Innovative FETs in Biosensing Applications: A Review

Deepanshu Tamta[+], Harsh Pant[*], Ashutosh Joshi[#], Sachin Dhariwal[`]
Department of Electronics & Communication Engineering
Delhi Technological University
[+]deepanshutamta_ec20b12_47@dtu.ac.in
[*]harshpant_ec20b12_58@dtu.ac.in
[#]ashutoshjoshi_ec20b12_31@dtu.ac.in
[`]sachindhariwal@dtu.ac.in

***Abstract*—The realm of biosensor technology has seen remarkable progress with the advent of innovative field-effect transistors (FETs) like gate-all-around junctionless field-effect transistors (GAA-JL-FETs), gate-all-around junction-less accumulated mode FETs (GAA-JAM-FETs), GAA-Schottky FETs, and conventional GAA FETs. These FETs have demonstrated superior performance in biosensing applications, leveraging their advanced figure of merits (FOMs) like heightened sensitivity, selectivity, low limits of detection (LOD), and rapid response times. This paper provides a comprehensive review of these advanced FET technologies, drawing comparisons between their sensing performances in various biosensing applications. Further, this paper focuses on each individual FET and its applications in the specific domain of biosensors. This comparative analysis aims to guide future research, fostering the development of more efficient, sensitive, and selective biosensors by leveraging the unique properties of these advanced FETs.**

Keywords*— *Bio-sensor, FET-type, GAA, JL-FET, JAM-FET, SilNW

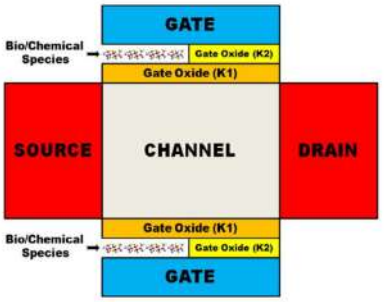
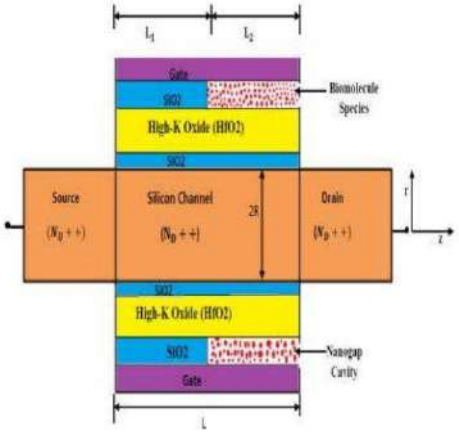
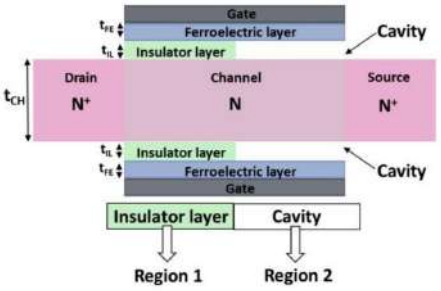
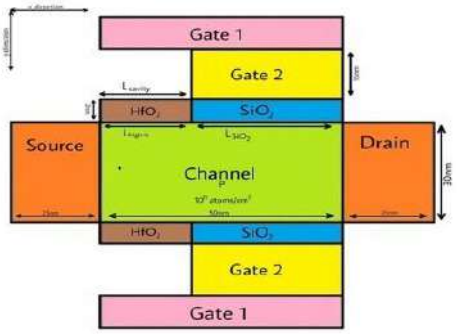
I. Introduction

Electronic sensing applications have benefited greatly from the use of nanowires, which are increasingly recognized for their ability to improve sensor technology's versatility and downsizing. Silicon nanowires (SilNW) stand out as a prime nanostructure for sensory applications, attributed to their one-dimensional, quasi-electronic structure and significant surface-volume ratio. A key advantage of SilNW is its seamless integration with conventional silicon (Sil) technology, allowing for the easy incorporation of additional circuitry on the same chip [1]. Typically, SilNW sensors are based on Field-Effect Transistor (FET) technology and include gate, drain, and source electrodes. The functionality of a SilNW biosensor hinges on the changes in current through the SilNW channel, which occurs in response to variations in surface charges due to the binding of biomolecules. FET-based SilNW sensors, benefiting from their compatibility with complementary metal-oxide semiconductors, their capability for direct electrical readouts, and high sensitivity, have shown significant promise in biosensing applications [2]. The efficacy of different SilNW biosensor FETs is outlined in Table 1. Initially, Metal-Oxide-Semiconductor FETs (MOSFETs) were utilized; however, the continuous reduction in MOS device sizes posed various challenges in device operation, performance, and fabrication. The emergence of Gate All Around (GAA) FETs marked an improvement over planar devices, especially with the progression of CMOS scaling. GAA MOSFETs are especially beneficial for devices scaled down below 50 nm [3], offering advantages like higher packing density and improved current driving capabilities. The GAA silicon nanowire (SiNW) FET, with its cylindrical gate-all-around structure, is designed to provide effective gate control, reducing off-state current and enhancing resistance to short-channel effects. Yet, a significant drawback of these scaled devices is the high series resistance resulting from abrupt source/drain junctions [4-5]. In response to these challenges, innovative approaches like Schottky-Barrier (metal) source/drain and Junctionless (JL) MOSFETs have been explored [6]. The JL MOSFET, characterized by uniformly doped source, drain, and channel regions, thereby avoiding P-N junctions, faces the issue of reduced carrier mobility due to high doping concentrations, impacting the drive current and transconductance [7-9]. To counteract these issues, doped source/drain regions have been replaced with Schottky Barrier metal source/drain (MSD), leading to increased on-current and improved transconductance in JL MOSFETs. The Schottky barrier metal-oxide-semiconductor (SB-MOSFETs), featuring metallic source and drain regions, present a viable option for deep submicron devices and offer manufacturing benefits by eliminating the need for uniform doping distribution in the channel [10–12]. Table 2 details the key features of each type of GAA-SiNW FET. Advancements in the field of nanowire-based sensors, particularly GAA-SiNW FETs, are propelling forward the frontiers of ultra-sensitive and miniaturized sensor technology. The focus is increasingly on optimizing these devices for real-world applications, addressing both technical and practical aspects. One significant area of development is the improvement in detection limits and response times of these sensors, essential for applications in environmental monitoring and healthcare diagnostics. This involves refining the surface chemistry of SilNWs to enhance their interaction with specific target molecules, thereby increasing sensitivity and reducing interference from other substances. Additionally, efforts are being made to integrate these nanosensors with wireless communication technology, enabling remote sensing capabilities. This integration is pivotal for the development of smart sensor networks, which are crucial for applications like smart cities and industrial monitoring. Another key aspect being addressed is the long-term stability and reliability of these devices in various environmental conditions, which is critical for ensuring consistent performance over time. Furthermore, research is being directed towards scaling up the production of GAA-SiNW FETs while maintaining cost-effectiveness and quality control. This includes the exploration of new materials and fabrication techniques that are compatible with existing semiconductor manufacturing processes. These advancements, when combined with the ongoing miniaturization trend, are expected to lead to the next generation of compact, efficient, and versatile

Table 1 Sensing performance and application of different SilNW FET biosensors [13]

Ref	SilNW sensor type	Target	LoD	Detection Range	Sensitivity	Response Time
[14]	SilNW-Polycrystalline FET biosensor	Ferritin	50 pg/mL	50 pg/mL to 500 ng/Ml	133.47 mV/pH	-
[15]	SilNW FET biosensor	Cardiac troponin I	~5 pg/mL	-	-	-
[16]	SilNW FET biosensor	PSA	23 fg/mL	23 fg/mL to 500 ng/mL	70 mV/pH	5 to 10 seconds
[17]	SilNW FET	pH detection	-	-	54.5 mV/pH	-
[18]	SilNW bio FET	Exosomes	2159 particles/mL	-	-	-
[19]	SilNW FET	MMP-9	7.6 pg/mL	-	86.96%	-
[20]	SilNW FET decorated with polyethylene glycol	MicroRNA	10 aM	10 aM to 10 pM	-	-
[21]	SilNW FET	ALT	4.1 ± 0.4 U/L ALT	-	-	-
[22]	SilNW FET	pH	5 nS/pH unit	-	-	-
[23]	SilNW FET	α-fetoprotein	-	500 fg/mL to 50 ng/mL	-	-
[24]	SilNW FET	Carcino embryonic antigen	1 fg/mL	-	-	-
[24]	SilNW FET	microRNA 126	0.1 fM	-	-	-
[25]	Magnetic graphene composite modified poly-SilNW-FET	APOA2 protein	6.7 pg/mL	19.5 pg/mL to 1.95 µg/mL	-	-
[26]	SilNW FET	α-fucosidase	1.3 pM	-	-	-
[27]	SilNW FET	ALCAM biomaker	15.5 pg/mL	-	-	30 minutes
[28]	SilNW FET	Vascular endothelial growth factor	2.59 nM	-	-	-
[29]	SilNW FET	Vascular endothelial growth factor	-	5 fM to 200 fM	-	-
[30]	SilNW FET	DNA	0.1 fM	-	-	-
[31]	SilNW FET Sensor Arrays	CRP proteins	-	-	1.2 nA/dec	-

