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An Energy Efficient TFET Based Device for Biomolecules Detection and Performance Analysis in Sensing Biomolecules

Batchu Lohith
Department of Electronics and Communication Engineering
Koneru Lakshmaiah Education Foundation
Green Fields, Vaddeswaram 522302

Nikhil Sai Kanolla
Department of Electronics and Communication Engineering
Koneru Lakshmaiah Education Foundation
Green Fields, Vaddeswaram 522302

Sujatha Moorthy
Department of Electronics and Communication Engineering
Koneru Lakshmaiah Education Foundation
Green Fields, Vaddeswaram 522302

***Abstract*— This paper introduces a TFET-based biosensor with a focus on enhancing sensitivity as well as current during biomolecule conjugation. The designed biosensor features a SiG source and an n+ doped pocket between the source and channel region. Adjustments in material and structural properties, which affect the bandgap and tunneling length, are developed to further increase the sensor's sensitivity to detect biomolecules with less interference from noise. The performance of the new design is compared to conventional biosensors and a newer design with a doped pocket inside the channel. The sensitivity of the biosensor, as defined by the drain current, was examined in detail. Results indicate that the new design has much greater sensitivity than the other structures. Additional practical factors, such as the effect of Trap-Assisted Tunneling (TAT) and partial fill factor, indicate that the envisioned biosensor is very promising as a viable solution. To confirm the sensor's detection effectiveness, the Biotin-Streptavidin binding system, a particular biomolecular recognition, was implemented. The results show that the envisioned biosensor would be very promising compared to current biosensor solutions..**

***Keywords*— sensitivity, TFET Biosensor, BTBT, SiG source, doped pocket.**

I. INTRODUCTION

The Tunneling Field-Effect Transistors (TFETs) represents a highly promising technological method which allows sensing applications especially biosensing since it combines high sensitivity with minimal power requirements. TFETs utilize band-to-band tunneling (BTBT) for conducting electrons which increases their sensitivity beyond conventional field-effect transistors (FETs). The exceptional usefulness of TFETs extends to detecting biomolecules including DNA and proteins with critical value in biomedical monitoring and industrial applications together with environmental surveillance. The rising requirement for label-free along with high sensitivity detection systems has drawn extensive research interest to TFET-based biosensors because these sensors enable real-time [1-2].

The developed TFET biosensor utilizes an optimized design structure which enables efficient biomolecule detection through three key capabilities including sensitive measurement and strong current transmission alongside reduced power usage. The main emphasis is to utilize Silicon-Germanium (SiG) as source material. The used bandgap source material together with its reduced tunneling distance creates more efficient band-to-band tunneling behavior. The overall efficiency of the sensor increases together with improved sensitivity to detect minimal amounts of biomolecules. An added n^+ doped pocket enhances device performance by inserting between the source and the channel region [3]. Bandgap remains relatively unchanged while electrons can freely move throughout the device structure because of this modification which ultimately improves overall efficiency of current flow. Through its double-gate structure the biosensor obtains enhanced control of current flow through the channel. The device sharpened its response capabilities because of this feature when biomolecules enter. Biomolecules get trapped within a microscopically small cavity found within the gate oxide. Any substance that enters the cavity space causes alterations in the nearby dielectric region which directly alters the instrument current flux allowing detection to become simpler and more sensitive. Besides that, the device uses a P-N-P-N structure rather than the traditional P-I-N structure . That gives it superior electrical performance, higher sensitivity, and more immunity to noise, all of which contribute to higher accuracy.

Finally, high-speed gate dielectric materials are utilized to keep low power consumption with no loss in control over the channel. As a whole, this TFET-based biosensor offers a competent, precise, and energy-efficient solution for upcoming biomedical sensing [5]. While they do have advantages, conventional TFET biosensors are beset by low drive current problems, which limit their overall performance. Furthermore, while TFETs reduce the impact of noise and other unwanted effects, traditional designs still suffer from charge transport

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inefficiencies that hinder effective biomolecule detection. To overcome these limitations, various strategies have been developed, such as the employment of SiG source engineering and the presence of a doped pocket within the channel region[3]. They shorten the tunneling length to enhance sensitivity through bandgap alteration and assistance but do not ultimately prevent the current bottleneck conduction that still needs rectification.

