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# High-k Dielectric Enhanced Gate-All-Around Junctionless SiNWFETs for Advanced Biomedical Sensing Applications

**Debasis Mukherjee**

Department of Electronics and Communication Engineering

Brainware University

Barasat, Kolkata, West Bengal 700125, India

debasismukherjee1@gmail.com

Orcid id: 0000-0003-3958-7251

**Subhadip Goswami**

Department of Electrical Engineering

NIT Arunachal Pradesh

Jote, Papum Pare, Arunachal Pradesh 791113, India

wondersubhadip@live.com

*** Tapas Das**

Department of Electronics and Communication Engineering

Brainware University

Barasat, Kolkata, West Bengal 700125, India

tapash825798tapash@gmail.com

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**Abstract:**

Metal oxide semiconductor field effect transistor (MOSFET) based biosensors are widely used due to their cost effectiveness and beneficial properties. This research introduces an all-side gate FET with an increased k value. It has no junction and is constituted of a nanowire of Si. It is used for detection of biomolecules and improving the action of the transistor by incorporating a stack of gate and increased work function. The neutral biomolecules considered in this study are Streptavidin, Uricase, APTES, Protein and ChOx. Various important parameters including DIBL, slope of subthreshold, leakage current, $V_{TH}$ and transconductance shifts are examined. Furthermore, the influence of crater, like its width, k value and device recognition are investigated. The findings suggest that the GS GAA SiNWFET displays enactment like ION/IOFF ratio and subthreshold slope. Hafnium Oxide (HfO2) is recognized for its compatibility and thermal stability in MOSFETs. In summary, the proposed device is capable to perform sensing of biological substances in a better and effective way.

**Keywords**: Sensing of Bio-substances, VLSI, Semiconductor, Electronics, Transistor

## 1. INTRODUCTION

The semiconductor manufacturing has evolved greatly over the years, and MOSFETs (Hu, 2009; Liu et al., 1993; Semenov et al., 2003) are essential in integrated circuits (ICs). Mechanical tunneling is a major challenge due to the continual scaling of the transistor size according to Moore's law, and it appears that the short channel effects (SCEs), drain-induced barrier lowering and various other problems become significant as the channel length decreases. Junctionless MOSFETs (JLMOSFETs) provide one by maintaining the same doping profile in the source-channel-drain region, effectively removing costly doping profiles needed in conventional junction-based transistors (Mukherjee & Mandal, 2022).

Due to the superior gate controllability and CMOS extension, such as Cylinder-shaped All-sided gate region is the most promising devices (Roy et al., 2023). These new devices also feature dramatically improved electrostatic modulation capabilities, making it possible to use the technology in applications well-beyond traditional charge-based transduction, e.g., mass and bio-sensing (Mukherjee, Sarkar, et al., 2024) applications in clinical or remote

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environments (Mukherjee, Das, et al., 2024). Thinning gate oxide to below 2 nm makes this problem worse but has an impact equivalent to performance degradation due to mechanical tunneling and SCEs (Mukherjee, Sanda, et al., 2024). High-k dielectric material (Hafnium Oxide ($HfO_2$)) has better thermal stability and a higher energy bandgap in comparison with conventional silicon dioxide ($SiO_2$) which makes it an attractive solution to the aforementioned problems (Saxena & Kumar, 2012; Yan et al., 1992; Zebrev et al., 2014).

The integrated circuit (IC) industry has evolved enormously over decades (Mandal & Mukherjee, 2023). The advent of MOSFETs (Metal Oxide Semiconductor Field Effect Transistor) (Mukherjee & Reddy, 2019), an integral component in ICs (Integrated Circuit) that enabled more transistors on a chip while sacrificing the actual size of the transistor, was extremely important for the idea that transistors can simply be placed on a chip. This evolution has led to some creative MOSFETs (Mukherjee & Reddy, 2020a).

Transistor dimensions have reduced rapidly as per the Church's law, and this has spawned new classes of device degradation, as nano dimension difficulties have become dominant with diminishing channel lengths near to the electron wavelength (Mukherjee & Reddy, 2020b).

To mitigate the complexities of doping profiles, the Junctionless MOSFET (JLMOSFET) (Mukherjee & Reddy, 2018a) was developed. This design eliminates the need for pn-junctions, which is particularly advantageous for devices with extremely short channel lengths, unlike traditional inversion mode (IM) transistors, JLMOSFETs have overcome these difficulties.

Other geometrical modifications were tested and independently verified along with the JLMOSFET (Mukherjee & Reddy, 2018b). Junctionless multi-gate devices are of considerable interest to the scientific community due to their potential benefits such as improved scalability, superior gate control, low fabrication cost, and mitigated SCEs (Mukherjee & Reddy, 2016). They help to us to control the channel region to a larger extent.

Among them, Cylinder Gate-All-Around Transistor (CGAA) is especially remarkable since this structure possesses excellent electrostatic control and transport properties. In this way, the metal gate completely surrounds the silicon channel and thus suppresses SCEs. It has favorable gate control and is CMOS-technology compatible.

Plus, junctionless gate-all-around transistors are on the rise in detecting biomolecular species in remote clinical and rural fields, and military scenarios where miniaturization of devices might not be applicable . These devices are implemented in order to eliminate the SCE, hot-electron effects and threshold voltage roll-off (Cesewski & Johnson, 2020; Wadhwa et al., 2019).

However, among the many critical issues concerning MOSFET performance, the reduction in gate dielectric oxide thickness to less than 2 nm has been identified as a particular challenge that significantly deteriorates the mechanical tunneling and short-channel effects, thereby weakening functionality of the device as a whole . This results in direct tunneling and therefore to high leakage currents in silicon-based MOS devices. These problems have been addressed by the integration of high-k dielectric materials like Hafnium oxide (HfO2). On the other hand, HfO2 has a better thermal stability and a larger energy gap (5.8 eV at room temperature) than silicon dioxide (1.1 eV), leading to SCEs reduction and better electrical isolation. The gate oxide in MOS device modeling now tends to be HfO2, with better gate control than SiO2 (Kulkarni et al., 2022; Ramesh et al., 2023).

