International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 04, April-2025

Design and Simulation of Silicon Germanium Based Full Gate Dielectric Modulated Tunnel FET for Sensing Applications

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***Abstract:-* This paper focuses on the utilization of a specific semiconductor device, the dielectrically modulated double gate junctionless tunnel field-effect transistor (DM-DG-JLTFET), for biosensing applications. The study employs extensive device-level simulations to assess the sensing capabilities of this device for both charged and charge-neutral biomolecules. This study investigates the fundamental physics and performance of the DM-DG-JLTFET structure. This device is potentially useful for biosensing applications due to its unique characteristics. This paper focuses on the device's ability to detect and interact with biomolecules, both those with a charge (charged biomolecules) and those without a charge (charge-neutral biomolecules). The research emphasizes the importance of gate and drain biasing conditions in enhancing the sensitivity of the biosensor. Adjusting these biasing parameters can optimize the device's efficiency in detecting biomolecules. This investigation utilizes TCAD simulation, which is a technology computer-aided design tool, to assess the potential of the DM-DG-TFET for biomolecule recognition. This simulation enables researchers to model and evaluate the device's behavior under various conditions. The research explores changes in key parameters such as drain current, energy band structures, and electric potential. These parameters are essential for understanding the device's performance and how it interacts with biomolecules. The results of this research could have significant implications for the development of advanced biosensors with improved sensing capabilities.**

***Keywords*—Biosensor, DM-TFET, Biomolecule, Nanocavities, TCAD, BTBT**

I. INTRODUCTION

Dielectrically modulated double gate Junctionless Tunnel Field-Effect Transistors (TFETs) have gained considerable attention and piqued interest in the realm of biosensors. These cutting-edge electronic devices offer distinct advantages for biosensing applications, owing to their remarkable sensitivity, minimal power consumption, and compatibility with bio-functionalization techniques. By incorporating TFETs into biosensors, scientists can attain exceptionally sensitive and swift biomolecule detection, including proteins, DNA, and enzymes[1-4]. This is achieved by capitalizing on TFETs' innate capacity to detect subtle changes in charge and potential within their channel regions. Consequently, TFET-based biosensors enable real-time monitoring of biological processes and the identification of specific disease-related biomarkers. This holds great promise for the advancement of point-of-care diagnostic tools and the field of personalized medicine. The utilization of dielectrically modulated double gate Junctionless TFETs as biosensors underscores the continuous evolution of semiconductor technology in tackling pressing challenges in healthcare and biotechnology [5-8].

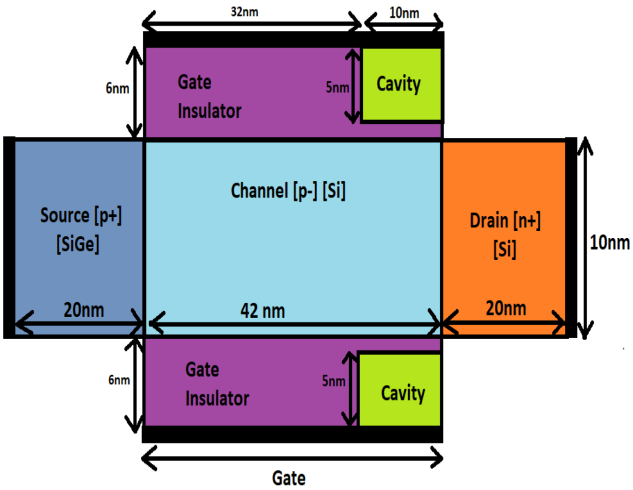
The transition from Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs) to Tunnel Field-Effect Transistors (TFETs) signifies a significant advancement in semiconductor technology. MOSFETs have long served as the backbone of the electronics industry, providing rapid switching speeds and low power consumption [9-13]. However, as the march toward miniaturization neared its physical limitations, MOSFETs encountered challenges tied to power leakage and diminishing performance improvements. In response, TFETs emerged as a promising alternative. TFETs operate on a fundamentally distinct principle, relying on quantum tunneling rather than the conventional thermionic emission for carrier transport[14-19]. This novel mechanism enables TFETs to achieve a reduced subthreshold swing, effectively curbing leakage currents and enabling operation at lower power supply voltages. Consequently, TFETs offer a potential resolution to some of the power efficiency obstacles faced by MOSFETs in cutting-edge semiconductor technologies. The shift from MOSFETs to TFETs underscores the industry's unwavering dedication to innovation and the tireless pursuit of more energy-efficient and compact electronic devices to meet the evolving needs of the modern era [20-24].

Tunnel Field-Effect Transistors (TFETs) are a class of semiconductor devices that have shown significant attention in recent years due to their unique operating principle and potential to address some of the challenges faced by traditional Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs). TFETs operate based on quantum tunneling, a phenomenon where electrons pass through an energy barrier, allowing for extremely low subthreshold swing and reduced leakage current[25-28]. This characteristic makes TFETs highly promising for low-power applications in the semiconductor industry, including mobile devices and IoT sensors. Researchers are actively exploring TFETs' potential to overcome the limitations of MOSFETs, such as the subthreshold slope, and to enable more energy-efficient and compact electronic devices in the future[29-31]. The paper presents a novel dielectrically modulated double gate junctionless tunnel field effect transistor (DM-DG-JLTFET) biological sensor designed to detect a wide range of biomolecules, including both neutral and charged variants. This innovative sensor is detailed in section-II of the paper. An nanocavity space is integrated above the tunneling junction to enable the capture of bio-molecules within the device. Section-III of the paper investigates changes in the device's electrical traits, including drain current, energy bands and surface potential, when biological molecules are confined within the nanocavity region. The DM-DG-TFET device underwent simulations considering various factors such as different dielectric constants and different cavity engineering.

