Tunnel Field Effect Transistor based Biosensors for detection of Biomolecules: A Review

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Abstract

This manuscript presents brief review on Tunnel Field Effect Transistor based Biosensor from initial phase to currently used Tunnel field Effect Transistors for biosensing application. TFET based Biosensors have gained attention due to phenomenal properties such as high sensitivity, low cost, and ability to detect label-free biomolecules. Conventional Field Effect Transistors have lots of advantages as biosensors in comparison to other biosensors but there exist various limitations on subthreshold swing where (SS>60 mv/decade), various short channel effects reduced the device sensitivity leading to restriction in using it as biosensors. For improving various research is going on so that scientists can find a way out to make a device overcoming all the disadvantages faced by previously developed biosensor made by different transistor devices. This manuscript aims to clearly distinguish between different TFET Biosensors based on their working and sensitivity parameters to provide better insights to the researchers to further carry on the research for making more reliable and advance Biosensors.

Keywords 1

Biosensor, TFET, sensitivity

1. Introduction

In this emerging world, where science has made so much progress scientists try hard to find solutions to every problem. The recent problem such as COVID pandemic has disrupted people lives and such problem was also seen a couple of years ago when smallpox was introduced therefore these issues are never-ending, Biosensors are the advancement of technology for such issues giving precise way to deal with the discovery of biomolecules [1]. Usually, a biosensor consists of two components: a recognition element (molecular) known as a receptor and target analytes like DNA, antibodies, cells, and a transducer to convert the information into a measurable quantity.

Biological analytes are hard to detect based on their intrinsic properties, they need labels such as enzymes, radioactive molecules attach with the analyte for detection and it was a drawback as label-based detection are expensive and also time-consuming. On the other hand, label-free detection does not require labels to facilitate measurements because they use intrinsic physical properties such as charge, size, dielectric permittivity, etc to detect the presence of biomolecules in a cheaper sample and time- saving. These ideal qualities of label-free biosensors spread their applications in numerous zones like the clinical field for beginning phase location of biomolecules, conveyance of medications, food handling, natural observing, security, and observation. A Biosensor is a device that produces an electrical signal from the biophysical response. The

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principal chemical-based biosensor was founded by Clark et al. in 1962 [1]and from that point forward this arising field has picked up loads of consideration among overall analysts for creating precise and more solid biosensors. The biosensor comprises of two different stages – 1) Biomolecule location and 2) Trans-conduction. The first stage comprising of biomolecule location is one of the important tasks as locating a biomolecule in a device where it could be recognized by the biosensors helps is detecting the biomolecules in a more precise manner. The second stage transduction defines the process that is used to define biosensors by converting the recognized biomolecules into an electrical form or readable form for precise detection. All these biosensors are utilized to improve human existence. There are various biosensors based on the transduction process.

The working principle of electrochemical biosensor [2] is to experience the adjustment in the electrical properties of the sensor by response focused on biomolecules. The noticed changes are utilized as estimating boundaries for the sensor and depending on boundary noticed they are additionally characterized into amperometric, potentiometric, and conductometric. The exceptionally ground-breaking substitute of ordinary insightful sort biosensor is optical biosensors as it needs extremely restricted groundwork for the location of the focused biomolecule. Optical fields with analyte are utilized in an optical biosensor to identify tumor cells, poisons, and so on Calorimetric and Acoustic biosensors discover great applications for the discovery of DNA. All these biosensors are utilized to improve human existence. Thermal and mass-based biosensors are unpredictable and have low reaction time. Optical and electrochemical biosensors have taken more consideration for dependable and precise reactions because of their low location limit and extremely high particularity. There is a lot of progress going on TFET based biosensors but researchers face lots of problem in finding all the information related to Tunnel Field Effect Transistor based biosensors at one time. This manuscript has been bifurcated into three sections. Section I elaborates the brief literature review, Section II describes the structure and performance comparison of various biosensors, and finally in Section III conclusion is drawn.