Here, we introduce a new concept for an n-type junctionless double-gate stack GAA SiNW biosensor transistor. In this design, HfO2 cap on top of silicon dioxide and high work function metal gate. For the first time, the analysis of the effect of the dielectric constant variation of the biomolecules on the neutral on the transfer characteristics of the proposed device, including ION/IOFF ratio, has been arranged in an objective to identify.

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## 2. DEVICE STRUCTURE AND SIMULATIONS

The proposed GS-GAA junctionless SiNWFET structure is simulated using the ATLAS-3D (Software, 2014) device simulator tool. The device features a 20 nm channel length and a 10 nm diameter silicon nanowire channel, enveloped by a 0.3 nm SiO2 and 1.5 nm HfO2 gate oxide stack. 4.8 eV is employed to achieve the desired threshold voltage, reducing DIBL. Simulations consider the effects of these constants on the device's electrical characteristics, including ION/IOFF ratio.

In present experiment, we computer-generated the presence of neutral biomolecules by incorporating their dielectric constants into the cavity region. These biomolecules include choline oxidase ($\varepsilon = 3.3$), protein ($\varepsilon = 2.5$), uricase ($\varepsilon = 1.54$), streptavidin ($\varepsilon = 2.1$), and APTES ($\varepsilon = 3.57$).

The studys simulations utilized Fermi Dirac statistics to accurately depict carrier behavior. To explore the impact of doping on mobility they applied the concentration mobility (CONMOB) model showcasing changes resulting from high channel doping. This was further bolstered by the band gap narrowing (BGN) model, which addresses the effects of doping on the bandgap. The semiconductor model considered both drift and diffusion processes while excluding impact ionization.

For scenarios, with carrier concentrations they examined how carrier interactions impacted the simulations. Furthermore they incorporated the CVT mobility model to address variations in mobility caused by parallel fields within the device.

This comprehensive simulation method offered an analysis of the characteristics and performance of the GS GAAJLT structure particularly concerning the incorporation of high k dielectric materials and diverse biomolecules. By optimizing these parameters the device could achieve heightened sensitivity and stability showcasing potential for applications, in biosensing and biomedical fields.

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## 3. WIDTH OF OXIDE

The width of oxide can be calculated by using the equation; $T_{SiO2} = T_{high\ k} \times (\epsilon_{SiO2} / \epsilon_{high\ k})$. Here TSiO2 represents the thickness of silicon dioxide Thigh k is the thickness of the high k material ϵSiO2 is the constant of silicon dioxide and ϵhigh k is the dielectric constant of the high k material.

In our research we utilized a silicon nanowire measuring 20 nm in length and 10 nm in diameter surrounded by a dual layer gate oxide setup. This configuration consists of a 0.3 $SiO_2$ layer, with a dielectric constant of 3.9 and a 1.5 nm thick $HfO_2$ layer, with a dielectric constant of 20. The source, drain and channel sections are evenly infused with n type material at a level of 1019 cm−3.

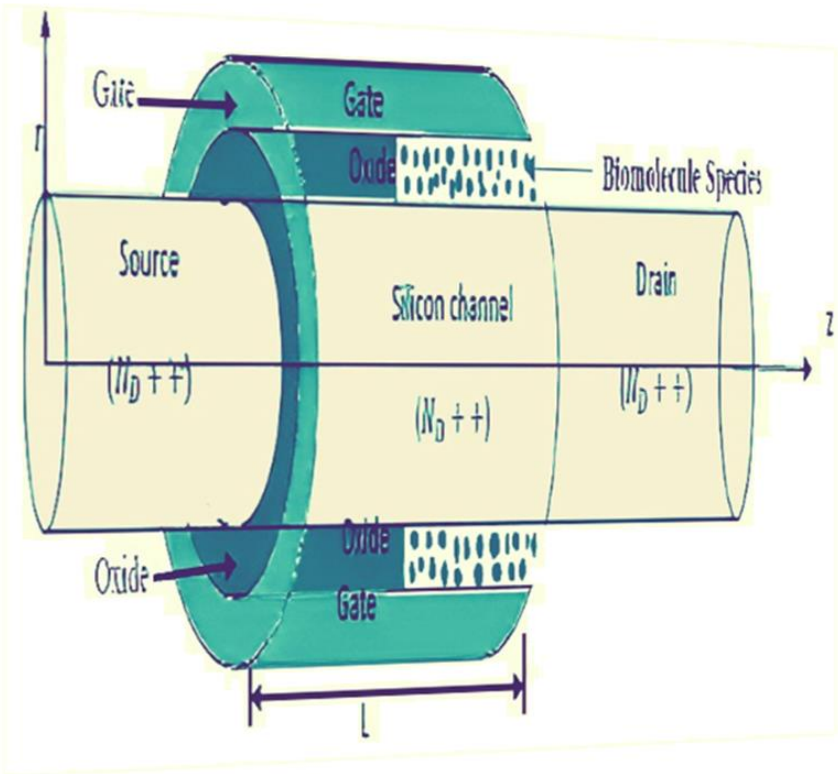
We have chosen a work function of 4.8 eV to achieve the desired threshold voltage and reduce drain induced barrier lowering (DIBL) effects and parasitic gate resistance. Gold (Au) known for its resistivity of 2.44 μΩ cm at 20°C was selected as the gate electrode material aiming to address critical challenges essential, for the smooth operation of nanoscale transistors.

The incorporation of high k dielectrics such as $HfO_2$ in the gate stack enhances control over the channel leading to decreased leakage currents and improved device stability. The higher dielectric constant of $HfO_2$ allows for a layer compared to $SiO_2$ effectively reducing tunneling currents while maintaining a low equivalent oxide thickness (EOT). This characteristic makes $HfO_2$ a material choice, for cutting edge MOSFET designs.

By combining $SiO_2$ and $HfO_2$ in the gate stack we leverage the strengths of both materials; $SiO_2$ offers interface quality with silicon while $HfO_2$ provides insulating properties. This hybrid gate oxide structure enhances device reliability and performance making it well suited for applications requiring high speed performance and low power consumption.