II.PROPOSED DEVICE ARCHITECTURE

In Figure 1, the schematic representations of the biosensor structures based on FG-DMTFETs that have been examined in this ongoing study. It's worth noting that these biosensors employ a dual-gate configuration where both gates operate concurrently, significantly amplifying the influence of the biomolecules dielectric constant or charge density. This results in an increased sensitivity of the sensors. To achieve a higher tunneling current, we've opted for silicon-germanium (SiGe) as the source material, with a germanium composition of 0.5 in both of these structures. The gate length for the FG-DMFETs is standardized at 42 nm, while the source and drain regions each span a length of 20 nm. The channel's thickness is maintained at 10 nm. In terms of uniform doping concentrations, we've set them as follows: 5×10^{19} cm−3 for the p+source, 1×10^{12} cm−3 for the p-channel, and 5×10^{18} cm−3 for the n+drain regions. The biosensor architecture incorporates a nanogap cavity, as elegantly illustrated in Figure 1. Within this nanogap cavity, a slim 1-nm thick SiO_2 layer functions as an insulator. This insulating layer plays a crucial role in preventing gate-to-channel leakage currents, effectively safeguarding the sensor against sensitivity degradation.

The device simulations of SG-DM-TFET has been done in Silvaco ATLAS TCAD Tool. Among the critical models integrated into the simulation were the doping-related mobility model, field dependent mobility model which accounts for the influence of doping on charge carrier mobility, and the Shockley–Read–Hall model, which considers recombination processes at defects in the semiconductor material. Additionally, non-local band-to-band tunneling was taken into consideration to capture quantum mechanical tunneling effects. Furthermore, band gap narrowing (BGN) models were integrated to address the impact of high carrier concentrations on the semiconductor's energy band structure. These models collectively contributed to the attainment of accurate and insightful results, facilitating a deeper understanding of the SG-DM-TFET performance characteristics and its potential applications in semiconductor technology.



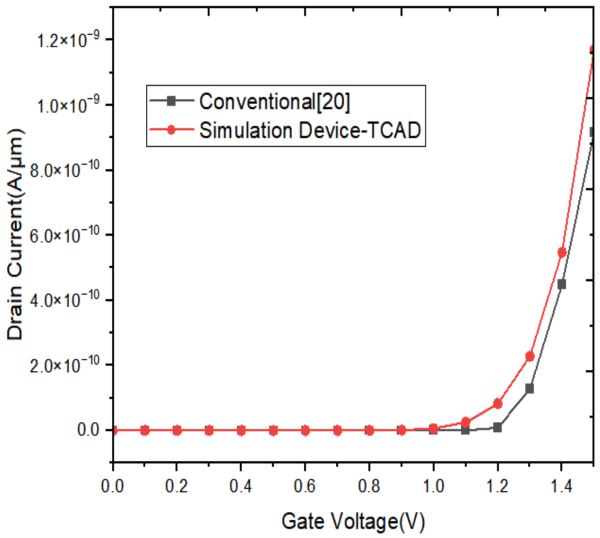


Fig.1 (a)proposed device structure SG-DM-TFET (b)calibrated graph

TABLE-1 The dimensions of the proposed device

Dimensions	Proposed Device
Thickness of channel	10nm
Channel length	42nm
Source/Drain length	20nm
Cavity Thickness	5nm
Cavity Length	10nm
Oxide Thickness	6nm
Channel Doping	1e12
Source Doping	5E19
Drain Doping	5E18

Table-2 The electrical characteristics of the proposed device

Parameters	Proposed device
Ion	5.73E-09
Ioff	2E-18
Ion/Ioff	28E08
SS	76 V/Dec

III. RESULTS AND DISCUSSIONS

In this paper, an in-depth evaluation of the SIG-DG-TFET is conducted utilizing the SILVACO TCAD ATLAS tool. This comprehensive analysis encompasses various key parameters, including drain current, electric field, and surface potential.

A. Cavity Length Engineering

In a DM-JL-TFET, the length of the cavity plays a critical role in determining its electrical characteristics. As the length of the cavity increases, several key parameters are affected, including the drain current, energy bands, and potential within the device. One of the most noticeable changes is the drain current. With a longer cavity, the device tends to exhibit higher drain current levels. This is primarily due to the increased space available for charge carriers to tunnel from the source to the drain electrode, reducing tunneling barriers and promoting electron flow. As a result, longer cavities can enhance the TFET's performance in terms of current-carrying capability, making it a promising choice for low-power electronic applications. Fig.3 (a) shows the change in drain current for different cavity lengths.

Additionally, the energy bands within the dielectrically modulated double gate TFET undergo significant alterations with an increased cavity length. The energy bands, particularly the valence and conduction bands, experience a lowering of their energy levels. This shift allows for improved tunneling conditions, as electrons can more easily overcome the reduced energy barriers. This change in energy band alignment contributes to the enhanced tunneling capability of the device, which is essential for its operation as a TFET. Fig.3 (b) shows the change in energy bands for different cavity lengths.

Furthermore, the potential distribution within the device is also affected by the increased cavity length. A longer cavity leads to a more gradual potential gradient across the channel region, which in turn influences the electric field within the device. A gentler electric field can reduce the impact of carrier scattering and velocity saturation, thereby improving the TFET's overall performance. Consequently, adjusting the cavity length is a critical design parameter for optimizing the drain current, energy bands, and potential distribution in dielectrically modulated double gate Junctionless TFETs, offering engineers greater flexibility in tailoring these devices for specific applications. Fig.2 (c) shows the change in surface potential for different cavity lengths.