1.1 Literature Review

Low cost, low power, rapid, small, ultra-sensitive, robust biosensors are highly recommended for Point of Care Applications. Biosensor build on Complementary metal oxide semiconductor compatible silicon nanowire tunneling field effect transistor (SiNW- TFET) has been proposed by Anran Gao (2016) [3]. It has been observed that SiNW- TFET provided good amount of parasitic capacity by using inherent ambipolar nature through biomarker of human lung cancer CYFRA21-1 and pH sensing as unfunctionalized Silicon nanowire TFET devices can be characterized as hydrogen ion sensors. Changes in surface charges at the Silicon nanowire surface gates the Tunnel Field Effect device that modulates the nanowire current. The ambipolar nature and conductivity was shown for both positive and negative voltages at gate. This ambipolar response discriminates the electrical noise to carry with object analysis.

Analytical model of p-n-p-n TFET for working as biosensor for label-free detection of biomolecules has been developed by Rakhi Narang (2012) [4]. It has been observed that the proposed model gives two important properties that is possessed by biomolecules 1) dielectric constant 2) charge. Comparison with conventional FET based biosensors was also made in the terms of sensitivity of TFET based biosensors consisting of various parameters like shift in threshold, variation in ON-current (Ion) level and ON-OFF ratio of current (Ion/Ioff). Also, it was concluded that TFET based sensors show wide deviation in current level and therefore change in ON current (Ion) can be considered as appropriate parameter for sensing.

Detection of biomolecules using electrical characteristics is attractive because inexpensive, label-free, provide stability and ease of on-chip fabrication of sensors [5]. TFET having nanostructures or particularly nanowires has gained importance because of enough surface to volume ratio and high electrostatic control. For biomolecule detection specific receptor is allowed to get in contact with oxide or dielectric layer of semiconductor device and because of their charge, it produces gating effect on the device thereby changing the electrical properties like current, subthreshold voltages, conductance etc. Therefore, sensitivity is in accordance with gating effect, higher the response of TFET with gate effect higher will be the sensitivity of the device .

It has been concluded by Deblina Sarkar and K Banerjee (2012) [5] that highest response to gating effects of the biosensors is obtained in subthreshold region but CFETs (Conventional Field Effect Transistors) cannot achieve minimal subthreshold swing that simultaneously limits the sensitivity and response.

Conventional DM-FET based biosensors showed less sensitivity in comparison to DM-TFET based biosensors but showed low subthreshold current.

In 2016, Sayan kanungo [6] investigated the effect of (SiGe) source and n+ pocket doped channel using extensive device level simulation. It has been observed that silicon-germanium source DMTFET showed high superiority in comparison to n+ pocket Dielectric Modulated TFET to obtain higher subthreshold current level while maintaining the sensitivity of device .

In 2019, experimental study has been done by Cao W [7] that provided good insights into Subthreshold Swing (SS) characteristics of TFET by examining effects of four critical parameters like level of source and doping, band gap, length, and tunnel effective mass in the perspectives of Fermi-Dirac Distribution and Tunneling probability variation. It was observed that shortening of Fermi Dirac Distribution, OFF-current and uncovered intrinsic Subthreshold Swing compete among themselves to provide minimum achievable Subthreshold Swing. This work also concluded that for homo junction TFET design: small channel length, suitably high doping level of source and small tunnel effective mass is suitable and for hetero junction Tunnel Field Effect Transistor design in these parameters, small band gap present at tunnel junction is preferable.

There are various types of biosensors as been discussed above and in that row M Waleed Shinwari (2011) [8] presented the effect of distribution of DNA probe on reliability of label-free biosensors. As we have observed that since the miniaturization for increasing the sensitivity parameter, there was lack of research in knowing the variation of received signals with respect to the position of probes over sensitive surface therefore a computational study has been done by them using finite element model on three dimensional biological field-effect transistor (BioFET) via Monte Carlo simulations on the DNA molecules position. It was also observed that SNR can be low enough to disturb the device functionality. Further study done by him was the effects of region of pinch-off and concentration of electrolyte on Signal to Noise ratio. It was concluded that sharing between ions across probes of DNA specifically at low-electrolyte concentration significantly increases the amount of change of charge inversion in FET thereby increasing the sensitivity. Therefore, there is a great need of properly controlled environment for achieving reliability of biosensors and mostly in miniaturization of devices.