The GS GAAJLT structure illustrated in Figure 1 features a cavity region that strategically positions the gate oxide layers and metal gates to optimize control and enhance sensitivity to biomolecules. Various dielectric constants, within the cavity area allow for the modeling of biomolecules, which enhances the versatility and accuracy of the biosensor.

By adjusting the thickness of the gate oxide and utilizing material properties the GS GAAJLT structure greatly enhances device efficiency showing potential, for future biomedical and biosensing applications. The incorporation of high k materials and simulation methods places this device at the forefront of innovation.



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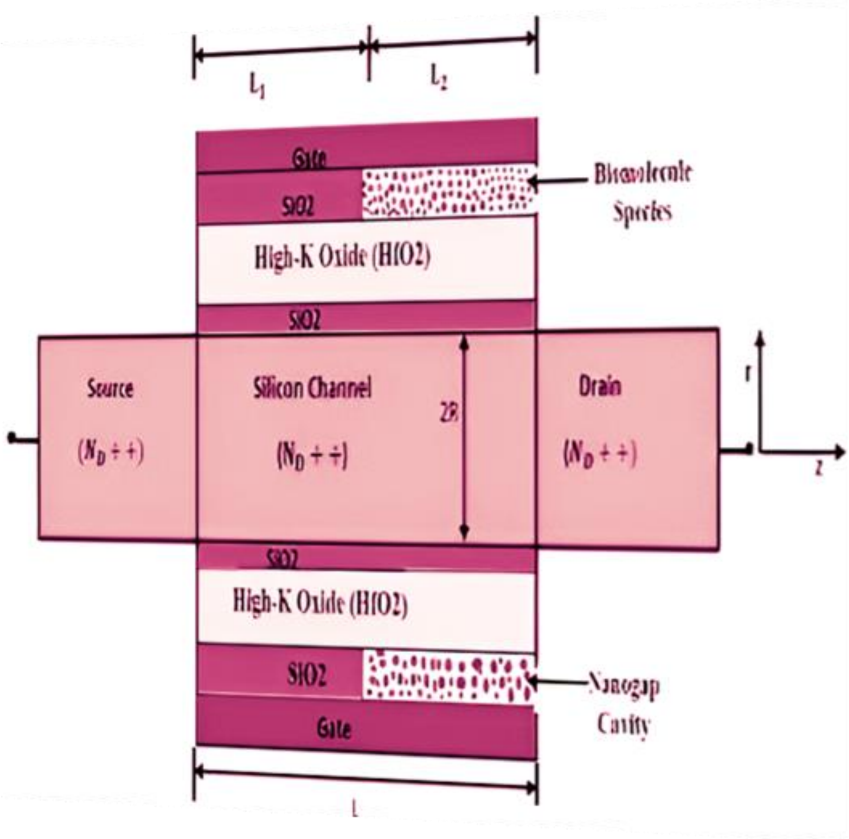


*Figure 1. Illustration of the construction.*

## 4. CALIBRATION PROCESS

It is calibrated with same other models which are used in GAAJLT Device. Simulations predict lower IOFF and higher drive current from the GS-GAAJLT structure using this high-k dielectric material relative to the GAAJLT, due to superior gate capacitance and lower leakage currents.

In order to have our results validated, we used the simulation models that were presented earlier for the GAAGLT structure for the GA-GAAGLT entirely as described. Each method, we run multiple tests to give a fair range of results, this way no method has a major advantage. Figure 2: Calibration methods in these simulations. We then used molecular simulations to analyze the impact of varied neutral biomolecules on the GS-GAAJLT and the GAAJLT configurations.

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One of the most important issues in the simulation of devices is, of course, the calibration that guarantees that the model is correctly reproducing real behaviors. This step consists in adjusting the values of the simulation parameters to be the same as the data in experimental data or theoretical predictions that are already known in the literature. We then tuned various dielectric constants, doping concentrations and material properties for our devices. Through controlling the dielectric constant in the cavity region, we have simulated different biomolecules and have studied its effect on the device performance.

Figure 2 displays the calibration simulation results for both devices without the presence ofV DS 0.1V, in the absence of a cavity region, This figure provides a device performance baseline that can be referred to for subsequent studies with biomolecules.

Figures 2 and 3 show that the GS-GAAJLT configuration has a smaller IOFF compared with the GAAJLT, which is confirmed by our simulations. That is because neutral biomolecules have a high gate capacitance, induced by hafnium oxide ($HfO_2$). This interaction improves the drivability (ID), degradation and variability in I OFF. This improves the performance of the GS-GAAJLT compared to MISFETs based on only $SiO_2$ gate dielectrics.

Figure 4 suggests that the OFF-current shows higher sensitivity than the ON-current, as changes in the dielectric are more effective below the threshold voltage. To study this sensitivity, we introduced a new figure of merit, SIOFF, as given by Equation (3). Figure 5 compares the transconductance characteristics of both devices, showing that the GS-GAAJLT has a 79.63% increase in gm.

The enhancement, in transconductance plays a role in the effectiveness of biosensors as it directly impacts the devices ability to detect biomolecules with sensitivity and precision. Our research and testing procedures have verified that the GS GAAJLT structure outperforms the GAAJLT design. By incorporating $HfO_2$ as a material we have significantly enhanced the devices performance by boosting gate capacitance optimizing electron transport efficiency and ensuring a more consistent electric field distribution. These improvements lead to decreased

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leakage currents, minimized short channel effects and increased on state currents positioning the GS GAAJLT as an option for high sensitivity biosensing applications. Our findings establish a groundwork for exploration and advancement, in nano scale biosensor technology.