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International Journal of Engineering Research & Technology (IJERT)
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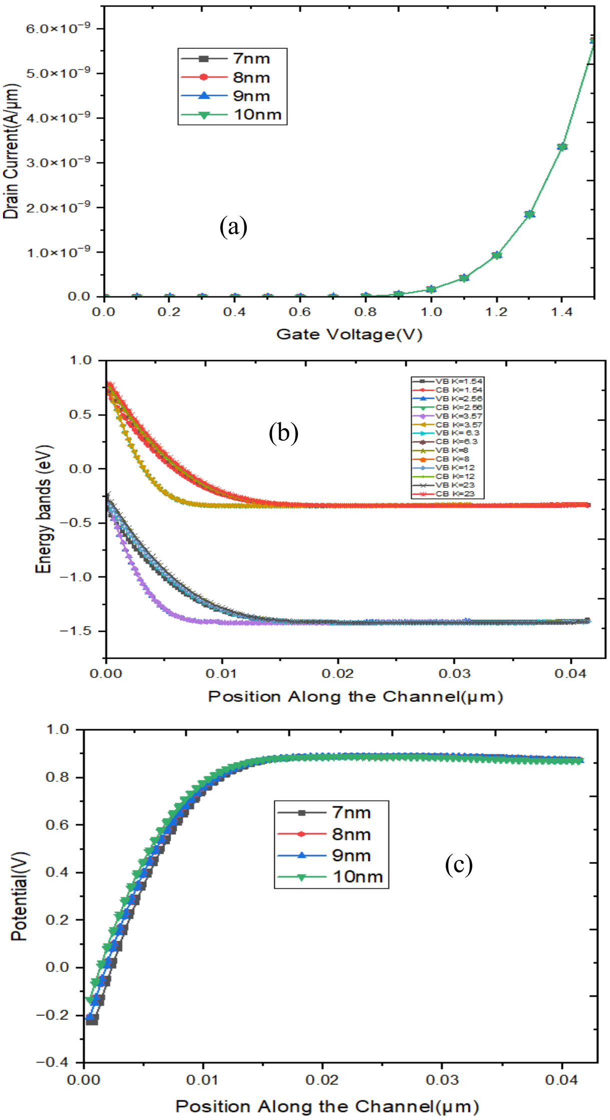

Fig.2 The change in electrical characteristics of the proposed device for different cavity lengths (a) Drain current (b) Energy bands (c) Potential

B. Effect of Biomolecule

The incorporation of biomolecules into the cavity of a DM-JL-TFET can induce significant alterations in its electrical behavior. To begin, the drain current within the JLTFET experiences substantial modifications. Biomolecules can act as charge traps or disrupt the charge distribution within the cavity, consequently influencing the tunneling current through the channel. The extent of this impact varies depending on the type and concentration of biomolecules present, potentially resulting in either an increase or decrease in drain current. This phenomenon is particularly valuable in applications like biosensors, where the JLTFET's sensitivity to specific biomolecules can be leveraged for precise detection and quantification. Fig.4 (a) shows the change in drain current for different bio-molecules in the cavity.

The introduction of biomolecules can exert a profound influence on the energy band structure of the JLTFET. Biomolecules, with their distinctive charge distribution and electronic properties, can introduce localized states within the semiconductor channel's bandgap. This phenomenon leads to a discernible shift in the energy bands, thereby altering the threshold voltage and overall device behavior. The perturbations in the energy bands also play a role in determining the tunneling probability, contributing to the adjustments observed in drain current. Consequently, a comprehensive understanding and effective control of these energy band shifts are pivotal for fine-tuning the JLTFET's performance in biosensing applications. Fig.4 (b) shows the change in energy bands for different bio-molecules in the cavity. The presence of biomolecules within the cavity can induce shifts in the electric potential distribution across the JLTFET. The charged or polar characteristics of biomolecules result in electrostatic interactions with the adjacent dielectric layers and gates, thereby influencing the potential landscape along the channel. These variations in potential further impact the electrical characteristics of the device, including the subthreshold swing and on-off ratio. Fig.3 (c) shows the change in potential for different bio-molecules in the cavity. Thus, the meticulous design and optimization of dielectrically modulated double-gate JLTFETs for biosensing applications necessitate a profound understanding of the potential alterations stemming from the introduction of biomolecules and their consequent ramifications on device performance.

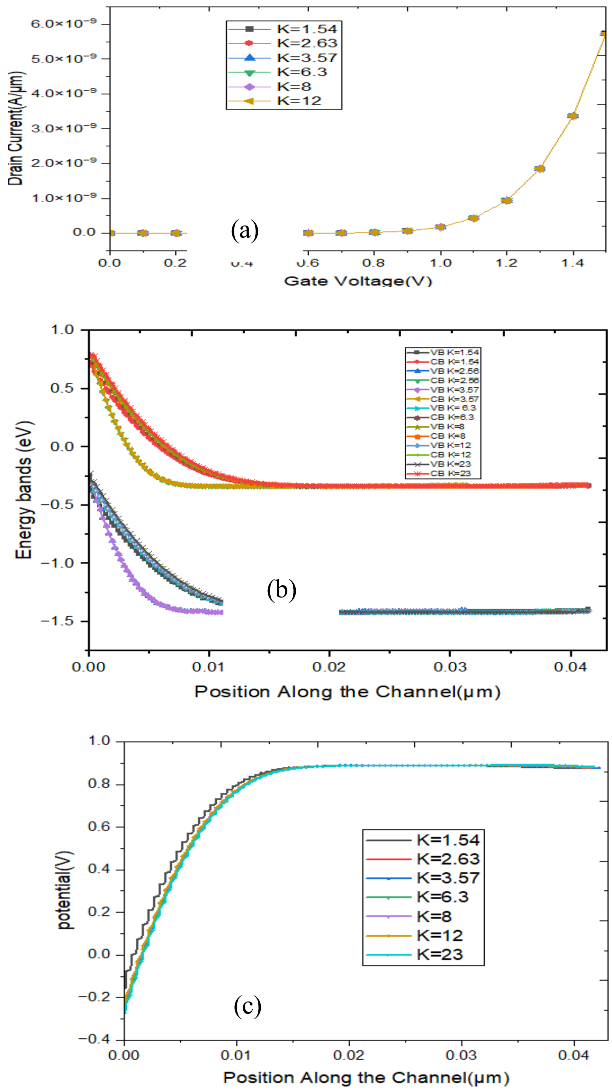

Fig.3 The change in electrical characteristics of the proposed device for different Biomolecule (a) Drain current (b) Energy bands (c) Potential

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International Journal of Engineering Research & Technology (IJERT)
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The introduction of positively charged biomolecules into the cavity of a DM-JL-TFET can bring about a substantial alteration in the drain current. Fig.4 shows the variation in drain current for different bio-molecules with positive charge in the cavity. Biomolecules with a positive charge, such as ions or specific proteins, assume the role of charge carriers within the semiconductor channel, effectively elevating the carrier concentration and the overall current flow. Furthermore, these biomolecules have the capacity to attract and accumulate electrons from the surrounding semiconductor material, leading to a reduction in the energy barrier for tunneling, resulting in an amplification of the tunneling current. Consequently, the presence of positively charged biomolecules tends to enhance the drain current in the JLTFET. This effect holds great promise for applications in biosensing, where the heightened sensitivity of the JLTFET to positively charged biomolecules can be harnessed for precise and selective detection, positioning it as a valuable asset in the field of bioelectronics and diagnostics.