Table 2 Summarized key features of each type of FET-type biosensors

Sensor Type	Definition	Schematic Structure	Characteristics
Conventional SilNW FET	A conventional field-effect transistor using a silicon nanowire as the conducting channel.		High sensitivity due to one-dimensional electron transport. Suitable for label-free detection of biomolecules.
JL SilNW FET	A FET without a p-n junction, utilizing silicon nanowires as the conducting channel.		Lower noise levels and decreased power consumption. Enhanced sensitivity for biomarker detection.
JAM SilNW FET	A FET without a p-n junction, utilizing silicon nanowires as the conducting channel.		Improved selectivity and control over the sensing process. Capable of detecting low-concentration analytes.
Schottky contact SilNW FET	Utilizes a Schottky barrier formed between a metal and silicon nanowire for sensing.		High sensitivity and fast response time. Effective in detecting charged species and small molecules.

nanowire-based sensors. This will not only enhance current applications but also open up new possibilities in areas such as wearable technology and Internet of Things (IoT) devices.

II. Computational Parameters

Recent years have witnessed remarkable advancements in the field of biosensing, leading to the development of diverse biosensor structures and designs. This rapid expansion, however, presents a challenge: the lack of standardized evaluation metrics hinders meaningful comparisons and consequently, impedes further development. It is within this context that the importance of comparative parameters in biosensing emerges.For this paper we will be focusing on parameters such as sensitivity, selectivity, Limit of Detection (LoD), Response Time and Signal-to-Noise Ratio (SNR).

A. SENSITIVITY

One of the most important metrics for comparing devices with different dimensions and transfer properties is the sensitivity of a biosensor, which is measured as the relative change in signal ($\Delta I/I$).[32] This dimensionless metric allows biosensors to be objectively evaluated and distinguished from one another, irrespective of their unique operational principles and designs. Consequently, a lot of theoretical as well as experimental conclusions are based on the optimization of this performance metric.[33-34]

Since this parameter is of the utmost importance, it is desired to be as high as possible but biosensors have reported high sensitivity only for neutral biomolecules and negatively charged biomolecules till now. Sensitivity remains quite low for the positively charged biomolecules. For a biosensor to identify even one biomolecule, it must possess exceptional sensitivity.[35] The sensitivity of a Biosensing FET can be summarized using the following equation:

$$\frac{dI_D}{I_D} = (dc\ \frac{d\rho}{dc})(\frac{dv_{EG}}{d\rho})(\frac{dI_D}{dv_{EG}}\ \frac{1}{I_D})$$

sensitivity (i) (ii) (iii)

where,

(i) the charge exchange at the sensor interface, quantified by the change in the drain–source current (dρ)

(ii) changes in effective gate voltage (dV_{EG})

(iii) the change in drain current (dI_D). Here, (dc) represents the change in analyte concentration, and I_D represents the change in the current without the target analyte (from a baseline exposure).[36]

B. SELECTIVITY

Sensitivity is a crucial factor in assessing the performance of biosensors, but it is not sufficient on its own. Selectivity, also known as specificity, also holds equal value to determine the efficiency of any biosensor. The ability of the biosensor to differentiate between the target analyte and any other possibly interfering chemicals in the sample is reflected in this attribute. An advantage of using biosensors with high surface specificity is that they enhance the number of biological molecules and the processes that may be studied. This helps in understanding how different biological materials interact helps to discover new interactions between those materials and opens the door to new disciplines.[37]

C. LIMIT OF DETECTION (LoD)

The Limit of Detection (LOD) is a key metric in evaluating the effectiveness of biosensors during method validation. It's important to focus on LOD alongside sensitivity, as it measures a biosensor's ability to detect the smallest concentration of an analyte [38]. LOD is defined as the smallest amount of an analyte that can be confidently identified as different from background levels, to a certain degree of certainty. In biosensor technology, the LOD is typically calculated using the standard deviation (s) of the signal when no target analyte is present, and a factor known as the k-factor. The k-factor represents the confidence level required to differentiate between the actual analyte signal and background noise. A higher k-factor sets a more stringent criterion, resulting in a lower LOD, while a lower k-factor implies a less strict threshold, leading to a higher LOD [39].

$$LOD = 3\sigma$$

where, σ represents the standard deviation (s) of the blank signal (signal without the target analyte).[40]

D. SIGNAL-TO-NOISE RATIO (SNR)

This is defined as the ratio of the actuating signal that is electrically transduced from the targeted biomolecules to the non-actuating signals that are electrically transduced from the non-targeted biomolecules. This signal-to-noise ratio is one of the important parameters to judge the efficiency of any biosensor and it will be high if the sensitivity along with the selectivity of the biosensor is high.[41] SNR reflects the fidelity and depends upon the impedance matching between different subsystems of FET-based biosensors. If the noise signal is generated from the testing environment, then it is called signal-to-background ratio.[37] It becomes essential, in the design of "better" sensors to consider a performance metric, which includes the effects of noise fluctuations, as well as, provides a physical model to understand the parameters which affect the LOD. Signal-to-noise ratio (SNR) can be used as such a metric[42-43] since it involves both the device transconductance (g_m) which is directly proportional to the signal generated, as well as the current noise power density (S_I), which is a function of device dimensions as well as oxide trap density (N_{ot}).[44]

$$SNR = \frac{g_m}{\sqrt{S_I}} = \frac{1}{\sqrt{S_{VFB}}} = \sqrt{\frac{W L C_{OX}^{\ 2} f}{\lambda k T q^2 N_{ot}}}$$

SNR here is defined per unit change of surface potential and per unit bandwidth. W and L are the widths and lengths of

the device, respectively. k is the tunneling parameter for electrons in silicon oxide (~10^{-10}m), k is the Boltzmann constant, T is the temperature, f is the frequency at which the power of the noise density is measured, and C_{ox} is the oxide capacitance per unit area. N_{ot} is the oxide trap density, and in the case of ultra-scaled devices, it includes contributions due to surface states and interface traps/defects.[45-46]

III. Conventional SilNW FET Biosensor

A. Structure:

Conventional Silicon Nanowire Field-Effect Transistors for biosensing consist of a silicon nanowire, which serves as the semiconducting channel, strategically positioned between two doped regions that act as the source and drain. The nanowire, typically with diameters ranging from a few nanometers to tens of nanometers, is the critical sensing element due to its high surface area relative to its volume. The increased surface area is highly beneficial for biosensing applications as it provides a larger binding site for biomolecules. A thin gate dielectric, usually silicon dioxide, encapsulates the silicon nanowire, providing insulation from the gate electrode. The gate electrode, often made from conductive materials like polysilicon or metal, is placed adjacent to, but not surrounding, the nanowire. This gate electrode is crucial for controlling the charge carriers in the nanowire channel.

B. Working Principle:

The operation of conventional SilNW FET biosensors is predicated on the field-effect principle, where the conductivity of the silicon nanowire channel is modulated by an electric field. When a voltage is applied to the gate electrode, an electric field is established across the gate dielectric, influencing the charge carrier density within the nanowire. This modulates the conductance of the nanowire channel. In biosensing applications, the surface of the silicon nanowire is typically modified with biological receptors such as antibodies, nucleic acids, or enzymes that specifically bind to target analytes. When the target biomolecule interacts with these receptors, it alters the surface charge of the nanowire, leading to a change in the electrical conductance. This change is proportional to the concentration of the target molecule and can be detected and measured as an electrical signal.

