

Innovative FETs in Biosensing Applications: A Review

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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, SiNW*

I. Introduction

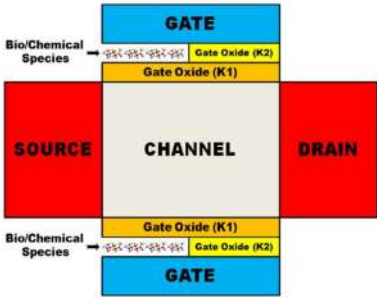
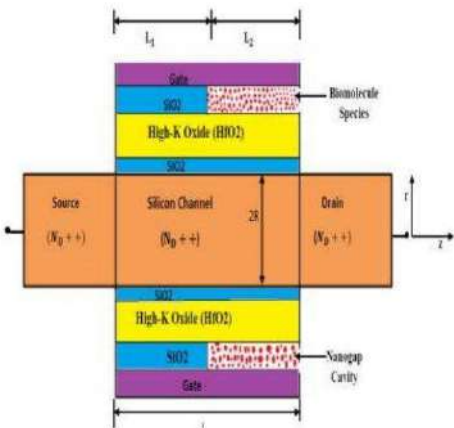
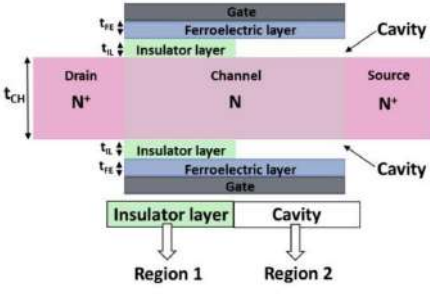
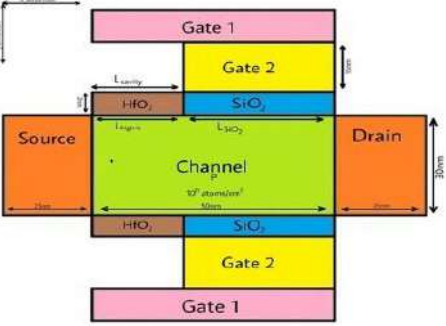
Electronic sensing applications have benefited greatly from the use of nanowires, which are increasingly recognized for their ability to improve sensor technology's versatility and downsizing. Silicon nanowires (SiNW) stand out as a prime nanostructure for sensory applications, attributed to their one-dimensional, quasi-electronic structure and significant surface-volume ratio. A key advantage of SiNW is its seamless integration with conventional silicon (Si) technology, allowing for the easy incorporation of additional circuitry on the same chip [1]. Typically, SiNW sensors are based on Field-Effect Transistor (FET) technology and include gate, drain, and source electrodes. The functionality of a SiNW biosensor hinges on the changes in current through the SiNW channel, which occurs in response to variations in surface charges due to the binding of biomolecules. FET-based SiNW 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 SiNW 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 SiNWs 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 SiNW FET biosensors [13]

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

The Gate-All-Around Silicon Nanowire Junctionless Field-Effect Transistor (GAA SiNW 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. SiNW 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 SiNW 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 SiNW 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].

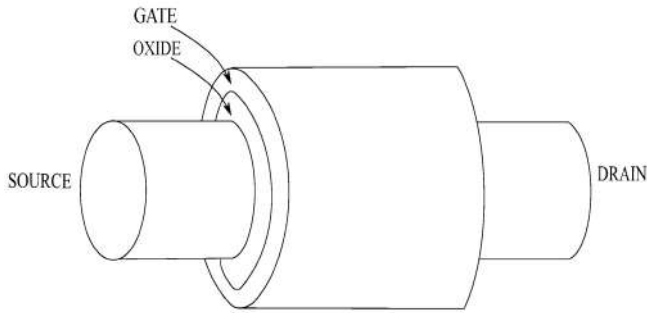


Figure 1: Three-dimensional (3D) structure of a cylindrical junctionless GAAFET.[51]

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].

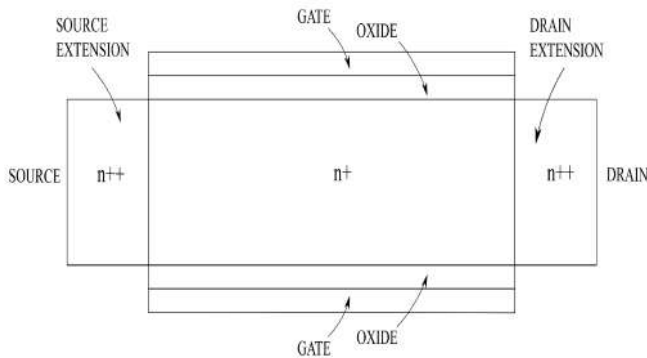


Figure 2: Cross-sectional view of improved cylindrical GAAFET through addition of source and drain extensions.[51]

Compared to inversion mode devices, junctionless GAAFETs typically show a higher I_{on}/I_{off} 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 (SiO_2) 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 I_{on}/I_{off} 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].