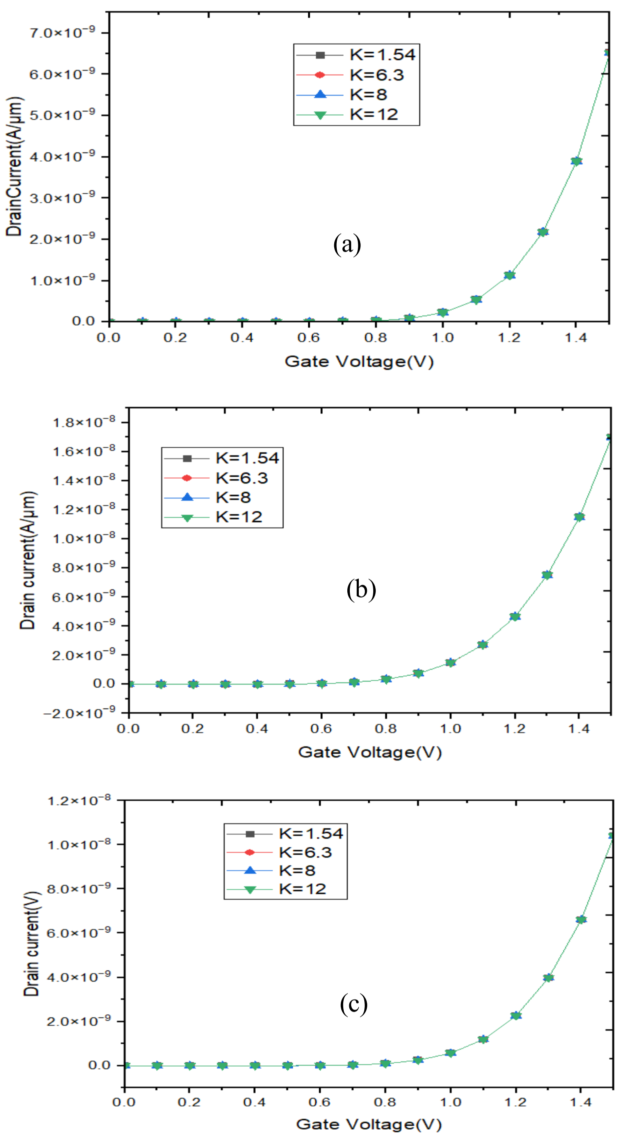

Fig.4 The change in drain current with respect to gate voltage of the proposed device for different positively charged Biomolecule.(a)1e11 (b)1e12 (c)5e11

Positively charged biomolecules, which can include ions or specific proteins, give rise to localized charge states within the bandgap of the semiconductor channel. These localized states serve as potential wells or barriers, exerting influence on the energy levels and electron distribution within the channel. Consequently, this modification results in a shift in the energy bands, leading to changes in the threshold voltage and overall device behavior. The presence of these positively charged biomolecules reshapes the electrostatic environment, effectively reshaping the potential landscape across the JLTFET and, consequently, influencing its electrical characteristics. This phenomenon holds particular significance in the realm of biosensing applications, where a meticulous understanding and precise control of energy band shifts prompted by positively charged biomolecules pave the way for tailored device designs geared towards superior biomolecule detection and analysis. Fig.5 shows the change in energy bands for different bio-molecules with positive charge in the cavity.

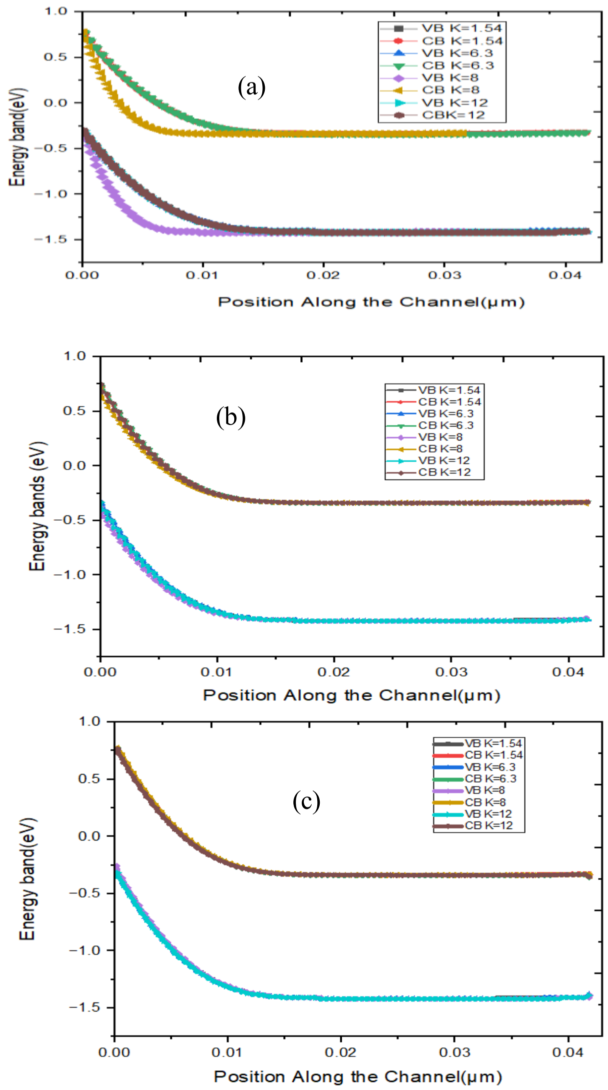

Fig.5 The change in energy bands with respect to position along the channel of the proposed device for different positively charged Biomolecule. (a)1e11 (b)1e12 (c)5e11

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 04, April-2025

The introduction of positively charged biomolecules into a confined cavity exerts a significant influence on the local energy band structure. These biomolecules, often manifested as ions or specific proteins, generate localized charge states within this environment. Fig.6 shows the change in potential for different bio-molecules with positive charge in the cavity. These charge states serve as potential wells or barriers, resulting in distinct adjustments to the energy levels and electron distribution within the cavity. Consequently, the presence of positively charged biomolecules brings about a noteworthy shift in the energy bands, subsequently reshaping the electrostatic configuration within the cavity. This alteration in energy bands holds paramount importance across various scientific and technological domains, particularly in fields like biosensing and biotechnology, where precise control and a thorough understanding of these shifts are imperative for enhancing device performance and facilitating advanced analytical methodologies.