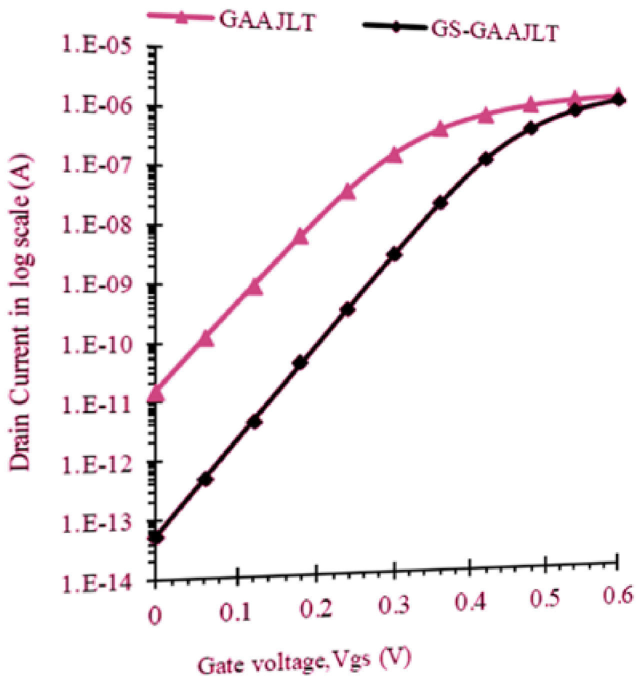


*Figure 2. VDS=0.1 V for the two devices; the calibration simulation results without cavity regions.*

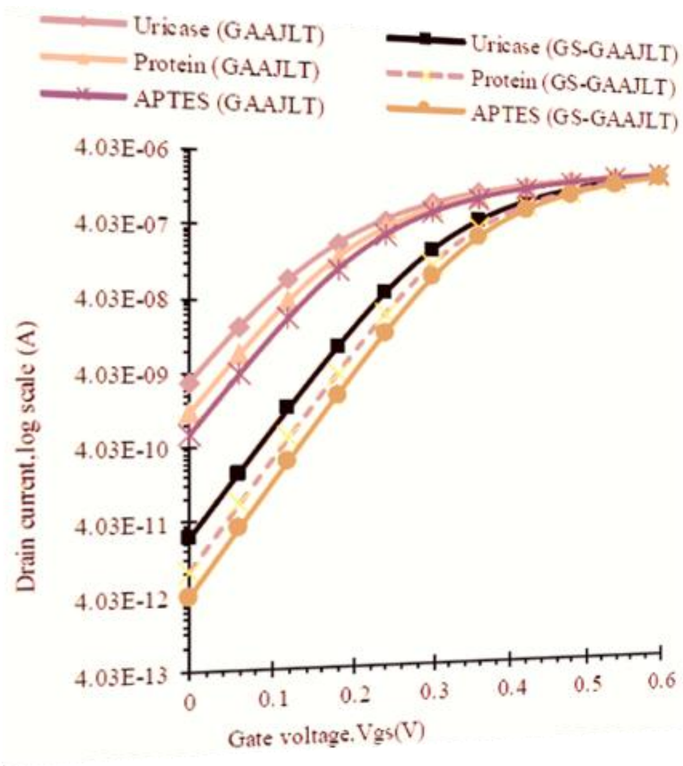


*Figure 3. ID vs.tube potential characteristics of the bio-molecules in neutral states in case of both devices with the tube potential of 0.1V.*