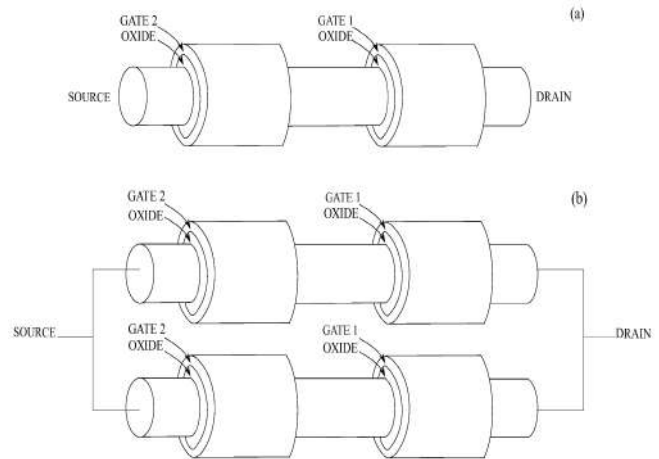


Figure 3: 3D Structure of (a) twin gate single channel GAAFET, (b) twin gate double channel GAAFET.[51]

B. Working Principle:

The Gate-All-Around Silicon Nanowire Junctionless Field-Effect Transistor (GAA SiNW 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

The structure of the device used is Figure 4.

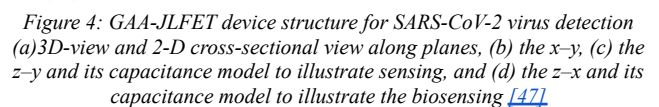


Figure 5: Potential contour for neutral bio-molecule with (a) $k=1$ (air) in the cavity; (b) $k=2$ in the cavity, and (c) $k = 1/4$ in the cavity at $V_{GS}=2$ V and $V_{DS}=1$ V [47]

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 nano-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 ($N_d = 10^{18} \text{ cm}^{-3}$), source/drain doping concentration ($N_d = 10^{19} \text{ cm}^{-3}$), gate oxide material (SiO_2 , $k = 3.9$), gate oxide thickness ($t_{ox} = 2 \text{ nm}$ and 3 nm), silicon pillar thickness (16 nm and 20 nm) and gate metal work function ($\phi_m = 5 \text{ eV}$). 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].

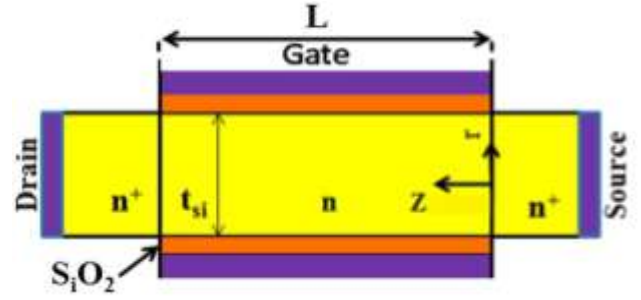


Figure 6: displays the cross-sectional view of the JAM-CSG MOSFET [71]

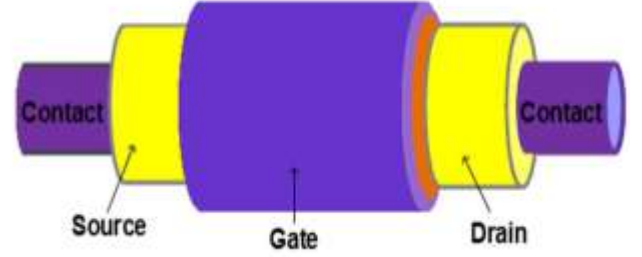


Figure 7: displays the 3D view of JAM-CSG MOSFET in which the z-axis and r-axis are parallel and perpendicular to channel direction respectively [71]

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 (V_{th}), 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 V_{th} . A larger V_{th} 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 (ΔV_{th}) 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]:

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

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)	9.949×10^{-5}	1.080×10^{-4}	1.1704×10^{-1}	1.3535×10^{-5}	6.3975×10^{-5}	9.394×10^{-5}	9.9496×10^{-5}	1.04461×10^{-4}	1.19824×10^{-4}	1.32565×10^{-4}
$\frac{I_{on}}{I_{off}}$	3.679×10^{15}	3.954×10^{15}	4.2736×10^{15}	8.4901×10^{15}	2.0247×10^{15}	2.8792×10^{15}	3.6797×10^{15}	9.1356×10^{15}	4.7168×10^{15}	2.46308×10^{15}
g_m ($\frac{A}{V}$)	5.519×10^{-5}	6.620×10^{-5}	7.8525×10^{-5}	4.2777×10^{-5}	5.2529×10^{-5}	5.5072×10^{-5}	5.5197×10^{-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 SiNW 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 SiNW surface, have a significant impact on the conductance. Target biomolecules are captured by certain receptors on the SiNW 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 SiNW 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 (SiNW 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.

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