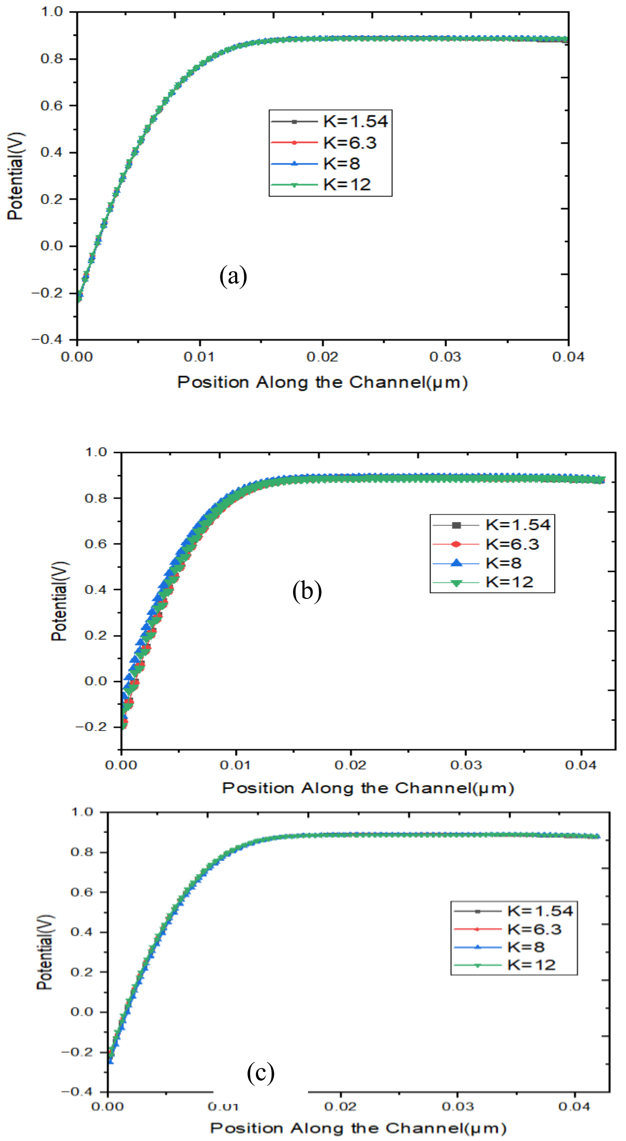

Fig.6 The change in potential with respect to position along the channel of the proposed device for different positively charged Biomolecule. (a)1e11 (b)1e12 (c)5e11

The alteration in drain current caused by negatively charged biomolecules residing within a designated cavity is a pivotal parameter. When biomolecules like DNA or proteins are introduced into a specially crafted sensor cavity or channel, they exert a significant impact on the electrical current's flow. This phenomenon emerges from the electrostatic interactions between these negatively charged biomolecules and the adjacent surface charges or gate electrodes. As these biomolecules attach or interact with the sensor's surface, they have the capacity to modify the local charge distribution, thereby resulting in a quantifiable shift in the drain current. By vigilantly monitoring these current fluctuations, scientists and researchers can glean valuable insights into the intricate world of biomolecule interactions. Fig.7 shows the change in drain current for different bio-molecules with negative charge in the cavity.

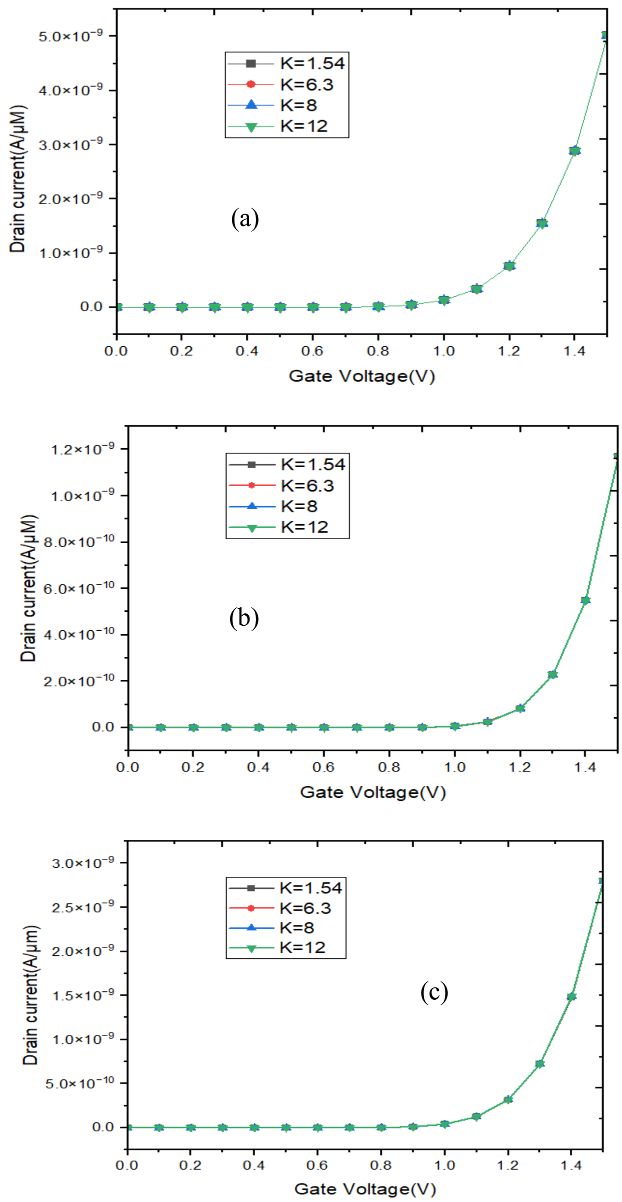

Fig.7 The change in drain current with respect to gate voltage of the proposed device for different negatively charged Biomolecule. (a)-1e11 (b)-1e12 (c)-5e11