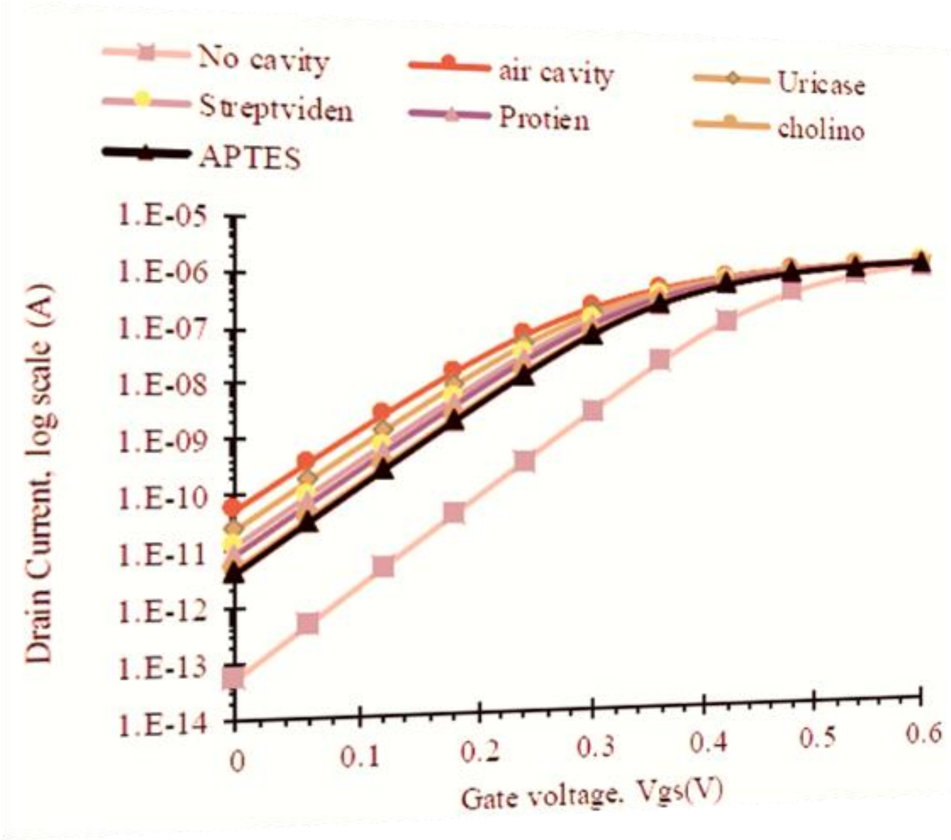


*Figure 4. IDS-IDG Transfer curves for biosensor.*

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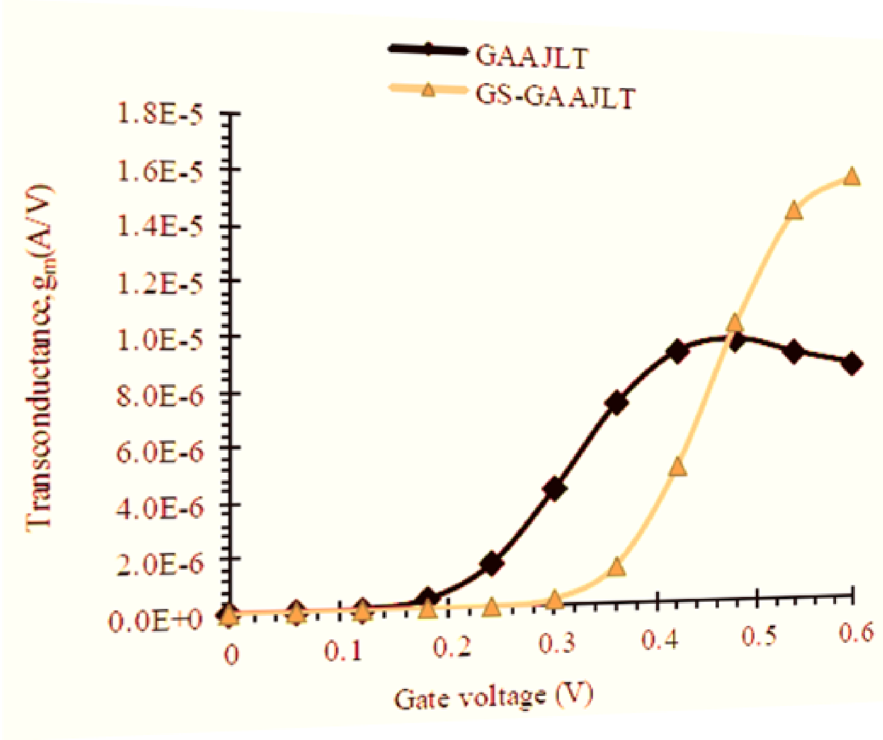


*Figure 5. Transconductance variation (gm) with VGS for both devices at VDS = 0.1V.*

## 5. Results and Discussion

In this part we explore tests and current leaks in biomolecular environments. The GS GAAJLT tool shows better functionality thanks, to its high k gate oxide, which minimizes short channel impacts and boosts electron transportation effectiveness. The findings emphasize the devices responsiveness in identifying biomolecules with notable changes in the OFF current when various biomolecules are detected suggesting higher sensitivity than shifts, in the ON current.

### A) Drain-Induced Barrier Lowering (DIBL)

Due to the different structures applied, the performance of the GS-GAAJLT and GAAJLT devices is much different, as shown in Fig. HfO2 is very effective to suppresses short channel effects. The influence of HfO2 is described by:

DIBL= $\Delta$Vth/ $\Delta$Vds

To improve the device performance, it is critical to eliminate DIBL such that the high drain voltage may have minimum effect on the threshold voltage, leading to a more promising device

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stability and reliability. Figure 6 shows the condition of VD1 = 0.1V, VD2 = 3V, with gate-source voltage (VGS) of 0.6V.

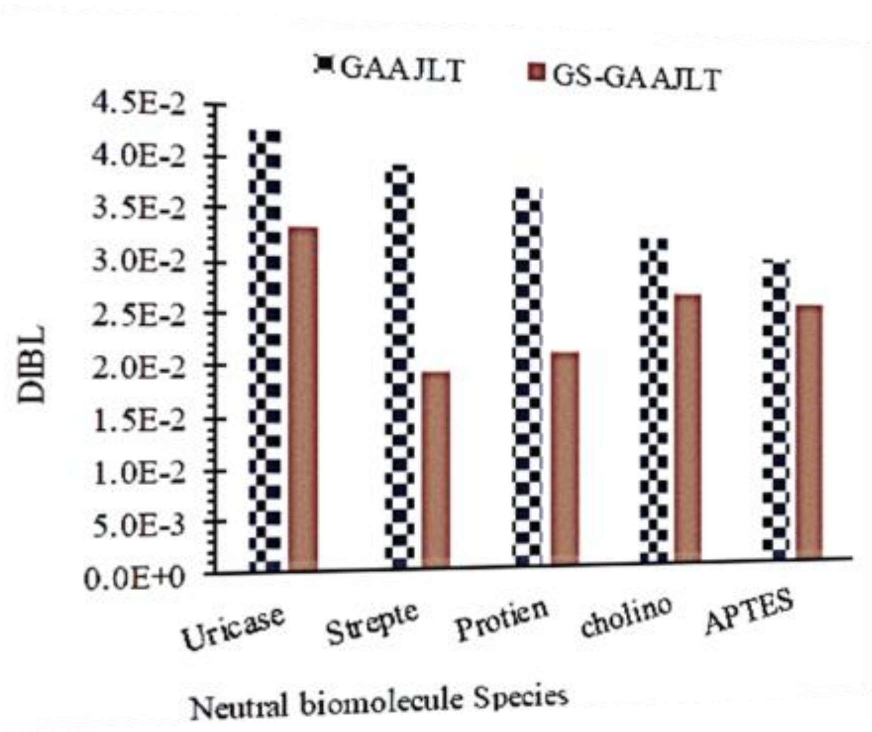


*Figure 6. DIBL comparison VD1 & VD2=0.1V&3V respectively for (VGS=0.6V & VDS=0.1V).*

**B) Slope of Subthreshold**

Slope of Subthreshold is a fundamental parameter that quantifies how effectively a device can switch from "OFF" to "ON" states. A smaller the SS would be better for changing quickly. Improved by having HfO2 as an aiding layer, the enhanced electron and hole mobilities in the GS-GAAJLT device are the reason in Figure 7. This makes the performance of GS-GAAJLT even more superior.