In 2010, Jae- Hyuk Ahn et al [9] proposed the double gate nanowire field effect transistor for increasing the sensitivity of conventional FET devices. Gate region was separated as G1 (primary) and G2 (secondary) allowing independent voltage control for modulating potential of channel and sensitivity was enhanced.

Due to the disadvantages of MOSFETs under miniaturization research on electronic devices has been moved to TFETs. Although TFET devices are suitable but still have few things that need to be controlled like it has low on currents that results in low switching speed and shows ambipolar behaviour. It was observed by Anne S. Verhulst (2007) [10] that reduction of gate length leads to several advantages like increase in switching speed and decrease in processing complexity.

Furthermore, short gate TFETs investigation has been carried to know the capability of tunnel field effect transistor by simulating low power digital applications using supply voltages less than 0.5 V. The study done showed that tunneling current has very less or negligible contribution on charging and discharging gate capacitance of TFETs. It was also observed that although short gate TFET has high resistance region but the charging and discharging speed still meets requirements for application in low voltages. The performance analysis was done on SG-TFETs using different materials like Silicon, Germanium and heterostructure studying various parameters such as voltage overshoot, static power, delay energy consumption etc. It was concluded that heterostructure Short Gate TFETs can be said as promising candidate for extending supply

voltages to lower the voltages below 0.5 because of short gate structures, small bandgap material for source and sufficient driving current in Tunnel Field Effect Transistors.
In 2018, Deepak Soni et al [11] carried out research for improving the speed of sensing and sensitivity of TFET based biosensor using the concept of formation of plasma. The research was carried out by adding an electrode on the source region of conventional biosensors using negative supply for extending cavity above the source region. The introduction of additional Source Electrode with negative supply voltage forms the cavity over source region overcomes the issues such as abrupt junction formation at source junction and channel junction. It was also observed that issues related to solubility limit of silicon material was also solved because of formation of plasma layer of holes near Silicon and HFO2 interface. It has been concluded that excess biomolecules in the region of source and cavity increased the concentration of plasma layer of holes near Silicon-HFO2 because of better coupling that in return improved the capability of sensing and the sensing speed of Biosensors.

A transition metal dichalcogenide material based TFET was proposed by Prabhat Kumar and Brajesh Kumar (2019) [12] as transition metal dichalcogenides (TMDs) are said to be promising candidates for sensing applications. It has been observed that TMDs have atomically thin-layered structure, dangling bond free structure and novel physical properties. The presented device showed Subthreshold swing of 50mv/ decade and measured sensitivity of 2.11 for 5mV change in voltage across gate.

Label free biosensors is preferable due to their simple operation. L- shaped TFET [13] based biosensors are used because of their low voltage Subthreshold Swing, power consumption and off state current. In 2020, Chong C proposed a dielectric modulated L-shaped TFET where a cavity was formed inside the electrode of gate in vertical direction. The cavity is filled with biomolecules for working it as a biosensor. The simulation was carried out and was observed that current sensitivity can be increased as high as 2321, the sensitivity of threshold voltage could reach 0.4 and sensitivity of SS could reach 0.7. The results assured that Dielectric Modulated L-shaped TFET sensor is good to go for increased sensitivity and less power consumption.

1.2 Comparison of Different TFET Based Biosensors

In this section Tunnel Field Effect Transistor device structure and their performance in terms of sensitivity for the application as biosensor is described.

1. Silicon Nanowire Tunnel Field Effect Transistor

The silicon nanowire TFET based biosensors was designed using novel CMOS compatible anisotropic wet etching approach and conventional lithography alongwith tetramethylammonium hydroxide. In Figure 1 (a), one can observe that SiNWs forms a cluster (10 wires each) that is used as one unit for sensing specific molecule. The structure clearly shows that the surface of Silicon nanowires are smooth and of high quality [3]. The I_D-V_G characteristics of SiNW-TFET and conventional TFET based biosensors in log scale was compared. It can be observed in Figure 1 (b) that subthreshold swing of TFET was decreased in comparison to conventional FET device (MOSFET).