The sensitivity of SilNW FET biosensors is partly attributed to the high surface-to-volume ratio of the nanowires, which amplifies the surface potential changes due to biomolecular binding events. Moreover, the field-effect modulation enables real-time, label-free detection, making SilNW FETs highly attractive for a wide array of biosensing applications, from medical diagnostics to environmental monitoring. The conventional architecture, while simpler than more advanced configurations like GAA FETs, still offers excellent sensitivity and specificity, essential for detecting low concentrations of biological analytes.

C. Applications

Gate All Around (GAA) Silicon Nanowire Field-Effect Transistors (SilNW FETs) are state-of-the-art biosensing devices with a plethora of innovative applications due to their unique electrical and structural features. Here are some of their most significant applications:

High-Sensitivity Disease Detection: Due to their exceptional sensitivity, GAA SilNW FETs are perfect for identifying biomarkers at low concentrations. For the early diagnosis of illnesses such as cancer or neurological disorders, where early identification can have a major influence on treatment results, this increased sensitivity is essential.

Environmental Monitoring: GAA SilNW FETs are used in environmental biosensing to identify minute concentrations of contaminants, poisons, or diseases in water and air. This capacity is essential for keeping an eye on and preserving the safety and health of the environment.

Lab-on-a-Chip Systems: The creation of lab-on-a-chip devices depends heavily on these FETs. They provide speedy and effective analysis by condensing and combining many laboratory procedures onto a single chip, which is especially advantageous for point-of-care testing and fast diagnostics.

Tailored Medicine: Applications for tailored medicine are made possible by the great specificity of GAA SilNW FET biosensors. They enable the customization of medical treatments to specific individuals, improving the safety and efficacy of medications, by tracking patient-specific biomarkers.

Biological Research: These FETs enable the real-time analysis of molecular and cellular interactions in the larger field of biological research. This will help develop many areas of biotechnology and the living sciences by providing essential insights into intricate biological systems and processes.

Drug Development and Testing: These biosensors play a crucial role in pharmaceutical research, especially in the fields of drug testing and discovery. They may be used to investigate how medications interact with biological systems, which can help in the creation of novel medications and treatment approaches.

IV. JL-SilNW FET Biosensor

The Gate-All-Around Silicon Nanowire Junctionless Field-Effect Transistor (GAA SilNW JLFET) is a type of the nanowire FET. It does not follow the conventional junction-based channel modulation; instead it has a uniform doping profile throughout the device. This design simplifies the fabrication process and can enhance the device's electrical characteristics, especially in the context of biosensing applications. SilNW JLFET have many advantages over other FETs such as highest gate controllability, potential vertical stacking, current industry trend compatibility, inherent ease of fabrication, and higher sensitivity.[47]

A. Structure:

The Gate-All-Around Silicon Nanowire junctionless Field-Effect Transistor (GAA SilNW JL FET) combines essential elements using silicon nanowires to optimize electronic control. Its central feature is a heavily doped silicon nanowire channel, enhancing electrical conductivity and eliminating junction capacitance for quicker biosensor response. The nanowire's one-dimensional structure provides a high surface-to-volume ratio, crucial for enhancing sensitivity in biosensing due to its efficiency in detecting surface interactions. The nanowire is enclosed in a

thin gate dielectric layer, typically made of silicon dioxide or high-k materials like hafnium oxide, which insulates the gate electrode from the semiconductor channel while maintaining ideal capacitance levels. This dielectric choice significantly influences the FET's performance, especially in modulating channel potential and current flow. Enveloping this structure is the gate electrode, following the GAA design to entirely surround the dielectric and channel, allowing excellent electrostatic control over the channel. At each end of the nanowire channel are the source and drain regions, heavily doped to form ohmic contacts vital for efficient carrier movement, crucial to the GAA SilNW JL FET's high performance in various applications, including sensitive biosensing.

Figure 1 illustrates a cylindrical junctionless Gate-All-Around (GAAFET) transistor. This device is unique due to its gate completely encircling the channel. The shape of the channel influences the complexity of the mathematical models needed to describe the device's behavior. Specifically, cylindrical coordinates make solving Poisson's equations more challenging in this context[48-49]. While GAAFETs with rectangular channels also exist, they tend to exhibit performance issues related to corner effects[50].

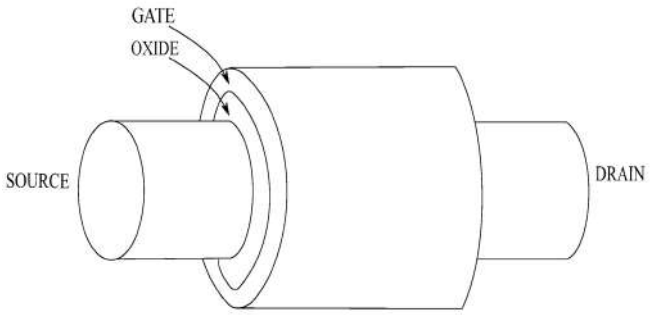


Figure 1: Three-dimensional (3D) structure of a cylindrical junctionless GAAFET.[51]

An essential design aspect of GAAFETs is the channel length. Reducing the channel length from 40 nm to 16 nm leads to an increase in Drain Induced Barrier Lowering (DIBL) from 12 $\frac{mV}{V}$ to 123 $\frac{mV}{V}$, and an increase in Subthreshold Slope (SS) from 62 $\frac{mV}{dec}$ to 82 $\frac{mV}{dec}$[52]. The channel radius also plays a crucial role, as a smaller radius results in quicker device operation[53].

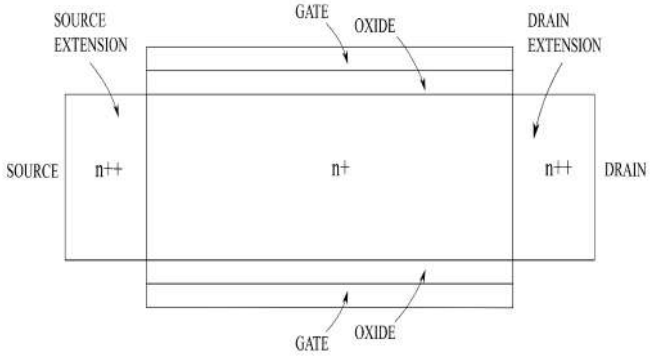


Figure 2: Cross-sectional view of improved cylindrical GAAFET through addition of source and drain extensions.[51]

Compared to inversion mode devices, junctionless GAAFETs typically show a higher Ion/Ioff ratio and are less affected by short channel effects[54-56]. In terms of Low-Frequency Noise (LFN), these devices are relatively unaffected by variations in gate bias and doping concentration[57]. However, the hot carrier effect can degrade intrinsic gain and cutoff frequency, with a reported reduction of about 15.44% in these analog parameters[58]. As shown in Figure 2, adding source and drain extensions can enhance analog performance, including small signal parameters and drain current drivability[59]. Modifying the device structure can further improve performance. For instance, using hafnium oxide (HfO_2) instead of silicon oxide (SiO2) as the gate insulator can enhance both DIBL and SS[60]. Additionally, implementing multiple gates can be advantageous. A twin gate transistor, depicted in Figure 3, facilitates the implementation of logic gates due to its dual inputs[61]. This concept is also applicable to a double channel GAAFET, as illustrated in Figure 3b. Such a device demonstrated impressive performance metrics, including an Ion/Ioff ratio of 7×10^8, a DIBL of 83$\frac{mV}{V}$, and an SS of 105$\frac{mV}{dec}$[62]. Exploring different channel materials has also been a focus. For instance, a gallium arsenide junctionless GAAFET achieved an SS near the theoretical limit[60]. Comparatively, germanium junctionless GAAFETs showed lower DIBL, SS, and $\frac{I_{On}}{I_{Off}}$ ratios than their silicon counterparts[63]. The choice of channel material also affects the threshold voltage's temperature sensitivity, with different materials like silicon, gallium arsenide, indium arsenide, and indium phosphide exhibiting varying degrees of threshold voltage variation[64].