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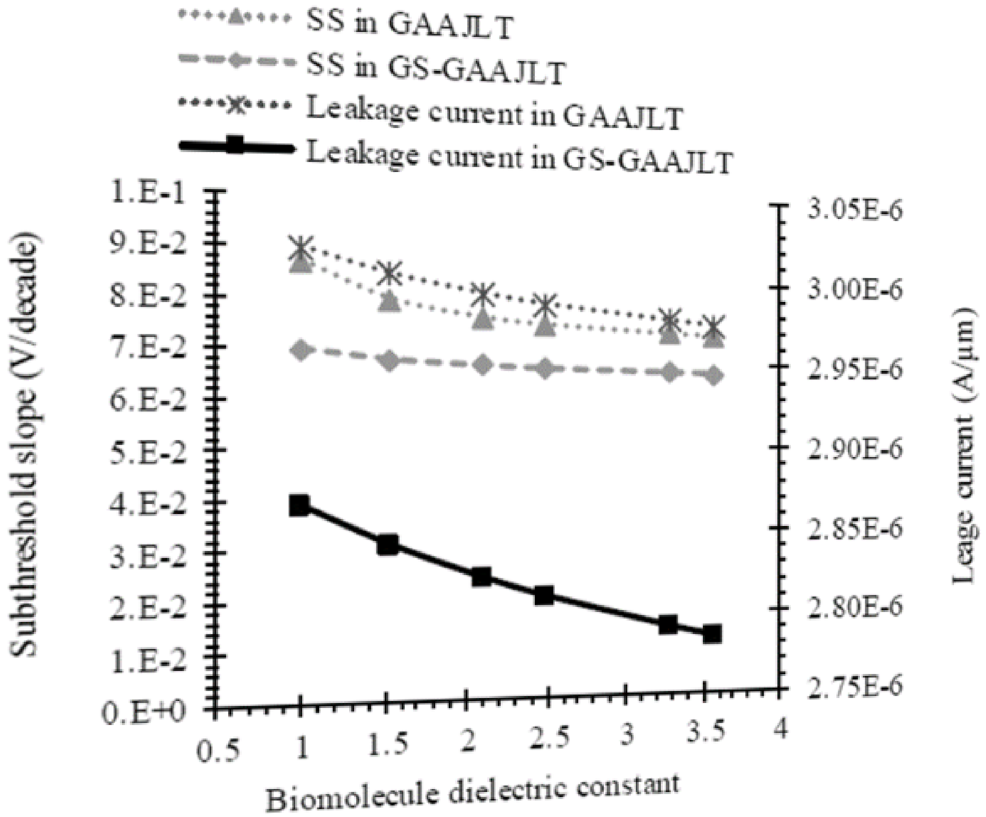


*Figure 7. Graphical representation at VGS=0.6V & VDS=0.1V.*

**C) Leakage Current**

Figure 7 also shows that in the case of no cavity region, the decrease of the OFF-current in GS-GAAJLT is 3.42x10^-3 times larger than GAAJLT. In particular, OFF-current values extracted are significantly reduced. Biomolecules biases free presence at crater can be very effectively and efficiently detected.

**D) Switching (ION / IOFF) Ratio**

From Fig. 8 it can be seen that the GS-GAAJLT structure has better switching (ION / IOFF) ratio than GAAJLT. This reveals that the proposed structure can well suppress short channel effects, then result in enhanced device performance. The smaller OFF-current in the HfO2 gate device than the SiO2 gate device results from the high-mobility carriers and low-bandwidth for the HfO2 gate oxide. This makes them highly useful for applications where both sensitiveness and high precision are needed, biosensing is one of them, as an example.

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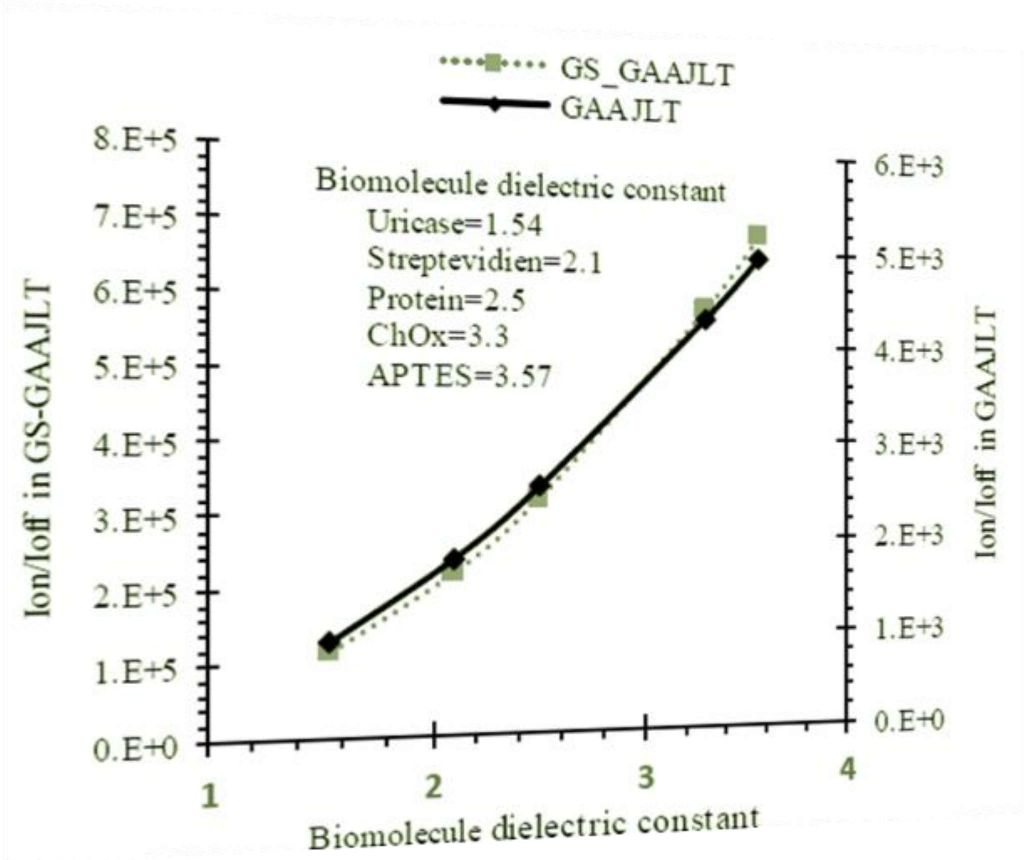


*Figure 8. Plot of ION / IOFF ratio of effect of biomolecule species on switching for Device 1 & Device 2 with VGS=0.6V & VDS=0.1V.*

Our study shows that the GS GAAJLT device outperforms the GAAJLT structure. By using HfO2, as a k gate dielectric we observed enhancements in various performance aspects of the device such as reduced DIBL improved subthreshold slope, lower leakage current and a higher switching ratio. These advancements are essential for advancing nanoscale devices with sensitivity and reliability in applications like biosensors. These results lay a groundwork, for research and refinement of transistors.

