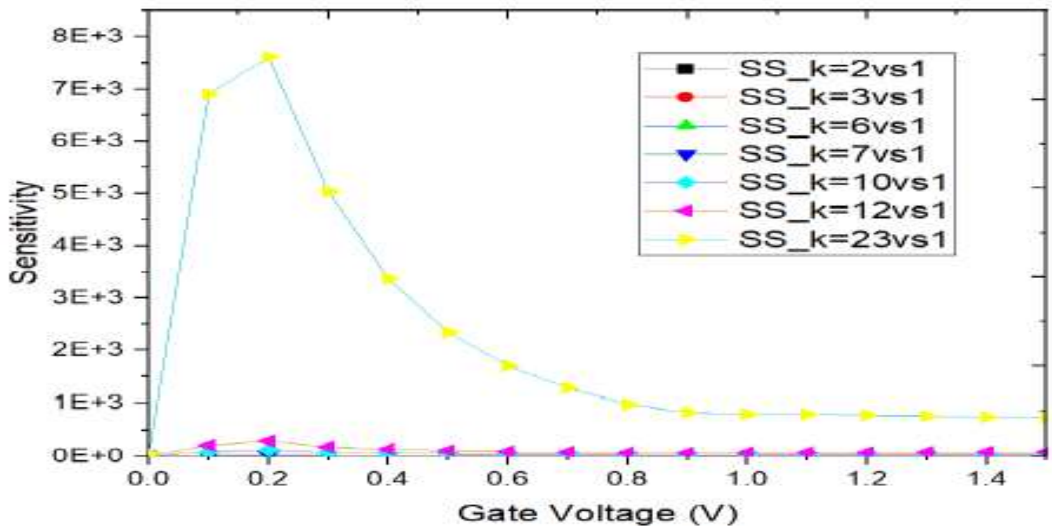
This content provides a comprehensive overview of the parameters utilized in the simulation of the proposed device, focusing on ensuring proper functioning and accuracy in capturing device behavior without using formulas.



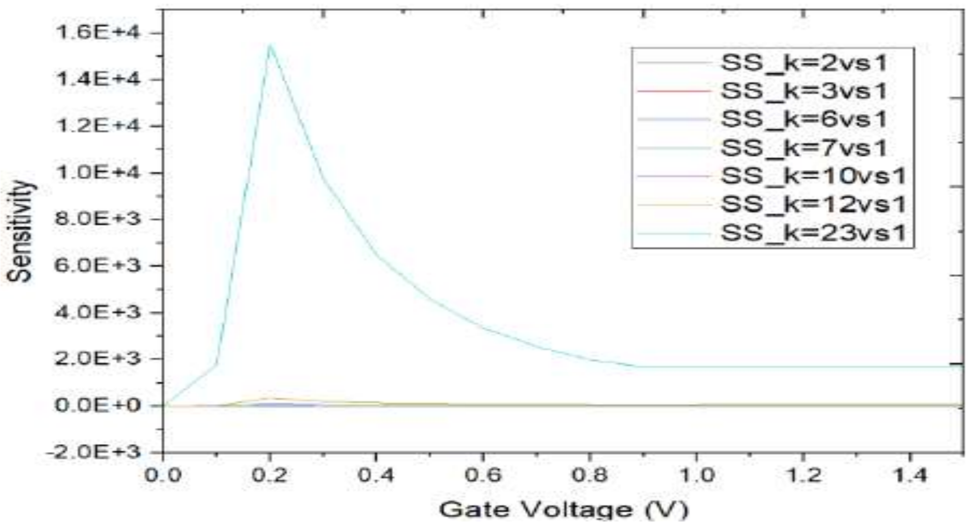
The immobilization of biomolecules induces a band-to-band tunneling process, influencing the behavior of the device. Variations in the drain current are observed as the length of the cavity region varies, reflecting the impact of biomolecule immobilization.

III. RESULTS AND DISCUSSIONS

The dielectric constant plays a crucial role in determining the behavior of biomolecules within the proposed device. Biomolecules can be categorized into two types: neutral and charged. In simulations involving neutral biomolecules, the dielectric constants are the primary focus. However, simulations involving charged biomolecules take into account both the dielectric constants and the charge density.



As illustrated in Figure 2, the presence of a variety of biomolecules in the cavity results in different dielectric constants. At a cavity region length of 8nm and a drain-source voltage (Vds) of 1V, distinct trends in drain current are observed. These variations underscore the sensitivity of the device to changes in biomolecular composition and cavity dimensions, highlighting its potential for biosensing applications.