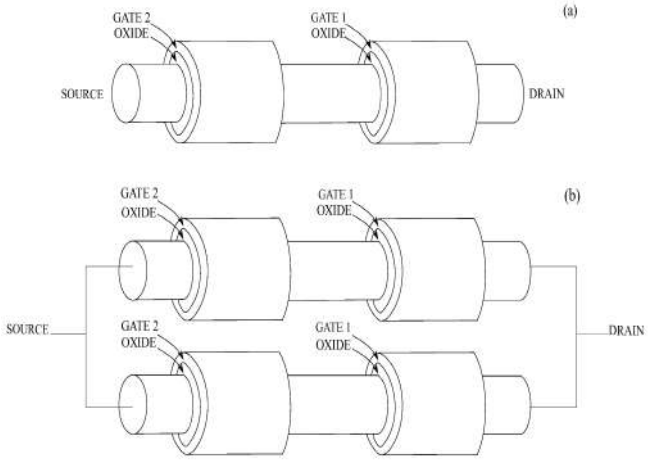


Figure 3: 3D Structure of (a) twin gate single channel GAAFET, (b) twin gate double channel GAAFET.[51]

B. Working Principle:

The Gate-All-Around Silicon Nanowire Junctionless Field-Effect Transistor (GAA SilNW JLFET) is a very sensitive biosensor that identifies specific compounds by converting biological interactions on its surface into detectable electrical signals. Transduction begins at the surface of the silicon nanowire, which has been functionalized with biological recognition elements precisely crafted to sense the target analyte. Due to their intrinsic charge or because they alter the ionic concentration

in the surrounding solution, these biomolecules preferentially bind to the surface upon coming into contact with the analyte, affecting the local charge density or potential. As a junctionless device, the SilNW can adapt to changes in the surface potential brought on by analyte binding by evenly varying the carrier density across the nanowire channel. The gate electrode encircles the nanowire, offering precise electrostatic regulation and augmenting the device's capacity to discern small variations in surface charge. This control is necessary because the interaction of the target molecule with the sensor surface changes the current flowing between the source and drain contacts in response to an applied voltage. The electrical interface of the biosensor then detects, amplifies, and processes changes in current that are related to analyte concentration. Consequently, the GAA SilNW JLFET functions as a link between the biological and electrical domains to facilitate quick, accurate, and digital tracking of diverse biomolecules. Because these industries depend on sensitive detection skills, it is therefore a vital tool for quality control in the food production industry, healthcare diagnostics, and environmental monitoring.

C. Applications:

The Gate-all-around silicon nanowire junctionless field effect transistor has many applications in the biosensing domain. One of such applications is label-free dielectric/charge modulation detection of SARS-CoV2 virus.

The gate-all-around junctionless field effect transistor (GAA-JLFET) that detects the virus because of the electrical properties (dielectric constant and charge) of spike protein, envelope protein, and virus DNA, for a highly sensitive and real-time bio-sensor. GAA-JLFETs are suitable for this application because of their highest gate controllability, potential vertical stacking, current industry trend compatibility, inherent ease of fabrication, and higher sensitivity. The SARS-CoV-2 virus is first immobilized in the etched nano-cavity embedded beneath the gate electrode, which is then used to detect it. The SARS-CoV-2 virus detection has been calibrated based on the change in system electrical properties after virus immobilization. For effective virus detection, the work takes into account both the dielectric property of S protein and the charge of DNA at the same time.[47]

The structure of the device used is Figure 4.

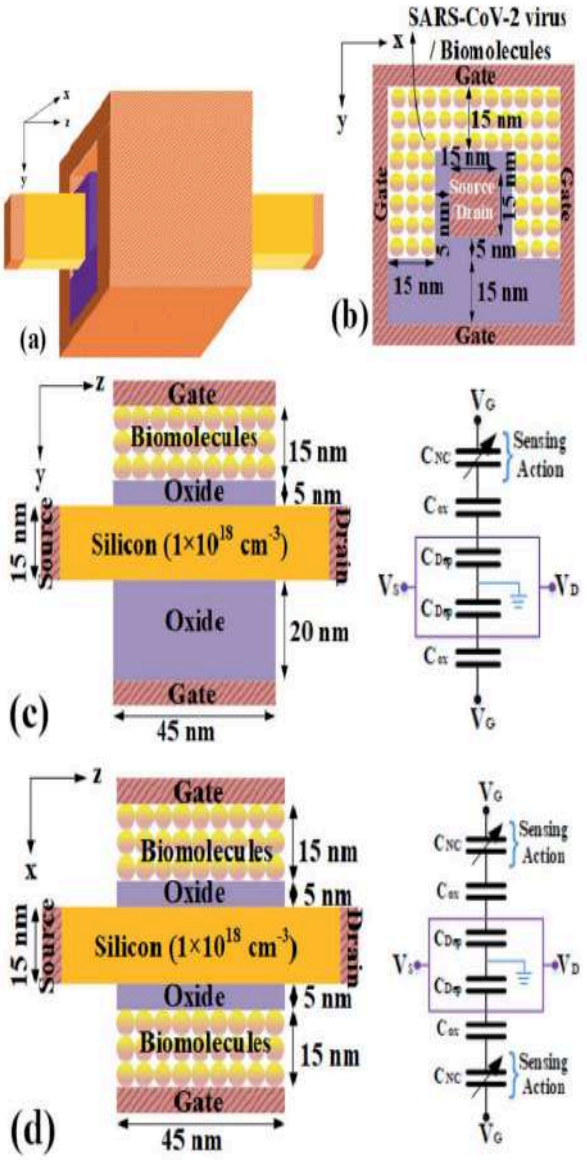


Figure 4: GAA-JLFET device structure for SARS-CoV-2 virus detection (a)3D-view and 2-D cross-sectional view along planes, (b) the x–y, (c) the z–y and its capacitance model to illustrate sensing, and (d) the z–x and its capacitance model to illustrate the biosensing [47]

The given figure shows the 3D model, xy plane, yz plane and xz plane in figure 4(a), 4(b), 4(c) and 4(d) respectively, along with the capacitance model of these planar models is also given in figure 4(c) and 4(d). The variation of electrical properties of the virus trapped in the cavity will change the electric properties of the device which will get detected.

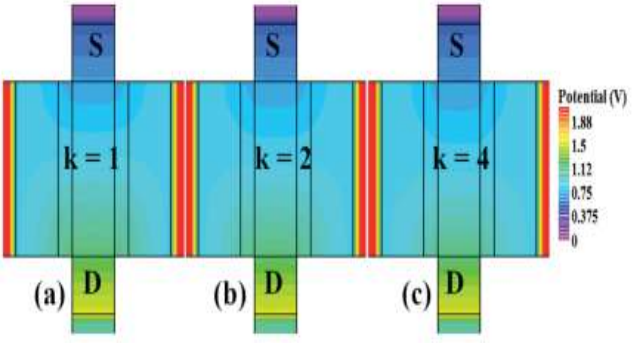


Figure 5: Potential contour for neutral bio-molecule with (a) k=1 (air) in the cavity, (b) k=2 in the cavity, and (c) k ¼ 4 in the cavity at VGS=2 V and VDS=1 V [47]

The results of the paper can be summarized in Table 3.
The mechanism of GAA-JLFET biosensor for SARS-CoV-2 works on the principle of trapping and immobilizing the virus in the etched nono-cavity embedded below the gate electrode. The study shows very high sensitivity towards DNA charge density. The TCAD investigation pledges for the potentials of this structure for the array-based screening and in vivo bio-species diagnostics.[47]

V. JAM-CSG FET Biosensor

When compared to inversion mode MOSFETs, JLT has lower transconductance and lower drain current [65] due to carrier mobility deterioration brought on by high doping concentration in the channel area. When the channel is completely exhausted, the primary conduction mechanism in a JLT, which depends on bulk conduction rather than surface conduction, shuts down [66]. Due to the depletion caused by the difference in the work function between the gate and the channel area, the JLT's effective gate length is longer than its physical length [66]. To address the JLT issue, a modified version of the junctionless MOSFET known as the Junctionless Accumulation Mode Cylindrical Surrounding Gate (JAM-CSG) MOSFET has also been developed. It is a single-doping-type structure with n+ –n–n+ homojunction [67-68] and the concentration of the channel region is low in comparison to the Source/Drain region. To enhance conductivity and prevent excessive parasitic access resistance, the JAM-CSG MOSFET employs greater doping in the source/drain regions [69].

A. Structure:

Figure 6 shows a cross-sectional view of the JAM-CSG MOSFET. Figure 7 shows the 3D view of JAM-CSG MOSFET in which the z-axis and r-axis are parallel and perpendicular to the channel direction respectively. The device parameters used for the analytical model and numerical simulation are: channel doping concentration (Nd= 1018 cm3), source/drain doping concentration (Nd + = 1019 cm3), gate oxide material (SiO2, k = 3.9), gate oxide thickness (tox = 2 nm and 3 nm), silicon pillar thickness (16 nm and 20 nm) and gate metal work function (φm = 5 eV). The simulation has been carried out using ATLAS-3D device simulator by activating doping dependence SRH recombination/thermal generation model, FLDMOB model for high electric field velocity saturation, CONMOB model for concentration-dependent mobility, BTBT model for band-to-band tunneling and Boltzmann carrier statistics for electron and holes. Newton–Gummel method has been adopted for numerical solution [70].