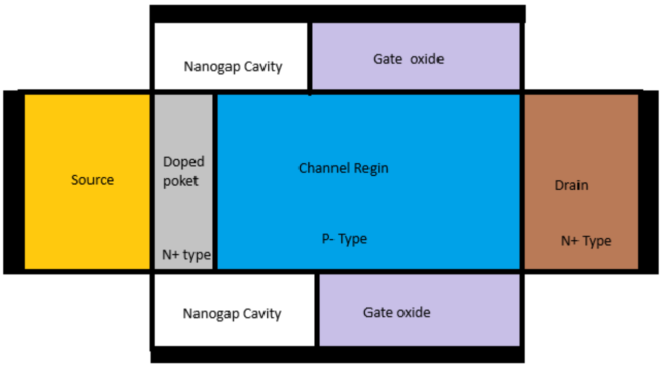

Fig. 1. The developed TFET

A novel TFET-based biosensor architecture that improves sensitivity and current by optimized material composition, doping levels, and structural design. By incorporating a SiG source to improve BTBT efficiency and an n+ doped pocket to reduce tunneling length, the novel architecture significantly improves charge transport. Gate dielectric engineering also reduces power consumption while providing robust electrostatic control. The developed biosensor shows enhanced sensitivity (85–92) and increased hybridization current (2.3E-10 to 2.8E-10 µA/µm) compared to traditional and cutting-edge TFET-based designs. The detection of biomolecular interaction by the biosensor, i.e., the Biotin-Streptavidin binding system, also confirms its suitability for real-world applications.

II. DEVELOPED DEVICE ARCHITECTURE

The TFET-based biosensor uses an innovative architectural design which emphasizes sensitivity along with high current flow and reduced power usage throughout biomolecule detection processes. The design centers its primary attention on employing Silicon-Germanium (SiG) source material. Because it exhibits a smaller bandgap along with a reduced tunneling distance the SiG source material enhances band-to-band tunneling processes. This design allows the sensor to detect smaller biomolecule quantities because of its superior sensitivity. An additional improvement to the design consists of using an n^+ doped pocket that intervenes between the source and channel regions. The passage of electrons occurs smoothly through the SiG material structure without major changes to the bandgap so the device efficiency improves. Through its double-gate design the biosensor attains additional control over its channel functions as the channel for current transmission. The device obtains improved control to react when biomolecules appear. The gate oxide contains an extremely small nanogap cavity which functions as a molecule capture zone. The device becomes simpler to detect because changes in the local dielectric environment inside the cavity affect the device current flow when something binds inside the cavity[6].

The device implements a P-N-P-N structural arrangement instead of operating with a conventional P-I-N structure. The P-N-P-N structure improves both electrical functionalities and sensitivity levels and noise tolerance which produces superior detection results. The device adopts high-speed gate dielectric materials to maintain control of the channel without compromising power consumption levels. The TFET-based biosensor demonstrates potential as an economically beneficial and precise and energy-efficient biomedical sensory technology for future applications.Along with that, the device uses a P-N-P-N structure instead of a typical P-I-N structure. That gives it enhanced electrical performance, more sensitivity, and higher immunity to noise, all of which contribute to better results. Finally, high-speed gate dielectric materials are utilized in order not to sacrifice channel control while being kept at low power consumption levels. In sum, this biosensor based on TFET yields a cost-saving, precise, and energy-efficient method for biomedical sensing in the future.

TABLE I

TFET BIOSENSOR PARAMETERS IMPLEMENTED IN THE SIMULATION DOMAIN.

Parameters	Values
Gate length, Lg	50 nm
Source/drain region length, (Ls, Ld)	25 nm
Gate oxide thickness, tox	10 nm
Nanogap cavity length, Lgap	15 nm
Thickness of Nanogap	10 nm
Silicon layer thickness, tsi	20 nm
Doping concentration of channel, (P- type)	1×1016 cm-3
Doping concentration of source, (P++ type)	1×1020 cm-3
Doping concentration of drain, (N+ type)	5×1018 cm-3
Gate metal workfunction	4.1 eV
Mole fraction Ge	0.3
Length of doped pocket, LP	10 nm

The layout of the suggested biosensor truly takes the game to a higher level when it comes to sensitivity and current response. It demonstrates a clear increase in sensitivity, achieving values ranging from 85 to 92, and raises the hybridization current from 2.3E-10 to 2.8E-10 µA/µm—far superior to what most current sensors provide. To test how well this design would perform in a real-world application, it was put to the test with the Biotin-Streptavidin binding system, a common model utilized in biosensing. The results were encouraging, indicating that the sensor isn't only theoretically robust—it actually works dependably and accurately in reality.