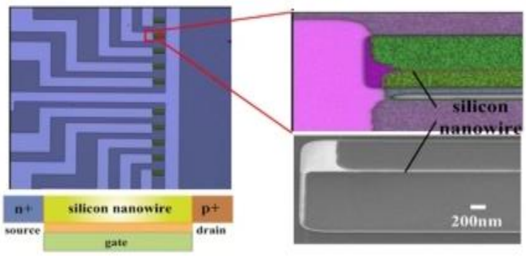

Figure 1 (a): Silicon nanowire-based Biosensor diagram [3]

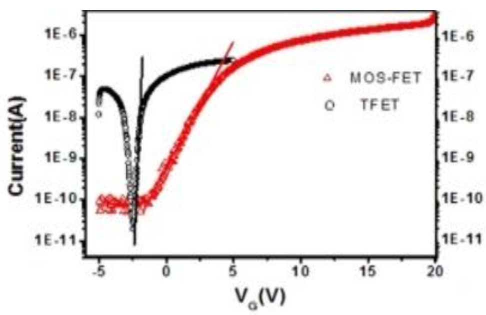

Figure 1 (b): I_D-V_G characteristics of Silicon nanowire-TFET and conventional TFET based biosensors in log scale [3]

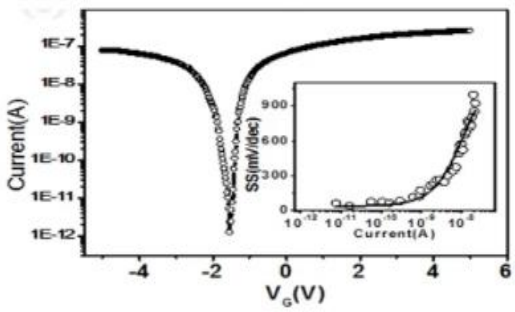

Figure 1 (c): I_D-V_G curve of Silicon nanowire TFET device for V_D = 1 V [3]

In Figure 1 (c), I_D-V_G curve of Silicon Nanowire TFET device for V_D = 1 V is shown that justify that this proposed structure has SS of 37 mv/dec for n-channel that simultaneously increased the sensitivity. The current and subthreshold swing (SS) of n-channel relation shows that subthreshold swing of TFET is not static like conventional FET and therefore, it is strongly dependent on gate voltage.

2. Dielectrically Modulated Tunnel FET based Biosensor.

The Dielectric modulated TFET based biosensor is basically a Dual gate geometry p-n-p-n architecture**.** The change of quality in physio-chemical reaction in analyte is complicated that fails to detect electrically neutral biomolecule. The challenges faced by label-based biosensor is suppressed using label free detection technique. The p-n-p-n (Tunnel source MOSFET) was considered shown in Figure 2 (a) because p-i-n structure have less on current.

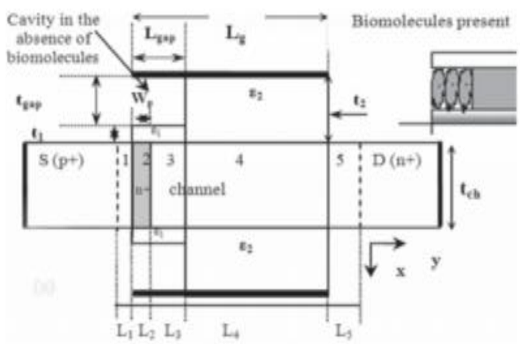

Figure 2 (a): Schematic diagram of Dielectrically modulated Tunnel FET based Biosensor [4]

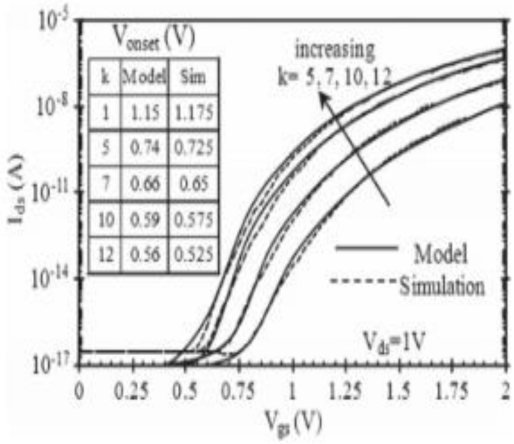

Figure 2 (b): I_D-V_G characteristics of DM-TFET [4]

We can observe I_D-V_G characteristics in Figure 2 (b) that shows good response for different dielectric constant values and therefore the sensitivity of biosensor is improved. The thing that was not taken care was ambipolar conductivity which effect the sensitivity of the device and limits the performance of this device. They performed the sensitivity analysis by considering dielectric constant and charge separately but if we observe practically then the charge is present only when biomolecules are present therefore this is the concerning factor for in proposed device.