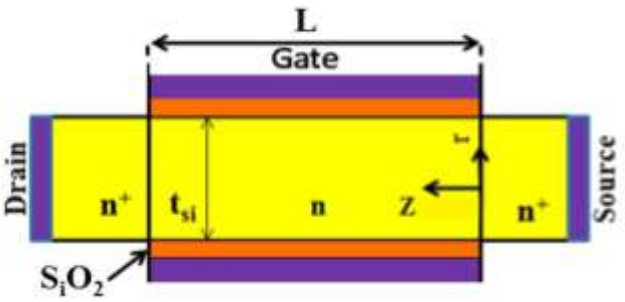


Figure 6: displays the cross-sectional view of the JAM-CSG MOSFET [71]

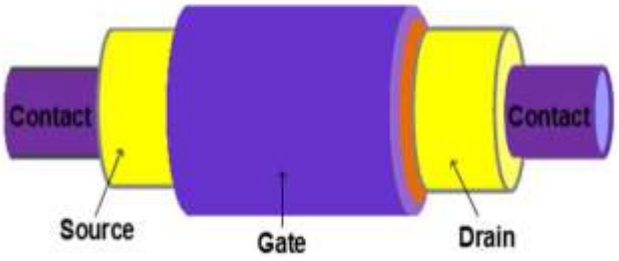


Figure 7: displays the 3D view of JAM-CSG MOSFET in which the z-axis and r-axis are parallel and perpendicular to channel direction respectively [71]

B. Working Principle:

The Junctionless Accumulated Mode - Cylindrical Surface Gate (JAM-CSG) Field-Effect Transistor (FET) is an advanced biosensor that can identify the presence and concentration of a wide range of biomolecules by utilising its intrinsic electrical characteristics.A biomolecule attaches itself to the nanowire's surface when it interacts with the nanogap cavity, subtly changing the channel's electrical characteristics. The redistribution of charges inside the nanowire is triggered by this change in electrical characteristics. The biomolecule-nanowire interaction causes a change in the threshold voltage (Vth), which is the lowest voltage needed to turn on the FET. It is possible to precisely determine the presence and concentration of the biomolecule by closely observing the change in Vth. A larger Vth shift translates to a higher concentration of biomolecules present. JAM-CSG FETs provide a simpler and faster way to detect molecules than traditional approaches by doing away with the requirement for pre-labeling.The JAM-CSG FETs have remarkable sensitivity, enabling the detection of minute variations in biomolecule concentration, owing to the high surface area-to-volume ratio of the nanowire. To determine the sensitivity of the device (ΔVth) toward the existence of biomolecules (both neutral and charged) in the cavity region, mathematical expressions [72] used are:
i. when neutral biomolecules are present [73]:

$$\Delta V_{th} = V_{th}(\kappa = 1) - V_{th}(\kappa > 1),$$

ii. when charged biomolecules are present [74]:

$$\Delta V_{th} = V_{th}(neutral\ biomolecule) - V_{th}(charged\ biomolecule)$$

C. Applications:

The unique properties of the Junctionless Accumulation Mode - Cylindrical Surface Gate (JAM-CSG) FET make it very promising for use in a variety of industries. A prominent use case for JAM-CSG FETs is in wearable biosensors, which may continually measure vital biomolecules like as glucose, lactate, and electrolytes in physiological fluids such as tears, saliva, or sweat. This innovation allows for real time health tracking and remote patient monitoring which has significant ramifications for personalised healthcare by identifying certain biomarkers JAM-CSG FETs provide a revolutionary tool for illness diagnostics making it easier to diagnose diseases including diabetes heart disease and cancer.[75-76]

Table 3 GAA-JLFET sensor parameters variation with dielectric modulation and charge modulation[47]

Parameter	Dielectric Modulation			Charge Modulation						
	Air	k=2	k=4	-1 × 10^{12}	-5 × 10^{11}	-1 × 10^{11}	0	1×10^{11}	5 × 10^{11}	1 × 10^{12}
$V_{th}(V)$	1.2535	1.3919	1.9701	3.1835	2.2574	1.4562	1.2535	1.04988	0.22648	− 0.81903
I_{On} (A)	9.9496 × 10^{-5}	1.08027 × 10^{-4}	1.17048 × 10^{-1}	1.35358 × 10^{-5}	6.39758 × 10^{-5}	9.394 × 10^{-5}	9.9496 × 10^{-5}	1.04461 × 10^{-4}	1.19824 × 10^{-4}	1.32565 × 10^{-4}
$\frac{I_{On}}{I_{Off}}$	3.67972 × 10^{15}	3.95461 × 10^{15}	4.27363 × 10^{15}	8.49015 × 10^{15}	2.02474 × 10^{15}	2.8792 × 10^{15}	3.67972 × 10^{15}	9.1356 × 10^{15}	4.7168 × 10^{15}	2.46308 × 10^{15}
g_m ($\frac{A}{V}$)	5.51979 × 10^{-5}	6.62049 × 10^{-5}	7.85259 × 10^{-5}	4.2777 × 10^{-5}	5.25296 × 10^{-5}	5.5072 × 10^{-5}	5.51979 × 10^{-5}	5.5294 × 10^{-5}	5.51121 × 10^{-5}	5.35667 × 10^{-5}
SS_{avg} ($\frac{mV}{dec}$)	97.16	83.333	76.666	90	93.33	95.66	97.166	98.333	111.666	130

Through testing on individual cells or tissues, JAM-CSG FETs are essential in the field of drug screening for discovering effective medications for certain disorders. By customizing techniques based on individual genetic composition, their high sensitivity and label-free detection capabilities put them at the forefront of personalized medicine and have the potential to revolutionize medical diagnosis and treatment.

The JAM-CSG FET addresses important issues in food safety in addition to healthcare. Its ability to quickly detect foodborne pathogens is critical to guaranteeing food safety and quality. By identifying dangerous microorganisms like Salmonella and E. Coli, this technology helps to avoid foodborne illnesses. Furthermore, as the references indicate, JAM-CSG FETs are able to detect adulterants like melamine in milk, hence enhancing public safety and reducing the dangers connected with hazardous substances. This adaptable application highlights how JAM-CSG FETs may improve food safety by enabling prompt and accurate risk detection, resulting in a safer and healthier food supply.

VI. Schottky Contact FET Biosensor

Schottky contact FET(Field Effect Transistor) is one of the nanowire FETs that are under active and intensive investigation. It can be an alternative to traditionally doped source drains and structures. This is because of its several advantages like straightforward low-temperature processing, good suppression of short channel effects, and the elimination of doping and subsequent activation steps [77].

A. Structure:

A nanowire FET with Schottky contact comprises a silicon Nanowire Channel which is its central element and acts as the conducting channel. This is heavily doped to enhance conducting properties. A high surface-to-volume ratio is achieved due to the one-dimensional nature of the cell which in turn helps in increasing sensitivity. There is a metal contact at both ends which creates a Schottky barrier when in contact with the semiconductor. The barrier helps in increasing speed and reducing power consumption. We have a high-quality, thin gate dielectric layer, such as silicon dioxide (SiO2) or high-k dielectrics like hafnium oxide (HfO2), that surrounds the nanowire and insulates the channel from the gate electrode. The nanowire and the dielectric layer is encircled by a gate

forming the 'gate-all-around' structure which gives us superior electrostatic control over the channel, and helps us to effectively modulate the Schottky barrier and channel conductance. Finally,the regions beyond the Schottky contacts are doped to form the source and drain regions, which helps in the injection and collection of carriers.