This makes it a good choice for future biomedical sensing applications where accuracy and sensitivity truly come into play. Through combining these two aspects, we were able to decrease the tunneling length even further, and that makes a significant contribution towards enhancing the overall performance of the device.

Two new types of TFET-based biosensors have been developed recently to enhance the sensitivity compared to conventional designs. One utilizes a SiG source, while the other employs a doped pocket within the channel. Both

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increase the rate of band-to-band tunneling (BTBT), which increases sensitivity. One major limitation of these individual designs is the comparatively low current output during sensing, which might impact overall performance[7-9]. For the SiG source, both TL and bandgap are minimized, enabling more efficient tunneling. The doped-pocket structure lowers the TL mainly and minimizes the bandgap to a lesser extent. Graphical analysis reveals that increasing the content of germanium (Ge) in the SiG source or increasing the doping concentration in the pocket brings about a more pronounced diminution of TL, thus enhancing the sensitivity.

To circumvent the disadvantages of the previous designs, we developed a biosensor that fuses the advantages of both the worlds—a SiG source and a DP channel—into a single intelligent, optimized configuration[10]. By combining these two characteristics, we were able to further decrease the tunneling length, which contributes significantly to enhancing the overall performance of the device. The performance curves demonstrate an enhanced sensitivity and current output because of this upgrade in comparison with previous versions. The integration of materials with crime engineering lets the device boost its tunneling capabilities and perform superior biomolecule detection leading to dependable biosensing functionality[11].

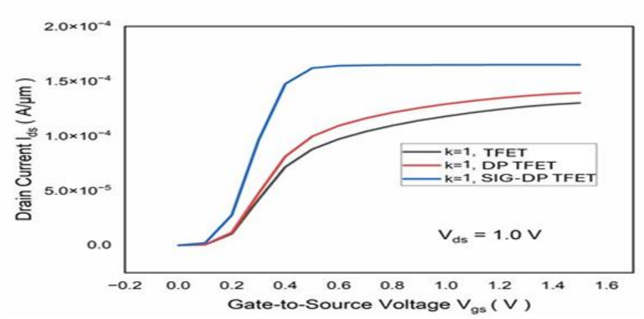

Fig.2: Transfer characteristics of TFET, DP-TFET, SIG_DP TFET

III. RESULTS AND DISCUSSIONS

A combined graph comparison of SiG Source Doped-Pocket TFET (SIDP-TFET) with Doped-Pocket TFET (DP-TFET) and traditional TFET shows vital information about their respective performances. When k=1 dielectric constant is applied the three devices exhibit different behaviours in their drain current (ID) variation versus gate voltage (VGS). Use of SiG source combination with doped pocket in SIDP-TFET improves tunneling effect to achieve highest ION and most steep subthreshold slope. hold swing, indicating its better sensitivity and switching performance. The DP-TFET, with the doped pocket alone, exhibits better tunneling than a regular TFET but lower ION than the SIDP-TFET because it lacks a SiG source. The traditional TFET, without these optimizations, exhibits a comparatively higher IOFF, moderate ION, and less steep subthreshold swing, reflecting lower efficiency in biomolecule detection. The transfer characteristics reflect the effect of structural changes on tunneling efficiency and device sensitivity, confirming the SIDP-TFET's capability for high-performance, low-power applications in biosensing. The energy band diagram of the SiG Source Doped-Pocket TFET (SIDP-TFET), Doped-Pocket TFET (DP-TFET), and the usual TFET supplies essential information concerning how structural disparities affect the nature of the device.