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ISSN: 2278-0181
Vol. 14 Issue 04, April-2025

The change in energy bands for negatively charged biomolecules within a cavity can have profound implications for their behavior and interactions. When these molecules enter the confined environment of a cavity, the electrostatic interactions between the charged biomolecules and the surrounding environment can lead to a redistribution of energy states. This redistribution can result in the modification of energy bands, affecting the electronic structure and reactivity of the biomolecules. Depending on the specific characteristics of the cavity and the surrounding molecules, these changes can either stabilize or destabilize the biomolecule, influencing its conformation, binding affinity, and overall function. Fig.8 shows the change in energy bands for different bio-molecules with negative charge in the cavity.

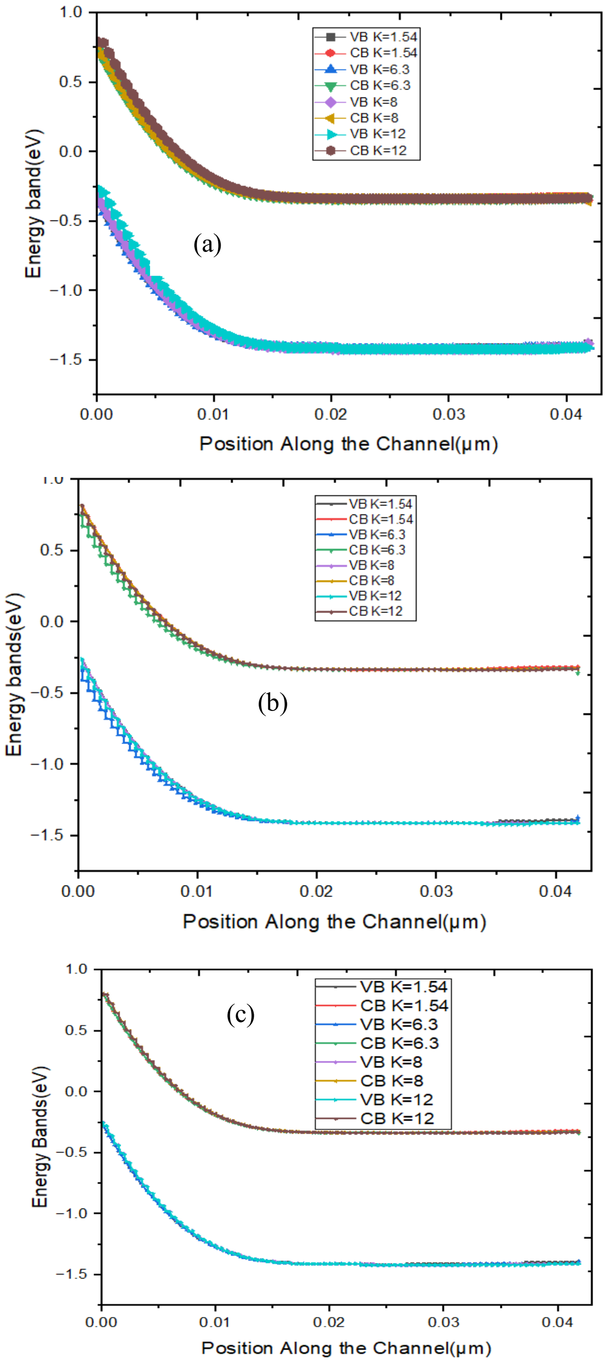

Fig.8 The change in energy bands with respect to position along the channel of the proposed device for different negatively charged Biomolecule.(a)-1e11 (b)-1e12 (c)-5e11

The change in potential for negative charge biomolecules within the cavity of a DMJLTFET is a critical parameter that profoundly influences device performance. DMJLTFETs are emerging as promising candidates for biosensing applications due to their high sensitivity to electrical charge changes. they interact with the electric field within the device, leading to a modulation in the potential energy landscape. This alteration in potential, often in the form of a shift in threshold voltage or a change in drain current, can be precisely measured and calibrated to detect and analyze the presence, concentration, or binding affinity of specific biomolecules. Fig.9 shows the change in potential for different bio-molecules with negative charge in the cavity.