3. Short Gate and Full Gate TFET Based Biosensor

Sayan Kanungo in 2015 carried out performance analysis of both SG-TFET and FG-DMTFET. In the device, the two gates operate simultaneously and the dual gate structure enhances biomolecule impact on dielectric constant and leads to high sensitivity of the sensors [6]. To enhance the value of tunneling current, Si-Ge was used as source with germanium concentration of 0.5 in both SG-TFET and FG-TFET. The gate length of short gate TFET was kept 20 nm and Full gate was kept 42 nm as we can see in Figure 3(a) and (b). The SG-DMTFET limited the impact of ambipolar conductivity and showed improved sensitivity.

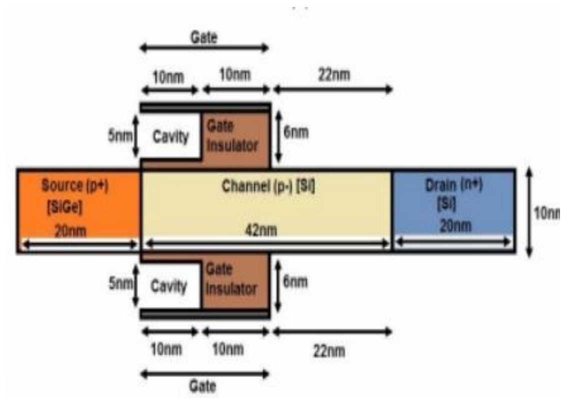

Figure 3 (a): Structure of Short gate Tunnel Field Effect Transistor based Biosensor [6]

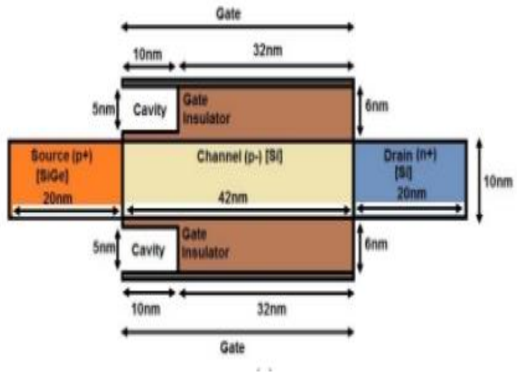

Figure 3 (b): Structure of Double gate Tunnel Field Effect Transistor based Biosensor [6]

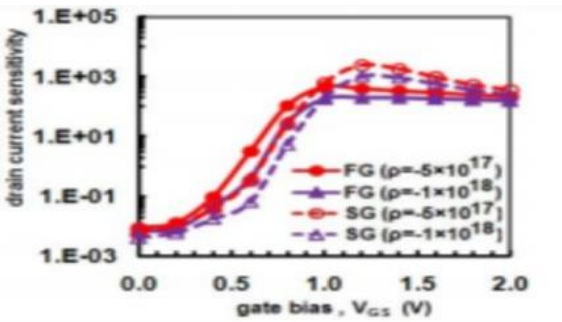

Figure 3 (c): Comparison of I_D-V_G characteristics of both SG and FG TFET based biosensor [6]

The full gated DMTFET consists of full gated intrinsic channel as which decreases the width of barrier and hence sensitivity is achieved. Further due to one-dimensional tunneling the on current of Dual metal gate is limited. The short gate TFET should be operated in specific biasing range and this precise biasing can enhance the sensitivity of SG-TFET (Short Gate Tunnel Field Effect Transistor) that can produce sensitivity of drain current almost seven times that of FG-TFET (Full Gate Tunnel Field Effect Transistor). The I_D-V_G curve of both short gate and full gate TFET based Biosensor is shown in Figure 3 (c). Further, it is being said that structural enhancement in FG-TFET and material specifications can increase the sensitivity performance.