**6. The Thoughtfulness of unbiased Bio-substances**

**A) Alteration of Thoughtfulness with IOFF (SIOFF)**

We studied how sensitive the GS GAAJLT and GAAJLT devices are when different bio substances are included. Our results show a remarkable 96% increase in sensitivity (SIOFF) in the GS-GAAJLT. This significant improvement is attributed to the high-k dielectric material, hafnium oxide (HfO2), employed in the gate structure. Figures 9, 10, and 11 provide detailed demonstrations of this effect.

SIOFF can be find out using the following equation:

$$S_{IOFF} = \frac{I_{off}(\text{With Biomolecule Species})}{I_{off}(\text{Without Biomolecule Species})}\Big|\text{at } V_{gs}=0$$

When the current, at zero gate voltage is measured the ratio of the current with biomolecule species to the current, without biomolecule species is calculated as SIOFF.

It enhances the gate control, increasing the gate capacitance and reducing the threshold voltage roll-off. This leads to a significant reduction in leakage current and an overall improvement in device sensitivity.

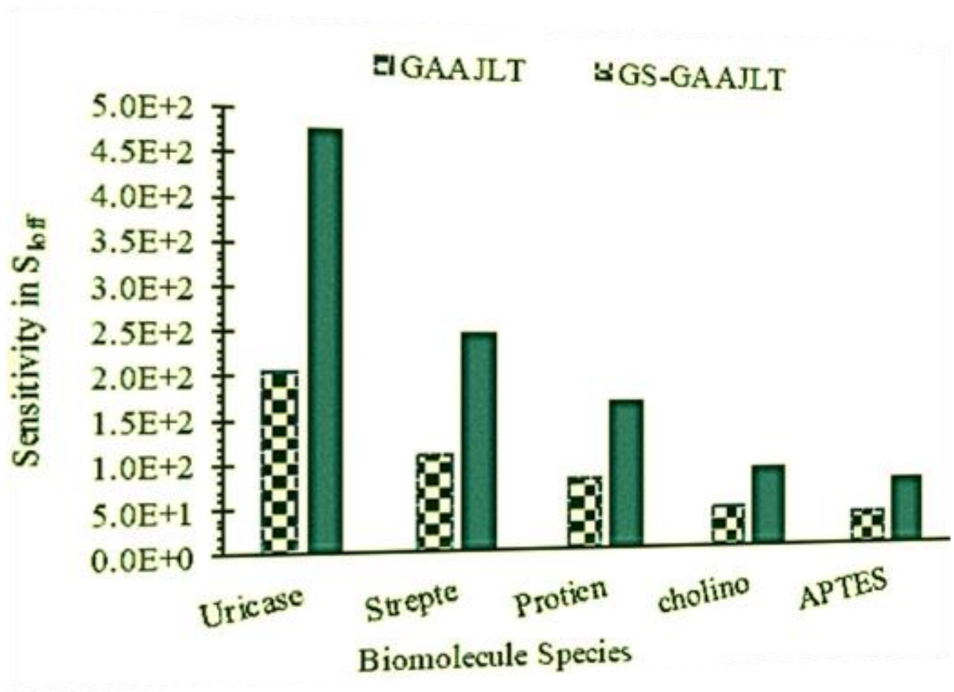


*Figure 9. Comparison of the drain-off current sensitivity parameter versus biomolecular species in Ni/AIGaN/GaN MOS device and only AIGaN/GaN MOS capacitor when repetitively gate voltage of 0.6 V and drain voltage of 0.1 V are applied to both devices.*

Additionally, as shown in Figure 12, the sensitivity variation is evident. The increased cavity thickness allows more neutral biomolecules to occupy the cavity region. Consequently, the device's sensitivity increases due to the presence of the high-k gate oxide material, which significantly influences the interaction between the gate and the biomolecules.

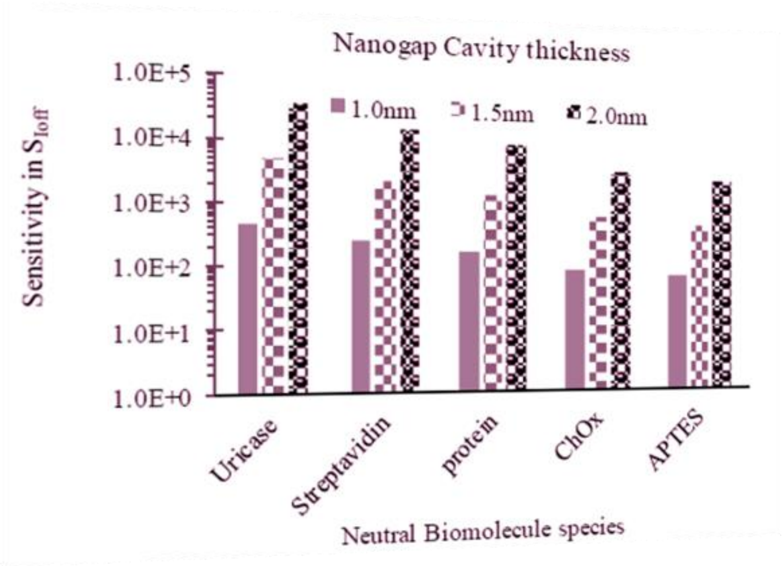


*Figure 10. Biomolecule species fall in drain feedback missions of GS-GAAJLT at (VGS=0.6V).*

**B) Different Thoughtfulness for changed $V_{TH}$**

Shift in threshold voltage (ΔVth) is directly related to the dielectric constant of the biomolecules present in the cavity region. As the dielectric constant of the biomolecule increases.