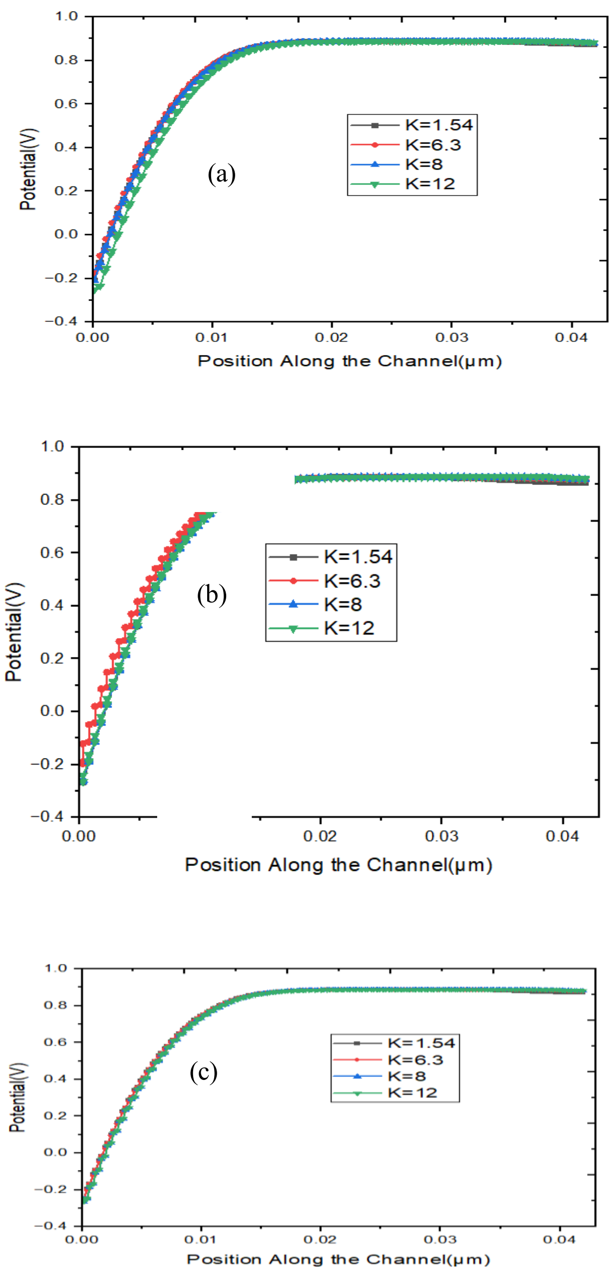

Fig.9 The change in potential with respect to position along the channel of the proposed device for different positively charged Biomolecule. (a)-1e11 (b)-1e12 (c)-5e11

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International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 04, April-2025

C. Drain Current Sensitivity

When neutral biomolecules find their way into a nano cavity within a semiconduct e, a subtle yet significant change quietly unfolds in in current a phenomenon of noteworthy relevance in the field of biosensing technology. This delicate shift in drain current emerges from the complicated interplay between these neutral biomolecules and the surrounding electronic environment within the cavity. These biomolecules, devoid of a positive or negative charge, gently push the nearby electric field, bringing about detailed adjustments in the flow of electrical current through the device. While these effects may not be as conspicuous as those induced by charged biomolecules, they are although instrumental for the functionality of biosensors. The capacity to detect and quantify neutral biomolecules in a sample holds profound importance in diverse applications, encompassing pharmaceutical research, environmental analysis, and biotechnology. Consequently, these understated alterations in drain current stand as an indispensable element within the tapestry of biosensing technology.

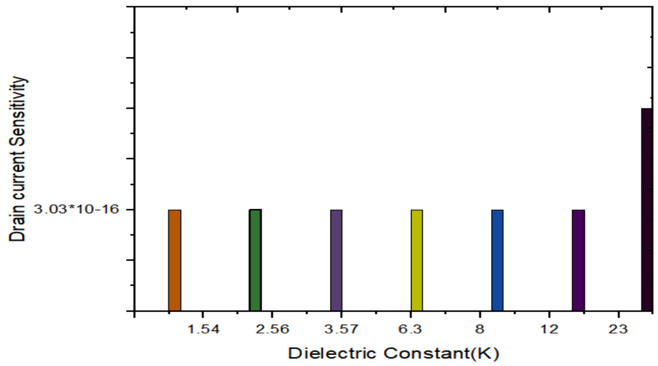


Fig.10 The change in Drain current sensitivity with respect to dielectric constant for neutral bio-molecules

The existence of positively charged biomolecules within a nano cavity in a semiconductor device triggers a notable change in the sensitivity of the drain current an occurrence of tremendous importance in the field of biosensing technology. This change in drain current sensitivity emerges from the intricate interplay between these charged biomolecules and the nearby electronic environment within the cavity. Biomolecules such as positively charged proteins or DNA strands gently mold the distribution and intensity of drain current sensitivity, exerting a noticeable influence over the neighboring electric field. As these biomolecules gracefully take up residence within the cavity, they finely tune the device's ability to perceive and respond to variations in current. The degree of this calibration subtly fluctuates, influenced by factors such as the charge and size of the biomolecules. These finely tuned adaptations carry significant weight, serving as an exceptionally sensitive signal that enables the instant and label-free detection of particular positively charged biomolecules. Becoming proficient in this alteration of drain current sensitivity is crucial for advancing biosensors renowned for their extraordinary sensitivity and precision. This proficiency firmly solidifies their crucial role across various applications, spanning critical domains like medical diagnostics and ecosphere observation.

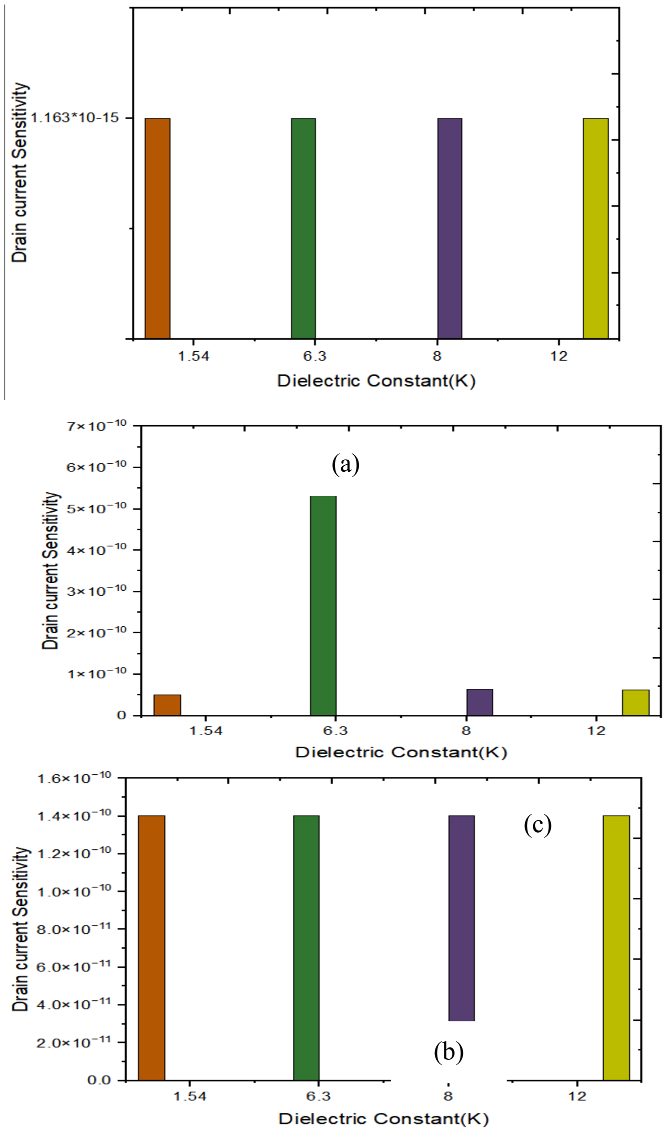
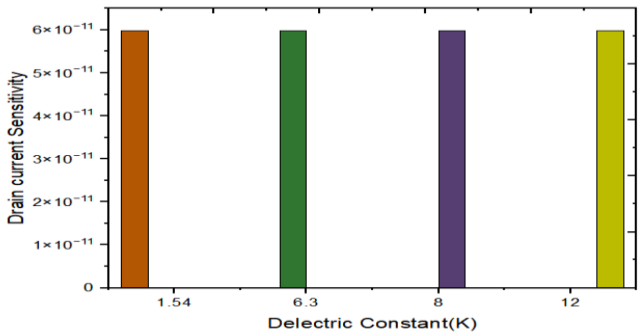