4. Junctionless based electrically doped TFET based Biosensor

The device structure is made of n^+ heavily doped Si layer and isolated gates to form intrinsic region and p^+ source region under the polarity gate (PG) and control gate (CG). The polarity bias of Si body is similar to that of conventional tunnel field effect transistor [14]. As the device is junction less, the device is free from doping control, thermal dissipation and fabrication complexity as shown in Figure 4 (a).

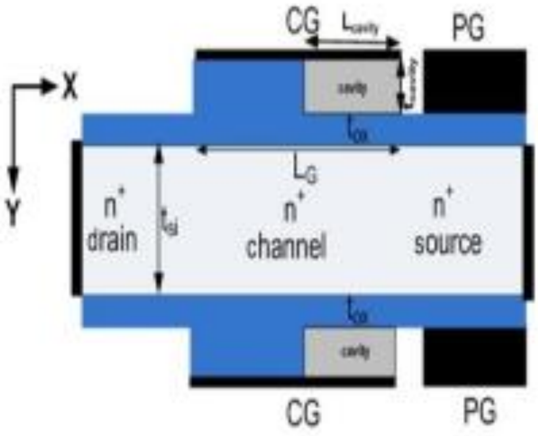

Figure 4 (a): Schematic of Junctionless based dielectric modulated TFET based Biosensor [14]

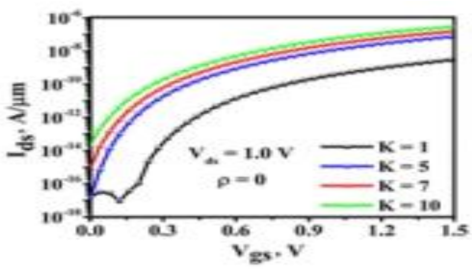

Figure 4 (b): I_D-V_G characteristics at different dielectric constant [14]

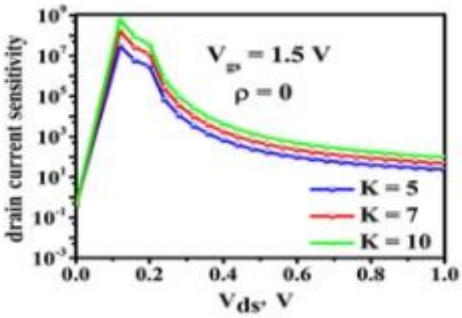

Figure 4 (c): drain current sensitivity at different dielectric constant [14]

The performance of device is increased due to the absence of junction and improved the issue of random dopant fluctuation. The drain current sensitivity curve is shown in Figure 4 (c) and I_D-V_G curve at different dielectric constant is shown in Figure 4 (b). Although it is free from short channel effects, fabrication issues etc but still the issue of ambipolar conductivity persist therefore structural modulation of the device is still needed.

5. Dual-gate source electrode dielectric modulated based Biosensor

Deepak Soni et al proposed a structure that uses charge plasma -based concept for detection of biomolecule for efficiently thereby increasing the sensitivity.

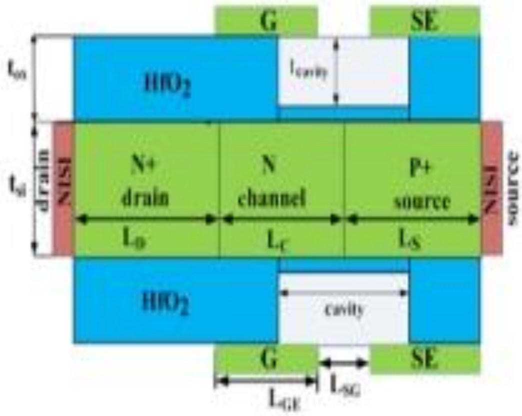

Figure 5 (a): Schematic of Dual gate source electrode dielectric TFET Biosensor [11]

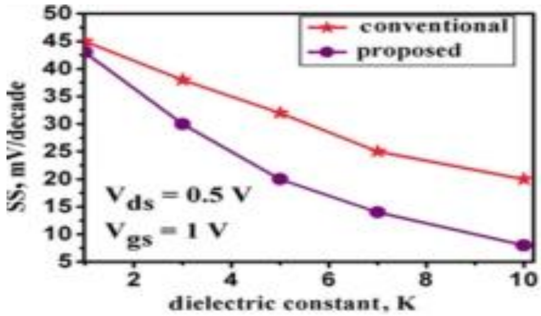

Figure 5 (b): SS comparison curve of conventional and proposed TFET device [11]