Table 4 Comparison between different FETs for biosensing applications

FET Type	Merits	Demerits	Sensitivity	LoD	SnR Ratio	Response Time	Selectivity
Conventional	Simple fabrication; Robust design; High surface-to-volume ratio for effective biosensing.	Limited electrostatic control compared to GAA structures; Possible short-channel effects in miniaturized devices.	High	Moderate	Moderate	Fast	High
JL (Junctionless)	Simplified fabrication due to uniform doping; Reduced scattering improves carrier mobility; Enhanced thermal stability.	Potential for increased off-state leakage current; Requires precise control in doping concentration.	Very High	Low	High	Very Fast	Moderate
JAM (Junctionless accumulated mode)	Enhanced control over sensing process; Improved selectivity; Capable of detecting low-concentration analytes.	Complex fabrication process; Requires precise tuning of the device parameters.	Highest	Very Low	Very High	Fast	Very High
Schottky	High sensitivity and fast response; Effective in detecting charged species and small molecules; Lower power consumption.	Schottky barrier height can be affected by surface states, impacting device stability.	High	Low	Moderate	Very Fast	High

B. Working Principle:

Voltage is applied to the gate electrode which modulates the height and width of the Schottky barrier at the metal-semiconductor interface. The majority carrier flow across the SilNW channel is affected by this modulation. By adjusting the Schottky barrier, the silicon nanowire's conductance can be controlled. Changes in surface charge, which are a sign of biomolecule binding events on the SilNW surface, have a significant impact on the conductance. Target biomolecules are captured by certain receptors on the SilNW surface. The surface potential changes when the biomolecules attach to the receptors. This in turn influences the nanowire's conductance and Schottky barrier. An output signal that correlates to the target biomolecule's concentration is obtained by measuring the change in conductance. The output provides quantitative data regarding the biomolecular interaction.

C. Applications:

GAA SilNW Schottky FET finds a lot of applications in the domain of biosensing. It can be used in the detection of biomolecules such as RNA, DNA, proteins, or enzymes. It interacts with the charge distribution in the biomolecule, leading to measurable changes in the transistor's electrical characteristics. One such specific application is the Biosensor based on a silicon nanowire field-effect transistor functionalized by gold nanoparticles for the highly sensitive determination of prostate-specific antigen [78]. Another application of it can be Protein

biosensor based on Schottky barrier nanowire field effect transistors [79].

To gain a clearer understanding of how Field-Effect Transistors (FETs) operate, we can examine the detection process of Biotin-BSA using a Silicon Nanowire (SiNW) FET. When a detectable molecule, such as Biotin-BSA, is deposited on a nanowire's surface, it essentially acts as a charged gate that is not physically connected. This deposition of Biotin-BSA induces a shift in the gate voltage characteristic towards a negative bias while maintaining the fundamental charge carrier transport mechanisms of the nanowire as in its original state. This shift towards the negative bias for n-doped SiNWs is attributable to the negative surface charge density, as it was demonstrated for n-doped SiNWs in Ref. [80]. In contrast, for p-doped SiNWs, the direction of the transfer characteristics shift depends on the charge of the detected molecule, either to the right or left. Given that streptavidin and Biotin-BSA possess negative charges, they act similarly to a floating upper gate. Since the protein's net charge in solutions with pH above its isoelectric point is negative, and considering BSA's isoelectric point is 5.85, the net charge in the utilized solution with $pH = 8.5$ remains negative. The functionalization of the SiNW surface with neutral APTES molecules results in a positive surface charge density due to the formation of coordinate covalent bonds. Additionally, when Biotin-BSA is detected, there's a marked reduction in the drain-source current: a decrease by two orders of magnitude at $-7\,V$ at the gate compared to a clean nanowire, and one order of magnitude compared to a streptavidin-activated nanowire surface at negative biases. This significant decrease is a useful feature for sensor implementation. The attachment of the protein to the nanowire surface imparts a negative charge, modulating the energy band bending by shifting the bands upward. This upward shift leads to a decrease in current in the inversion mode of the transistor since the conduction band edge at the Si/SiO2 interface is further elevated from the Fermi level, reducing the 2D electron gas concentration. Conversely, in the accumulation mode, the hole current increases as the valence band edge at the Si/SiO2 interface moves closer to the holes' Fermi level, resulting in an increase in the 2D hole gas concentration. Therefore, the overall impact of these mechanisms is a positive shift in the associated threshold voltage of the device.

VII. Comparison

Table 4 compares the various Silicon Nanowire Field-Effect Transistors (SilNW FETs) utilized in biosensing applications, including Schottky, Junctionless (JAM), Conventional, and Junctionless (JL) FETs. Each type of FET is evaluated using critical performance parameters that are significant in biosensing contexts, such as sensitivity, Limit of Detection (LOD), signal-to-noise ratio (SNR), response time, and selectivity. The table also provides a brief summary of the benefits and drawbacks of each of these FET types, making it easier to select the appropriate FET type for a particular set of biosensing applications.

VIII. Conclusion

In this article we have examined the significant advancements in the realm of biosensor technology, particularly focusing on the development and application of various innovative field-effect transistors (FETs) like GAA-JL-FETs, GAA-JAM-FETs, GAA-Schottky FETs, and conventional GAA FETs. These technologies have demonstrated superior performance in biosensing, marked by enhanced sensitivity, selectivity, low limits of detection, and rapid response times. By providing a comprehensive analysis of these advanced FETs and drawing comparisons between their sensing performances in various biosensing applications, this paper contributes significantly to the field. The detailed exploration of each FET type and their specific applications in biosensors not only adds to the existing body of knowledge but also opens new avenues for future research. The comparative analysis presented in this paper is aimed at guiding further studies and development, encouraging the creation of more efficient, sensitive, and selective biosensors. This, in turn, leverages the unique properties of these advanced FETs, promising significant strides in the field of biosensor technology and its practical applications.

Acknowledgment

The Authors are grateful to Mr. Sachin Dhariwal and the Electronics and Communications department at Delhi Technological University for providing us with the resources and knowledge for writing this review paper.

References

[1] Sreejith S, Ajayan J, Devasenapati SB, Sivasankari B, Tayal S (2023) Critical review on reliability and short circuit robustness of silicon carbide power MOSFETs. Silicon 15:623–637

[2] Fobelets K, Meghani M, Li C (2014) Infuence of minority carrier gas donors on low-frequency noise in silicon nanowires. IEEE Trans Nanotechnol 13:1176–1180

[3] Ivanov YD, Romanova TS, Malsagova KA, Pleshakova TO, Archakov AI (2021) Use of silicon nanowire sensors for early cancer diagnosis. Molecules 26:3734

[4] L. Risch, Pushing CMOS beyond the roadmap, Solid State Electron. 50 (no. 4) (April 2006) 527–535.

[5] B. Liu, C. Zhan, Y. Yang, R. Cheng, P. Guo, Q. Zhou, Y.J. Kong, N. Daval, C. Veytizou, D. Delprat, B.Y. Nguyen, Y.C. Yeo, Germanium multiple gate field-effect transistor with in situ boron doped raised source/drain, IEEE Trans. Electron Devices 60 (no.7) (July 2013) 2135–2141.

[6] C.H. Shih, J.T. Liang, J.S. Wang, D. Chien, A Source-Side Injection Lucky Electron Model for Schottky barrier Metal-Oxide-Semiconductor Devices, IEEE Electron Device Lett. 32 (no. 10) (October 2011) 1331–133

[7] X. Qian, Y. Yang,A. Zhu, S.L. Zang and D. Wu, “Evaluation of DC and AC performance of junctionless MOSFET in the presence of variability,” IEEE International Conference on IC Design and Technology (ICICDT), 2011.

[8] R.K. Baruah, R.P. Paily, A dual-Material gate Junctionless Transistor with high-k spacer for enhanced analog performance, IEEE Trans. Electron Devices 61 (no. 1) (January 2014) 123–128.

[9] J. Coling, C Lee, A. Afzalian, N. Akhavan, R Yan, I. Ferain, P. Razavi, B.O. Neill, A Blake, M. White, A.M. Kelleher, B.M. Carthy, R. Murphy, Nanowire transistor without junctions, Nat. Nanotechnol. 5 (no. 3) (March 2010) 225–229.

[10] R. Rios, A. Cappellani, M. Armstrong, A. Budrevich, H. Gomez, R. Pai, N.R. Orabi, K. Kuhn, Comparison of junctionless and

conventional trigate transistors with down to 26 nm, IEEE Electron Device Lett. 32 (no. 9) (September. 2011) 1170–1172

[11] C.J. Koeneke, S.M. Sze, R.M. Levin, E. Kinsbron, Schottky MOSFET for VLSI, Int. Electron Device Meet. (Dec. 1981) 367–371 (7-9).

[12] B.Y. Tusi, C.P. Lu, H.H. Liu, Method for extracting gate-voltage-dependent source injection resistance of modified Schottky Barrier (MSB) MOSFETs, IEEE Electron Device Lett. 29 (no. 9) (September 2008) 1053–1055.