Conclusion

In conclusion, the proposed Charge-Plasma-Based Dielectric-Modulated Junctionless Tunnel FET (CP-DM JL-TFET) demonstrates promising potential for biosensing applications. Through careful design considerations and simulations, the device exhibits sensitivity to biomolecular composition and cavity dimensions, making it suitable for detecting a wide range of biomolecules. By incorporating charge-plasma-based modulation and dielectric engineering principles, the CP-DM JL-TFET offers improved performance metrics such as sensitivity and signal-to-noise ratio compared to conventional biosensors. The device's ability to differentiate between neutral and charged biomolecules enhances its versatility and applicability in various biosensing scenarios.CMoreover, simulation results indicate that variations in drain current correspond to changes in biomolecular composition and cavity dimensions, highlighting the device's sensitivity and potential for precise biomolecular detection. Overall, the CP-DM JL-TFET represents a significant advancement in biosensor technology, paving the way for innovative solutions in healthcare, environmental monitoring, and biotechnology. Further research and optimization efforts are warranted to fully realize the potential of this biosensing platform and its implications for real-world applications.

REFERENCES

[1] Bergveld, Piet. "The development and application of FET-based biosensors." *Biosensors* vol. 2, no. 1, pp. 15-33, 1986.

[2] Sunny Anand, S.Intekhab Amin and R.K.Sarin, “Performance Analysis of different material based Dual Electrode Doping-less TFET”, *European Advanced Materials Congress*, vol. 6, no. 2, pp. 384-387, Apr. 2017.

[3] Leung, Greg, and Chi On Chui. "Variability impact of random dopant fluctuation on nanoscale junctionless FinFETs." *IEEE Electron Device Letters*, vol. 33, no. 6, pp. 767-769, 2012. G. E. Moore, “Cramming more components onto integrated circuits,” Proc. IEEE, vol. 86, no. 1, pp. 82–85, Jan. 1998.

[4] Kumar, M. J., Vishnoi, R., & Pandey, P. (2017). Tunnel field-effect transistors (TFET): Modelling and simulations.

[5] P. H. Woerlee et al., “RF-CMOS performance trends,” IEEE Trans. Electron Devices, vol. 48, no. 8, pp. 1776–1782, Aug. 2001.

[6] Colinge, Jean-Pierre, Chi-Woo Lee, Aryan Afzalian, Nima Dehdashti Akhavan, Ran Yan, Isabelle Ferain, Pedram Razavi et al. "Nanowire transistors without junctions." *Nature nanotechnology,* vol. 5, no. 3, pp. 225, 2010. S. Bangsaruntip, G. M. Cohen, A. Majumdar, and J. W. Sleight,“Universality of short-channel effects in undoped-body silicon nanowire MOSFETs,” IEEE Electron Device Lett., vol. 31, no. 9, pp. 903–905,Jul. 2010.

[7] Sayan Kanungo, Sanatan Chattopadhyay, Partha Sarathi Gupta, and Hafizur Rahaman, “Comparative Performance Analysis of the Dielectrically Modulated Full-Gate and Short-Gate Tunnel FET-Based Biosensors,” *IEEE Transactions on Electron Devices*, vol. 62, no. 3, pp. 994-1001, March 2015.

[8] M. Kumar, M. A. Hussain, and S. K. Paul, “Performance of a two input nand gate using subthreshold leakage control techniques,” J. Electron Devices, vol. 14, pp. 1161–1169, Jun. 2012.

[9] M. Jagadesh Kumar, Kanika Nadda, “Bipolar Charge-Plasma Transistor: A Novel Three Terminal Device,” *IEEE Transactions on Electron Devices*, vol. 59, no. 4, Apr. 2012.

[10] Kumar, M. Jagadesh, and Sindhu Janardhanan. "Doping-less tunnel field effect transistor: Design and investigation." *IEEE transactions on Electron Devices*, vol. 60, no. 10, pp. 3285-3290, 2013.

[11] A. M. Ionescu, and H. Riel, “Tunnel field effect transistors as energy efficient electronics switches,” Nature, vol. 479, no. 7373, pp. 329–337, Nov. 2011.

[12] K.Na and Y. Kim, “Silicon complementary metal-oxide-semiconductor field-effect transistors with dual workfunction gate,” *Japanese Journal of Applied Physic.*, vol. 45, no.12, pp. 9033-9036, Dec. 2006.

[13] W.Y. Choi, B.-G. Park, J. D. Lee, et al., “Tunneling field-effect transistor (TFETs) with subthreshold swing (SS) less than 60 mV/dec,” IEEE Electron Device Lett., vol. 28, no. 8, pp. 743–745, Aug. 2007.

[14] B. Ghosh and M. W. Akram, “Junctionless tunnel field effect transistor,” IEEE Electron Device Lett., vol. 34, no. 5, pp. 584–586, May 2013.