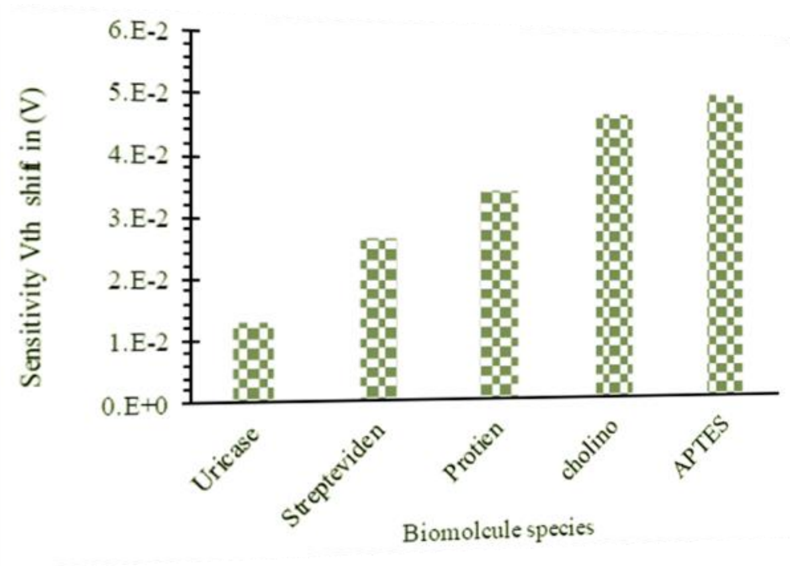


*Figure 11. Change in sensitivity due to Vth.*

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Figures 11 and 12 illustrate how the $V_{TH}$ shift be contingent on the k value of the gate material, the dielectric constant of the biomolecules, and the thickness of the nanogap cavity. Both the threshold voltage shift (ΔVth) and the IOFF ratio are critical parameters for detecting neutral biomolecule species. This calculation is determined using the equation

$$\Delta Vth = |Vth(\epsilon bio) - Vth(\epsilon air)|$$

This connection emphasizes how biomolecules affect the properties of the device offering a reliable way to sense and identify biomolecules, with precision and sensitivity.

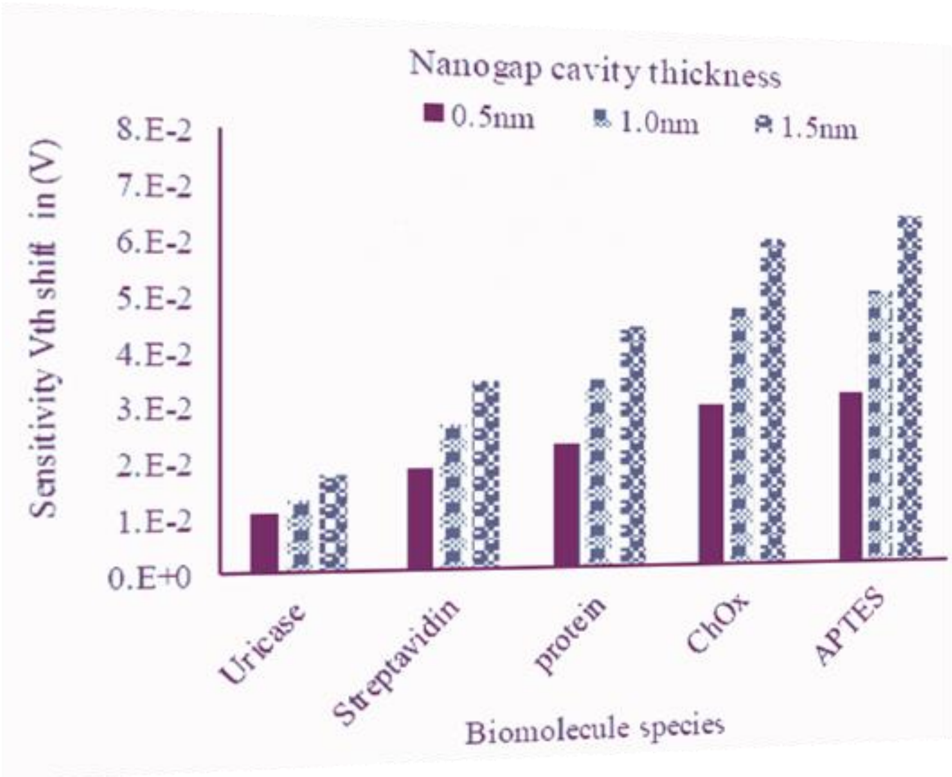


*Figure 12. Shift behavior of the Vth.*

The addition of HfO2, in the gate design of GS GAAJLT greatly boosts the devices ability to detect biomolecules. By adjusting the thickness of the crater and manipulating the properties of proposed transistor shows sensitivity, demonstrated by a significant rise in SIOFF and noticeable changes in threshold voltage. These results highlight the promise of GS GAAJLT

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devices, for cutting edge biosensing purposes emphasizing the importance of sensitivity and accurate detection.

**7. Conclusion**

In the proposed work, a high-k dielectric gate stack based on GS-Si3N4 gate stack field effect transistors biosensor is designed to achieve high performance biosensor for biomolecule detection using a junctionless SiNWFET. The device can be more sensitive and stable as a potential clinical diagnostic tool and for remote sensing applications.

Finally, our results demonstrate dramatic enhancement in the electrical properties of GS-GAAJLT devices relative to those of conventional GAAJLT devices Full size image The GS-GAAJLT exhibits pronounced lower subthreshold slope, leakage current, and DIBL, evidencing the best performance. Moreover, the gate stack structure provides a higher transconductance and switching (ION/IOFF) ratio, representing improved device operation and reliability.

The most critical of the achievements of this research is that the under APTES neutral biomolecules that IOFF ratio (improvement of about 97% relative to GAAJLT at the same operation parameter) was way better. This impressive enhancement is indicative of the promise of GS-GAAJLT devices for biosensing applications.

Consequently, our work suggests that GS-GAAJLT-based biosensors are well- suited to the diagnosis of a number of biomarker diseases, of which some are life- threatening. The enhanced sensitivity and superior performances of these devices provide us with clear insights and a promising avenue for futuristic medical diagnostics and biomolecular detection.

The resulting GS-GAAJLT device thereby exhibits highly improved sensitivity and electrical performance, rendering it a strong contender in future applications of biomolecular sensors. This discovery sets the stage for more sophisticated means of spotting and diagnosing intricate diseases by utilizing the higher-functionality park.

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