[13] Capua L, Sprunger Y, Elettro H, Risch F, Grammoustianou A, Midahuen R, Ernst T, Barraud S, Gill R, Ionescu AM (2022) Label-free C-reactive protein Si nanowire FET sensor arrays with super-Nernstian Back-gate operation. IEEE Trans Electron Devices 69:2159–2165

[14] W. Y. Wang, H. D. Xiong, M. D. Edelstein, D. Gundlach, J. S. Suehle, C. A. Richter, W. K. Hong, and T. Lee, J. Appl. Phys. 101(4), 044313 (2007).

[15] Yen L-C, Pan T-M, Lee C-H, Chao T-S (2016) Label-free and real-time detection of ferritin using a horn-like polycrystallinesilicon nanowire feld-efect transistor biosensor. Sensors Actuators B 230:398–404

[16] Kim K, Park C, Kwon D, Kim D, Meyyappan M, Jeon S (2016) Jeong-Soo Lee, silicon nanowire biosensors for detection of cardiac troponin I (cTnI) with high sensitivity. Biosens Bioelectron 77:695–701

[17] Presnova G, Presnov D, Krupenin V, Grigorenko V, Trifonov A, Andreeva I, Ignatenko O, Egorov A, Rubtsova M (2017) Biosensor based on a silicon nanowire feld-efect transistor functionalized by gold nanoparticles for the highly sensitive determination of prostate specifc antigen. Biosens Bioelectron 88:283–289

[18] Zhou K, Zhao Z, Pan L, Wang Z (2019) Silicon nanowire pH sensors fabricated with CMOS compatible sidewall mask technology. Sensors Actuators: B Chem 279:111–121

[19] Zhao W, Hu J, Liu J, Li X, Sun S, Luan X, Zhao Y, Wei S, Li M, Zhang Q, Huang C (2022) Si nanowire bio-FET for electrical and label-free detection of cancer cell-derived exosomes. Microsystems Nanoengineer 8:57

[20] Lu Z, Liu T, Zhou X, Yang Y, Liu Y, Zhou H, Wei S, Zhai Z, Wu Y, Sun F, Wang Z, Li T, Hong J (2022) Rapid and quantitative detection of tear MMP-9 for dry eye patients using a novel silicon nanowire-based biosensor. Biosens Bioelectron 214:114498

[21] Vu C-A, Lai H-Y, Chang C-Y, Chan W-H, Chen W-Y (2022) Optimizing surface modifcation of silicon nanowire feldefect transistors by polyethylene glycol for MicroRNA detection. Colloids Surfaces B:Biointerfaces 209:112142

[22] Muratore KA, Zhou D, Du JJ, Chlystek JS, Motesadi K, Larsen EK, Molgora BM, Lee TC, Pamarti S, Erramilli S, Mohanty P (2023) Alanine aminotransferase assay biosensor platform using silicon nanowire feld efect transistors. Commun Eng 2:8

[23] Lehoucq G, Bondavalli P, Xavier S, Legagneux P, Abbyad P, Baroud CN, Pribat D (2012) Highly sensitive pH measurements using a transistor composed of a large array of parallel silicon nanowires. Sensors Actuators B 171–172:127–134

[24] Zhu K, Zhang Y, Li Z, Zhou F, Feng K, Dou H, Wang T (2015) Simultaneous detection of α-fetoprotein and Carcinoembryonic antigen based on Si nanowire feld-efect transistors. Sensors 15:19225–19236

[25] Gao A, Yang X, Tong J, Zhou L, Wang Y, Zhao J, Mao H, Li T (2017) Multiplexed detection of lung cancer biomarkers in patients serum with CMOS-compatible silicon nanowire arrays. Biosens Bioelectron 91:482–488

[26] Chen H-C, Chen Y-T, Tsai R-Y, Chen M-C, Chen S-L, Xiao M-C, Chen C-L, Hua M-Y (2015) A sensitive and selective magnetic graphene composite-modifed polycrystalline-silicon nanowire feld-efect transistor for bladder cancer diagnosis. Biosens Bioelectron 66:198–207

[27] Yang C-Y, Chiang H-C, Kuo C-J, Hsu C-W, Chan S-F, Lin Z-Y, Lin C-H, Chen Y-T (2018) Hepatocellular carcinoma diagnosis by detecting α-Fucosidase with a silicon nanowire feld-efect transistor biosensor. ECS J Solid State Sci Technol 7:Q3153–Q3158

[28] Tran DP, Wolfrum B, Stockmann R, Pai J-H, PourhassanMoghaddam M, Ofenhäusser A, Thierry B (2015) CMOS compatible silicon nanowires on-a-Chip: fabrication and pre-clinical validation for the detection of a cancer prognostic protein marker in serum. Anal Chem 87:1662–1668

[29] Zida SI, Chu-Chun Yang YL, Khung Y-DL (2020) Fabrication and characterization of an Aptamer-based N-type silicon nanowire FET biosensor for VEGF detection. J Med Biol Eng 40:601–609

[30] Puppo F, Doucey M-A, Delaloye J-F, Moh TSY, Pandraud G, Sarro PM, De Micheli G, Carrara S (2016) SiNW-FET in-air biosensors for high sensitive and specifc detection in breast tumor extract. IEEE Sensors J 16:3374–3381

[31] Gao A, Lu N, Wang Y, Dai P, Li T, Gao X, Wang Y, Fan C (2012) Enhanced sensing of nucleic acids with silicon nanowire feld efect transistor biosensors. Nano Lett 12:5262–5268

[32] M.K. Husain, X.V. Li, C.H. d. Groot, High-quality Schottky contact for limiting leakage currents in Ge-Based Schottky Barrier MOSFETs, IEEE Trans. Electron Devices 56 (no. 3) (March 2009) 499–504.

[33] A. Tarasov, W. Fu, O. Knopfmacher, J. Brunner, M. Calame, and C. Schonenberger, Appl. Phys. Lett. 98(1), 012114 (2011).

[34] P. R. Nair and M. A. Alam, IEEE Trans. Electron Devices 54(12), 3400–3408 (2007).

[35] M. H. Sorensen, N. A. Mortensen, and M. Brandbyge, Appl. Phys. Lett. 91(10), 102105 (2007).

[36] Pratap Y, Kumar M, Kabra S, Haldar S, Gupta RS, Gupta M (2018) Analytical modeling of gate-all-around junctionless transistor based biosensors for detection of neutral biomolecule species. J Comput Electron 17(1):288–296

[37] Manimekala, T., Sivasubramanian, R. and Dharmalingam, G., 2022. Nanomaterial-based biosensors using Field-Effect Transistors: A review. Journal of Electronic Materials, 51(5), pp.1950-1973.

[38] Wadhera, T., Kakkar, D., Wadhwa, G. and Raj, B., 2019. Recent advances and progress in development of the field effect transistor biosensor: A review. Journal of Electronic Materials, 48, pp.7635-7646.

[39] M. M. N. Nuzaihan et al., "Electrical detection of dengue virus (DENV) DNA oligomer using silicon nanowire biosensor with novel molecular gate control," Biosens. Bioelectron., vol. 83, pp. 106–114, 2016, doi: 10.1016/j.bios.2016.04.033.

[40] Justino, C.I., Rocha-Santos, T.A. and Duarte, A.C., 2010. Review of analytical figures of merit of sensors and biosensors in clinical applications. TrAC Trends in Analytical Chemistry, 29(10), pp.1172-1183.

[41] Yadav, S. and Rewari, S., 2022, November. Trench Gate JAM Dielectric Modulated Nanowire FET (TG-JAM-DM-NWFET) Biosensor. In 2022 IEEE International Conference of Electron Devices Society Kolkata Chapter (EDKCON) (pp. 23-28). IEEE.

[42] Das, A., Rewari, S., Kanaujia, B.K. and Gupta, R.S., 2022. Recent technological advancement in surrounding gate MOSFET for biosensing applications-a synoptic study. Silicon, 14(10), pp.5133-5143.

[43] I. Heller, J. Mannik, S. G. Lemay, and C. Dekker, Nano Lett. 9(1), 377–382 (2009).

[44] N. K. Rajan, D. A. Routenberg, and M. A. Reed, Appl. Phys. Lett. 98(26), 264107 (2011).

[45] R. Jayaraman and C. G. Sodini, IEEE Trans. Electron Devices 36(9), 1773–1782 (1989).

[46] S. T. Hsu, Solid-State Electron. 13(11), 1451 (1970).