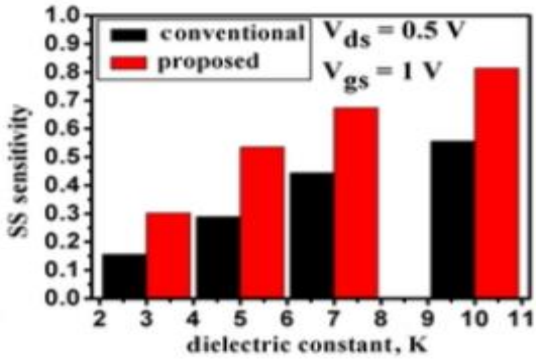

Figure 5 (c): Sensitivity comparison curve of both conventional and proposed TFET device [11]

This research was carried out for improving the response time and sensitivity of Tunnel Field Effect based biosensor using the concept of formation of Plasma. The sensitivity was improved by adding an electrode on the source region of conventional biosensors using negative supply for extending cavity above the region of source [11]. The introduction of additional Silicon Electrode with negative supply voltage for forming the cavity over the source region overcomes the issues related to abrupt junction formation at junction of source and channel as shown in Figure 5 (a). It was also observed that issues related to solubility limit of silicon material due to layer of Plasma formation of holes near Si-HFO2 interface was also solved. It has been concluded that excess biomolecules in the region of source and cavity increased the concentration of plasma layer of holes near Si- HFO2 because of better coupling that in return improved the subthreshold swing, capability of sensing and the sensing speed of Biosensors as shown in Figure 5 (b) and (c).

Figure 8. Comparison Chart of TFET based Biosensors

S no.	Device name	Performance	Limitations
1	Silicon Nanowire Tunnel Field Effect Transistor	Low Subthreshold swing of 30mv/decade in n-channel and 79mv/decade in p-channel that results in improved sensitivity as compared to conventional FET devices	Ambipolar conductivity
2	Dielectrically modulated Tunnel FET based Biosensor	Improved sensitivity for varying Dielectric Constant	The sensitivity analysis was performed using charge and dieletric individually but practically charge is present only when biomolecules are present and that is one of the concern
3	Short Gate and Full Gate TFET based Biosensor	Proper Biasing results in sensitivity improvement almost seven times that of Full gate TFET based Biosensor	On Current (Ion) is limited due to one directional tunneling
4	Junctionless dielectric modulated electrically doped TFET based Biosensor	Performance of device is increased due to absence of Junction and imporved issue of random dopant fluctuation	Device is free from short channel effects but still faces issue of ambipolar conductivity
5	Dual gate source electrode dielectric modulated based Biosensor	Charge Plasma concept overcomes issues such as abrupt junction, solves issue of solubility imit of silicon material and increased sensing speed of biomolecules resulting in quick response time	Random Dopant Fluctuation was still a serious issue in proposed device
6	Transistion metal Dichalcogenides material based Biosensor	Showed excellent sensitivity and sharp threshold of 50 mv/dec	Results in reduction of mechanical flexibility due to brittle nature of the material
7	Dielectric modulated L-Shaped Gate Field Effect Transistor based Biosensor	Proposed device is suitable for ultra sensitive and low consumption biosensors.	Sensitivity of proposed device highly depends on amount of positive charge present in the biomolecules

6. Transition metal Dichalcogenides material based Biosensor

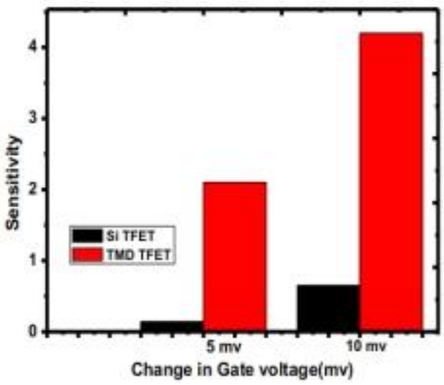

Figure 6 Sensitivity comparison of Silicon based TFET and TMD material based TFET [12]

Transition Metal Dichalcogenides material based TFET is proposed in 2019 for label-free detection of Biomolecules. In recent years stretchable and flexible electrons have gained more attention in different fields like robotic and medical fields because of their advancement in performance. The TFET biosensor made by using silicon are offering excellent performance but their mechanical flexibility is not good due to its brittle nature. This device showed sharp threshold of 50 mv/dec as shown in Figure 6 and excellent sensitivity.