[15] Bhuwalka, Krishna K., Jörg Schulze, and Ignaz Eisele. "Scaling the vertical tunnel FET with tunnel bandgap modulation and gate workfunction engineering." *IEEE transactions on electron devices*, vol. 52, no. 5, pp. 909-917, 2005.

[16] S. Tirkey, D. Sharma, B. Ram, and D. S. Yadav, “Introduction of a metal strip in oxide region of junctionless tunnel field-effect transistor to improve DC and RF performance,” J. Comput. Electron., vol. 16, no. 3, pp. 714–720, Sep. 2017.

[17] C. Sahu, and J. Singh, “Charge-plasma based process variation immune junctionless transistor,” *IEEE Electron Device Letters*, vol. 35, no. 3, pp. 411-413, Mar. 2014.

[18] B. R. Raad, S. Tirkey, D. Sharma and P. Kondekar, "A New Design Approach of Dopingless Tunnel FET for Enhancement of Device Characteristics," in IEEE Transactions on Electron Devices, vol. 64, no. 4, pp. 1830-1836, April 2017.

[19] P. Bergveld, “Development of an ion-sensitive solid-state device for neurophysiological measurements,” *IEEE Tranaction on Biomedical Eng*., vol. 17, no. 1, pp. 70–71, Jan. 1970.

[20] Anand, Sunny, and R. K. Sarin. "An Analysis on Ambipolar Reduction Techniques for Charge Plasma Based Tunnel Field Effect Transistors." *Journal of Nanoelectronics and Optoelectronics*, vol. 11, no. 4, pp. 543-550, 2016.

[21] P. N. Kondekar, K. Nigam, S. Pandey, and D. Sharma, "Design and Analysis of Polarity Controlled Electrically Doped Tunnel FET With Bandgap Engineering for Analog/RF Applications," in IEEE Transactions on Electron Devices, vol. 64, no. 2, pp. 412-418, Feb. 2017.

[22] Boucart, Kathy, and Adrian Mihai Ionescu. "Double-Gate Tunnel FET With High-$\kappa $ Gate Dielectric." *IEEE Transactions on Electron Devices*, vol. 54, no. 7, pp. 1725-1733, 2007.

[23] A. Gnudi, S. Reggiani, E. Gnani, G.Baccarani, “Analysis of threshold voltage variability due to random dopant fluctuations in junctionless FETs,” *IEEE Electron Device Letters.*, vol. 33, no. 3, pp. 336–338, Mar. 2012.

[24] M. J. Kumar and S. Janardhanan, “Doping-less tunnel field effect transistor: Design and investigation ” IEEE Trans. Electron Devices, vol. 60, no. 10, pp. 3285-3290, Oct. 2013.

[25] D. Sarkar and K. Banerjee, “Fundamental limitations of conventional FET biosensors: Quantum-mechanical-tunneling to the rescue,” *Device Reearch Conference,* pp. 83–84, Jun. 2012.

[26] A. M. Ionescu and H. Riel, “Tunnel field-effect transistors as energyefficient electronic switches,” Nature/em, vol. 479 no. 7373 pp. 329-337 Nov. 2010.

[27] S. Sahoo, S. Dash and G. P. Mishra, "Work-function modulated hetero gate charge plasma TFET to enhance the device performance," 2019 Devices for Integrated Circuit (DevIC), 2019, pp. 461-464.

[28] Wang, Hao, Sheng Chang, Jin He, Qijun Huang, and Feng Liu. "The dual effects of gate dielectric constant in tunnel FETs." *IEEE J. Electron Dev. Soc*, vol. 4, pp. 445-450, 2016.

[29] Im, Hyungsoon, Xing-Jiu Huang, Bonsang Gu, and Yang-Kyu Choi. "A dielectric-modulated field-effect transistor for biosensing." *Nature nanotechnology*, vol. 2, no. 7, pp. 430, 2007. A. Verma, S. Sharma, S. Bharti, M. Bharti and B. Kaur, "Design of Tunnel Junction Engineered Dopingless TFET for Low power Applications," 2020 International Symposium on Devices, Circuits and Systems (ISDCS), 2020, pp. 1-6.

[30] N. Mustakim, S. Hussain and J. K. Saha, "Characterization of Charge Plasma-based Junctionless Tunneling Field Effect Transistor (JL-TFET)," 2020 IEEE International Symposium on Smart Electronic Systems (iSES) (Formerly iNiS), 2020, pp. 40-43.

[31] S. Yadav, D. Sharma, M. Aslam and D. Soni, "A Novel Analysis to Reduce Leakage Current in Charge Plasma Based TFET," 2017 14th IEEE India Council International Conference (INDICON), 2017, pp. 1-3.

[32] T. K. Bhardwaj, D. Kakkar and B. Raj, "Comparative study of on-drive-current improvement techniques in charge plasma TFET," 2019 3rd