[47] Sreejith, S., Ajayan, J., Uma Reddy, N.V. and Manikandan, M., 2023. Recent Advances and Prospects in Silicon Nanowire Sensors: A Critical Review. *Silicon*, pp.1-27.

[48] Priyadarshani, K.N., Singh, S. and Mohammed, M.K., 2022. Gate-all-around junctionless FET based label-free dielectric/charge modulation detection of SARS-CoV-2 virus. RSC advances, 12(15), pp.9202-9209.

[49] Sharma, M.; Gupta, M.; Narang, R.; Saxena, M. Investigation of Gate All Around Junctionless Nanowire Transistor with Arbitrary Polygonal Cross Section. In Proceedings of the 2018 4th International Conference on Devices, Circuits and Systems (ICDCS), Coimbatore, India, 16–17 March 2018; pp. 159–163.

[50] Lime, F.; Ávila-Herrera, F.; Cerdeira, A.; Iñiguez, B. A compact explicit DC model for short channel Gate-All-Around junctionless MOSFETs. Solid State Electron. 2017, 131, 24–29.

[51] Arefín, U.A. Impact of Temperature on Threshold Voltage of Gate-All-Around Junctionless Nanowire Field-Effect Transistor. ULAB J. Sci. Eng. 2015, 6, 14–18.

[52] Moon, D.I.; Choi, S.J.; Duarte, J.P.; Choi, Y.K. Investigation of silicon nanowire gate-all-around junctionless transistors built on a bulk substrate. IEEE Trans. Electron. Devices 2013, 60, 1355–1360.

[53] Priyadarshani, K.N., Singh, S. and Mohammed, M.K., 2022. Gate-all-around junctionless FET based label-free dielectric/charge modulation detection of SARS-CoV-2 virus. RSC advances, 12(15), pp.9202-9209.

[54] Lime, F.; Ávila-Herrera, F.; Cerdeira, A.; Iñiguez, B. A compact explicit DC model for short channel Gate-All-Around junctionless MOSFETs. Solid State Electron. 2017, 131, 24–29.

[55] Moon, D.I.; Choi, S.J.; Duarte, J.P.; Choi, Y.K. Investigation of silicon nanowire gate-all-around junctionless transistors built on a bulk substrate. IEEE Trans. Electron. Devices 2013, 60, 1355–1360.

[56] Sharma, S. An Extensive Evaluation of Futuristic Gate All Around Junctionless Nanowire MOSFET Using Numerical Simulation. Int. J. Res. Appl. Sci. Eng. Technol. 2017, V, 1974–1979.

[57] Han, M.H.; Chang, C.Y.; Jhan, Y.R.; Wu, J.J.; Chen, H.B.; Cheng, Y.C.; Wu, Y.C. Characteristic of p-type junctionless gate-all-around nanowire transistor and sensitivity analysis. IEEE Electron. Device Lett. 2013, 34, 157–159.

[58] Singh, P.; Singh, N.; Miao, J.; Park, W.T.; Kwong, D.L. Gate-all-around junctionless nanowire MOSFET with improved low-frequency noise behavior. IEEE Electron. Device Lett. 2011, 32, 1752–1754.

[59] Ferhati, H.; Djeffal, F.; Bentrcia, T. Investigation of analog/RF performance of gate-all-around junctionless MOSFET including interfacial defects. In Proceedings of the 2015 4th International Conference on Electrical Engineering (ICEE), Boumerdes, Algeria, 13–15 December 2015; pp. 1–4.

[60] Djeffal, F.; Ferhati, H.; Bentrcia, T. Improved analog and RF performances of gate-all-around junctionless MOSFET with drain and source extensions. Superlattices Microstruct. 2016, 90, 132–140.

[61] Nobrega, R.; Fonseca, Y.; A Costa, R.; Duarte, U. Comparative Study on the Performance of Silicon and III-V Nanowire Gate-All-Around Field-Effect Transistors for Different Gate Oxides. In Proceedings of the XIII Workshop on Semiconductors and Micro & Nano Technology, São Bernardo do Campo, Brazil, 19–20 April 2018.

[62] Pratap, Y.; Gautam, R.; Haldar, S.; Gupta, R.; Gupta, M. Physics-based drain current modeling of gate-all-around junctionless nanowire twin-gate transistor (JN-TGT) for digital applications. J. Comput. Electron. 2016, 15, 492–501.

[63] Liu, T.Y.; Pan, F.M.; Sheu, J.T. Characteristics of gate-all-around junctionless polysilicon nanowire transistors with twin 20-nm gates. IEEE J. Electron. Devices Soc. 2015, 3, 405–409.

[64] Kumar, P.; Singh, S.; Singh, N.P.; Modi, B.; Gupta, N. Germanium v/s silicon Gate-all-around junctionless nanowire transistor. In Proceedings of the 2014 2nd International Conference on Devices, Circuits and Systems (ICDCS), Combiatore, India, 6–8 March 2014; pp. 1–5.

[65] Nowbahari, A., Roy, A. and Marchetti, L., 2020. Junctionless transistors: State-of-the-art. Electronics, 9(7), p.1174.

[66] Cho S et al. A RF performance and small-signal parameter extraction of junctionless silicon nanowire MOSFETs. IEEE Trans Electron Devices 2011; 58(5):1388–1396.

[67] Colinge JP et al. Junctionless nanowire transistors (JNT): properties and design guidelines. Solid State Electron 2011; 55(3):33–37

[68] Zeghbroeck BV. Principal of semiconductor device, 2011, online

[69] Hun Choi J, Kyun T, Min Moon J, Gwang Yoon Y, Woon Hwang B, Hyunkim D, Lee S-H. Origin of device performance enhancement of junctionless accumulation-mode (JAM) bulk FinFETs with High-k Gate Spacers. IEEE Electron Devices, Letters 2014; 35(12):1182–1184.

[70] Holtij T, Graef M, Marie Hain F, Kloes A, Iniguez B. Compact model for short channel junctionless accumulation mode double gate MOSFETs. IEEE Trans Electron Devices 2014; 61(2):288–299.

[71] SILVACO Int. Santa Clara, CA, ATLAS 3D DEVICE Simulator, 2012.

[72] Trivedi, N., Kumar, M., Haldar, S., Deswal, S.S., Gupta, M. and Gupta, R.S., 2016. Analytical modeling of Junctionless Accumulation Mode Cylindrical Surrounding Gate MOSFET (JAM‐CSG). International Journal of Numerical Modelling: Electronic Networks, Devices and Fields, 29(6), pp.1036-1043.

[73] Narang R, Saxena M, Gupta M. Investigation of dielectric modulated (DM) double gate (DG) junctionless MOSFETs for application as a biosensors. Superlattices Microstruct. 2015;85:557-572.

[74] Im H, Huang X-J, Bonsang G, Choi Y-K. A dielectric-modulated field-effect transistor for biosensing. Nat Nanotechnol. 2007;2(7): 430-434.

[75] Kim J-Y, Ahn J-H, Choi S-J, et al. An underlap channel-embedded field-effect transistor for biosensor application in watery and dry environment. IEEE Trans Nanotechnol. 2011;11(2):390-394.

[76] M. Ali et al., "Label-free detection of Salmonella typhimurium using junctionless accumulation-mode cylindrical surrounding-gate field-effect transistor biosensor," Journal of Food Science and Technology, vol. 57, no. 1, pp. 123-130, 2020.

[77] Y. Li et al., "A label-free platform for exosome detection based on dual-metal gate engineered junctionless accumulation-mode cylindrical surrounding gate field-effect transistor," Biosensors and Bioelectronics, vol. 165, 2020.

[78] S.M. Koo, M.D. Edelstein, Q. Li, C.A. Richter, E.M. Vogel, Silicon nanowires as enhancement-mode Schottky barrier field-effect transistors, Nanotechnology 16 (2005)

[79] Presnova, G., Presnov, D., Krupenin, V., Grigorenko, V., Trifonov, A., Andreeva, I., Ignatenko, O., Egorov, A. and Rubtsova, M., 2017. Biosensor based on a silicon nanowire field-effect transistor functionalized by gold nanoparticles for the highly sensitive determination of prostate specific antigen. *Biosensors and Bioelectronics*, *88*, pp.283-289.

[80] Smolyarova, T.E., Shanidze, L.V., Lukyanenko, A.V., Baron, F.A., Krasitskaya, V.V., Kichkailo, A.S., Tarasov, A.S. and Volkov, N., 2022. Protein biosensor based on Schottky barrier nanowire field effect transistor. *Talanta*, *239*, p.123092.