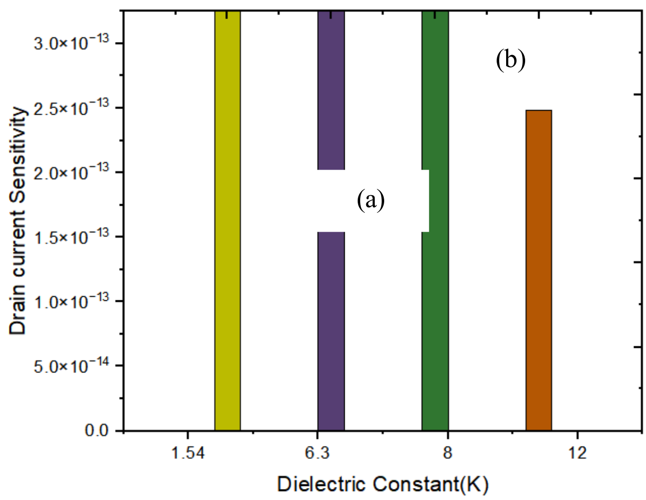
Fig.11 The change in Drain current sensitivity with respect to dielectric constant for positive charged bio-molecules .(a)1e11 (b)1e12 (c)5e11

When electrically charged biomolecules with a negative charge infiltrate a nano cavity within a semiconductor device, they set in motion a noteworthy change in the sensitivity of the drain current. an effect of substantial significance in the realm

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 04, April-2025

of biosensing technology. Biomolecules like negatively charged proteins or DNA strands exert considerable sway over the nearby electric field, gently molding the pattern and strength of drain current sensitivity.When these biomolecules find their home within the cavity, they gently elevate the device's skill in detecting and accommodating current fluctuations. The level of improvement varies subtly, influenced by factors such as the biomolecules' charge and size.Mastering the understanding and utilization of this shift in drain current sensitivity is crucial for the progression of biosensors renowned for their exceptional sensitivity and precision. This expertise firmly establishes their indispensable role across a spectrum of applications, encompassing vital domains such as medical diagnostics and environmental surveillance.





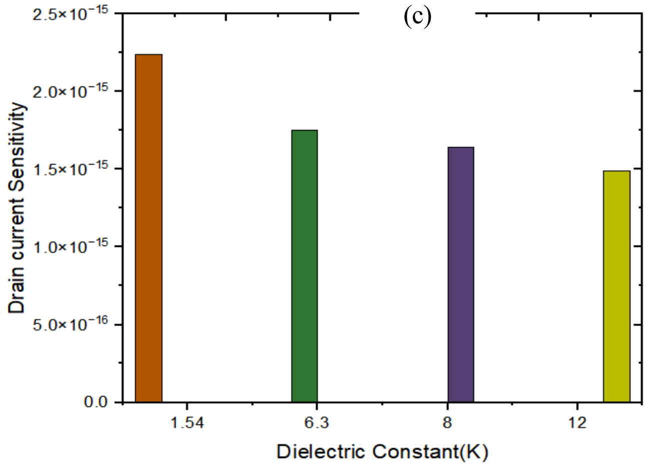


Fig.12 The change in Drain current sensitivity with respect to dielectric constant for neutral bio-molecules. (a)-1e11 (b)-1e12 (c)-5e11

Table-3 The comparison of electrical characteristics of proposed device with literature works [20, 26, 30]

Parameter	Proposed Device	[20]	[26]	[30]
Ion	5.73E-09	1.90E-11	6.35E-13	3E-04
Ioff	2E-18	3.56E-18	3.85E-18	2.4E-17
Ion/Ioff	28E08	5.3E+06	1.64E+03	1.2E+13
SS	76 V/Dec	98V/Dec	---	--

IV. CONCLUSIONS

This research presents the promising prospects of utilizing a dielectrically modulated double gate junctionless tunnel field effect transistor (DM-DG-JLTFET) structure for biosensing applications. Through an exploration of the fundamental physics governing these device architectures, we assessed their suitability and performance in sensing applications. Extensive device-level simulations were conducted to comprehensively evaluate their sensing capabilities for both charged and charge-neutral biomolecules. This study also scrutinized the impact of the dielectric constant and charge density of biomolecules on sensing performance. Importantly, our findings emphasized the critical role played by gate and drain biasing conditions in enhancing sensor sensitivity. Consequently, we identified gate and drain bias as pivotal design parameters for optimizing sensor efficiency. Through TCAD simulations, we shed light on the potential of the DM-DG-TFET for bio-molecule recognition by analyzing changes in essential parameters, such as drain current, energy band structures, and electric potential. This comprehensive investigation provides valuable insights into the capabilities and limitations of this device in biosensing. Our research contributes to the understanding of novel transistor structures for biosensing applications and paves the way for future developments in this exciting field.

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