The diagrams displayed at k = 1 reveal dissimilarities between both energy band structures and tunneling barriers of the distinct devices. A downhole combination of SiG source elements and doped pockets makes up the SIDP-TFET bringing forth the optimum band structure for tunneling functions. The SiG source shrinks both bandgap and tunneling length but the doped pocket strengthens the electric field at the tunneling junction. Band-to-band tunneling efficiency rises together with current flow through steep band slopes and narrow tunneling barriers which makes these devices suitable for highly sensitive biosensing applications [12-16].

Through the use of just a doped pocket the DP-TFET attains shorter tunneling lengths making tunneling more probable when compared to standard TFETs. Without SiG source bandgap reduction the SIDP-TFET produces less on-current than its equivalent device due to its wider barrier width. The standard TFET by itself presents larger tunneling barriers with unfavourable band alignments that reduces tunneling efficiency while decreasing biomolecular sensitivity. During TFET-based biosensor operation the electric field controls both biomolecule detection efficiency and detection sensitivity level.

The dielectric constant determines the efficiency of holding electrical energy which shapes the strength of this electric field.During k = 1 conditions corresponding to free space permittivity the device presents heightened electric fields for a given voltage. An enhanced electric field provides bigger tunneling effects leading to higher device current output suitable for sensitive biomolecule detection apparatuses. The sensor becomes more responsive with enhanced tunneling but the process introduces undesirable noise along with leakage current.

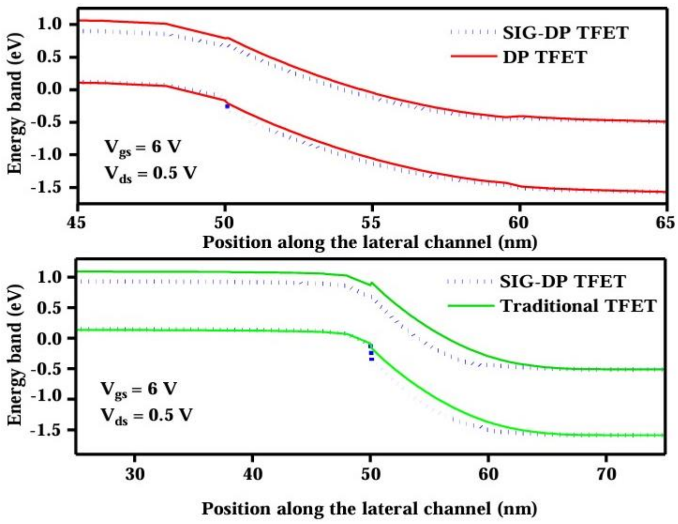

Fig.3: Energy Band of DP_TFET and SIG_DP TEFT

The dielectric constant influences this electric field because it determines how well a material holds electrical energy. The electric field intensifies for a specified voltage whenever the dielectric constant definition sets k = 1 (the permittivity of free space). Higher electrical fields caused by increased dielectric constant strengthen tunneling effects that result in enhanced

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electrical current through the sensor making it suitable for high-sensitivity applications. The sensor's response speed increases through tunneling enhancement yet this improvement creates undesirable noise effects and leakage current problems.
Conversely, when the dielectric constant is increased to k = 1.5, the electric field becomes less strong. The consequence is that the tunneling rate is less, and the sensor's sensitivity can be compromised. But as a trade-off, this lesser electric field may stabilize the device by reducing noise and leakage current, thus improving the overall reliability. Hence, the selection of the appropriate dielectric constant is important to optimize the electric field for the optimum performance in TFET-based biosensors, particularly in sensitive applications such as medical diagnostics, environmental monitoring, and food safety[17].