7. Dielectric Modulated L-shaped Gate Field Effect Transistor based Biosensor.

The research carried out by Chen Chong, Hongxia Liu shows the range of current sensitivity, subthreshold swing sensitivity and sensitivity of threshold voltage of the proposed structure. The material used for making source, drain, channel and substrate was silicon. The gate dielectric used was HfO_2 [13]. The study was carried out by using six small biomolecules with different dielectric constant filled in different nanocavity thickness operated at different gate voltages as shown in Figure 7 (a)

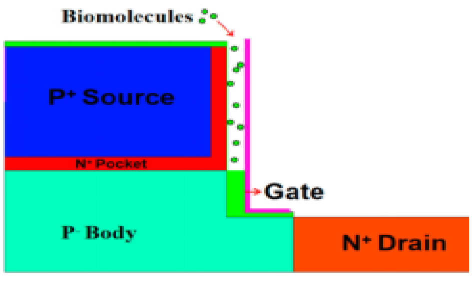

Figure 7 (a): Schematic view of Dielectric Modulated L-shaped Gate Field Effect Transistor based Biosensor [13]

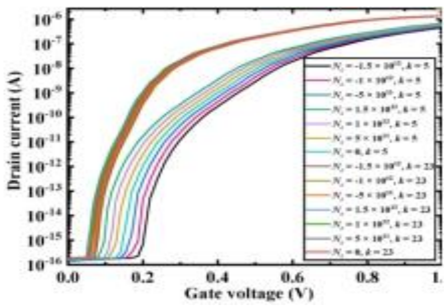

Figure 7 (b): I_D-V_G characteristics at different dielectric constant [13]

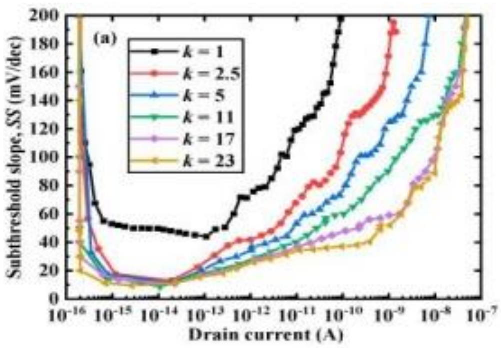

Figure 7 (c) Subthreshold slope of device at different dielectric constant [13]

The simulation was carried out and was observed that current sensitivity can be increased as high as 2321, the sensitivity of threshold voltage could reach 0.4 and sensitivity of SS could reach 0.7 as shown in Figure 7(b) and 7(c). The proposed device is appropriate for ultra-sensitive, low-consumption biosensors. It can be said from the simulated result that greater the relative permittivity of biomolecules, smaller the cavity will be and the higher the amount of positive charge, higher will be the sensitivity of the proposed biosensor.

1.3 Conclusion

In the above discussion a brief literature review and performance comparison in terms of device structure and sensitivity is done along with summary of comparison based on performance and limitations as shown in Figure 8. It can be concluded that sensitivity is related to various parameters but majorly 5 parameters are directly related to improvement in sensitivity 1) Device size and structure 2) material used to make device 3) Oxide thickness and gate length 4) position of cavity and fill factor 5) subthreshold characteristic and drain current. Although TFET based devices are free from short channel effects but there are another factors that are of high concern like ambipolar conductivity, steric hindrance, fabrication complexity and precise biasing condition. This review analyzed various biosensors and therefore different structures has been proposed to make device more sensitive having quick response time but still various parameters could be studied for further improvement in Biosensing application to be able to work in real time as biosensor. This study further concluded that Dielectric modulated L-shaped TFET [11] based biosensors achieved good range of sensitivity as compared to all the previously designed biosensors.

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