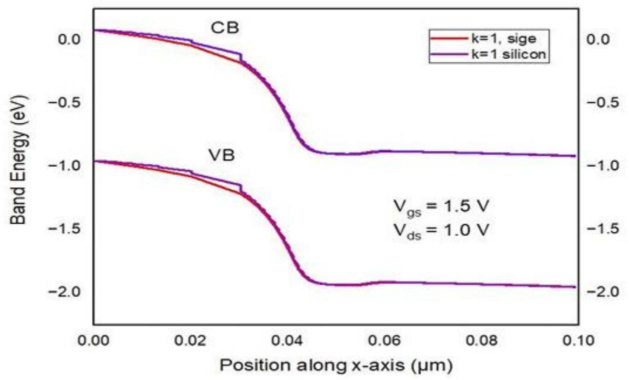

Fig.4: Energy Band of DP_TFET and SIG_DP TEFT for k=1

The TFET-based biosensor development finds support from a robust simulation platform based on Technology Computer-Aided Design (TCAD) for optimizing performance in terms of high sensitivity and energy efficiency.The authors make a performance comparison between their new biosensor and both standard TFET-based sensors as well as doped-pocket TFET architectures. The new design provides superior performance characteristics through sensitivity analysis and current level assessment and noise immune tests. Simulation results show that BTBT improvements substantially boost sensitivity together with energy efficiency which makes the developed biosensor well-suited for future biosensing technologies. The TCAD approach is capable of capturing BTBT effects and dielectric variation effects, thus enabling the quantitative description of the biosensor's response to biomolecular interactions like the biotin-streptavidin binding. Further, the simulation accounts for the contributions of TAT noise as well as environmental noise to analyze the actual world reliability of the sensor[18-23].

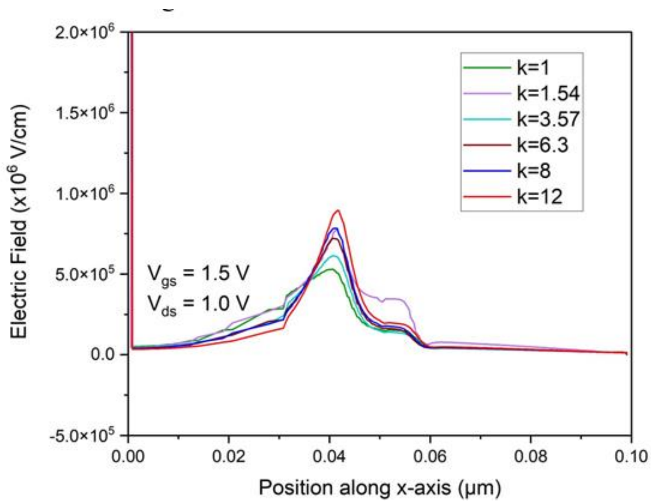

Fig.5: Electric Field of DP-TFET

The authors make a performance comparison between their new biosensor and both standard TFET-based sensors as well as doped-pocket TFET architectures. The new design provides superior performance characteristics through sensitivity analysis and current level assessment and noise immune tests. Simulation results show that BTBT improvements substantially boost sensitivity together with energy efficiency which makes the developed biosensor well-suited for future biosensing technologies.
A DP-TFET with k = 1, whose dielectric constant is k = 1, clearly exhibits band-to-band tunnelling (BTBT) between the channel and the source in its energy band diagram. The tunnelling is very sensitive to the electric field between the source and the channel, which is dependent on the dielectric constant. At k = 1, the same as free space permittivity, the electric field is higher, which increases the tunnelling current at reduced gate voltages. For the SiG Source Doped-Pocket TFET (SiG-DP TFET), at k = 1 also, the implementation of SiG material in the source pocket changes the band alignment by decreasing the conduction band offset. This alteration improves tunneling at reduced gate voltages, further reducing the threshold voltage (VTH). Consequently, the SiG-DP TFET exhibits improved sensitivity and enhanced energy efficiency, suitable for applications that require accurate voltage control and low power consumption[24].

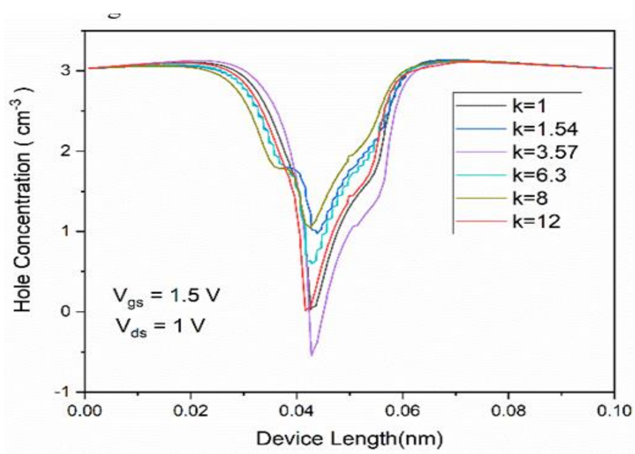

Fig.6: Hole Concentration of SIG_DP TEFT

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Through simulation and optimization of sensor devices Technology Computer-Aided Design (TCAD) allows researchers to develop energy-efficient highly sensitive sensors that serve many applications. Different simulation techniques in TCAD enable meter-scale and nanoscale monitoring of sensors through process modeling coupled with complexity device modeling methods. Process simulation duplicates sensor manufacturing operations starting from doping through etching and material deposition steps with entire control of key structural components including junction depths and oxide layers as well as electrode dimensions. An improvement in sensor sensitivity and selectivity requires simulation because devices that detect minor environmental changes need it[25-28].

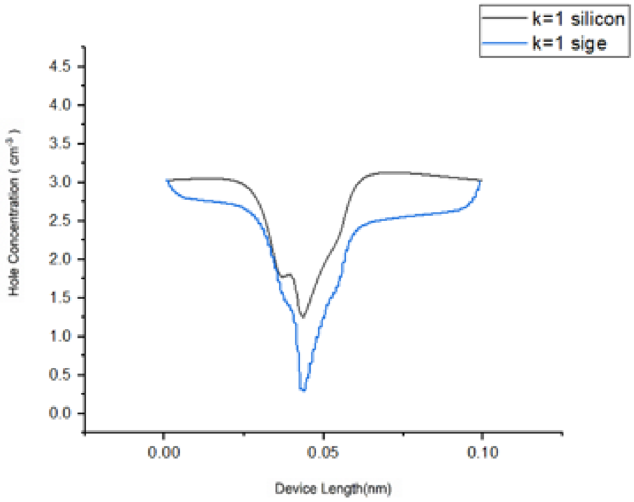

Fig.7: Hole Concentration of SIG_DP TEFT and DP-TFET

TCAD requires device simulation as its second vital element since it examines how sensors perform electrically during different conditions. Engineers achieve optimal device performance through TCAD solutions of complex equations comprising the Poisson equation and drift-diffusion equations because this operation predicts critical performance parameters such as sensitivity and response time and signal-to-noise ratios [29-30].

Sensor design uses TCAD by implementing application-specific sophisticated physical models. Sensor analysis through both carrier transport and surface recombination models allows optimum chemical and gas sensor performance by exploring target molecule surface interactions. The utilization of optoelectronic models for optical sensors allows the enhancement of light absorption and carrier generation as well as recombination processes for improved detection of optical signals. The modeling capabilities of TCAD extend to sensors made from current advanced materials including Silicon-Germanium (SiG) and graphene and piezoelectric components through inclusion of material characteristics such as bandgap and mobility and dielectric constants data. High-performance sensors require this feature because it enhances their capability for biomedical diagnostics and environmental monitoring applications[31-32].

III. CONCLUSIONS

Research into TFET-based biosensor systems with double-gate configuration presents a pathway to dramatically boost biomolecular detection capabilities of sensors through identification and detection processes. Researchers tested the system with biotin-streptavidin binding interactions because these biomolecular interactions serve as a typical example for such studies. A biosensor structure made up of SiG source and doped pocket elements together intensify band-to-band tunneling (BTBT). Tunneling distance shortens because of the SiG source in combination with the doped pocket which leads to increased channel conduction and better biosensor operational outcomes.

The SiG-DP TFET biosensor demonstrates excellent sensitivity features and strong drain current detection capabilities to become a dependable biosensing instrument. The developed biosensor achieves a high sensitivity value (SBio = 76) together with 1.6E-10 µA/µm drain current before hybridization, demonstrating its superior performance attributes. The biosensor reveals exceptional performance in low biomolecule detection capability because of its extraordinary 50% fill factor characteristic. The researchers took into consideration how three vital factors which involve charged biomolecules and other biomolecules and trap-assisted tunneling (TAT) components affect the SiG-DP TFET's sensitivity. Under actual biosensing conditions the above design replaces both classical biosensors and DP-TFETs as the top selection because of its superior performance in sensitivity measurements.

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