Performance Analysis of High-K Dielectric Heterojunction High Electron Mobility Transistor for RF Applications


1. INTRODUCTION

The technology develops year to year, there is drastic demand for VLSI devices as its device dimensions are scaled down to nanometer technology and more evident of short channel effects. In submicron technology, the channel length is very less i.e. less than 5 nanometer innovation and able to control the nanodevices due to decreases in gate length and subsequent undesirable conditions of Drain Induced Barrier Lowering (DIBL). To suppress the short channel effects, Double Gate (DG) structure, Triple Gate (TG) structure, and Nanowire (GAA) structures are excellent scalability over the conventional devices in nanometer technology [1].

The traditional Metal Oxide Semiconductor Field Effect Transistors (MOSFETs) are considered moderate and slower devices compared to Nanomaterial Oxide Nanowire High Electron Mobility Transistors (NWHEMTs). Therefore, Gallium Nitride (GaN) HEMT devices have a large bandgap, larger critical electric field, higher electron drift velocity, and attained good thermal conductivity and good thermal stability [2]. The optoelectronic devices such as high-power devices utilize the III-V bandgap semiconductors being Aluminum nitride, Gallium nitride, and Low-k dielectric material such as Silicon dioxide being SiO₂ and High-K dielectric material being hafnium oxide represented as HfO₂ and Titanium Dioxide (TiO₂) [3]. Due to its heterostructure undoped channel is possible in Nanowire HEMT and
attained higher breakdown voltages due to its higher band gap semiconductors being Gallium nitride (GaN) and Silicon dioxide as SiO$_2$ and high-k dielectric material (HfO$_2$) [4].

The Nanowire High Electron Mobility Transistor (HEMT) is a specific Heterostructure field effect transistor (H-FET) and it gives very high realization at RF and microwave frequencies as well as exhibits lower noise [5]. The working principle of HEMT is based on two-dimensional electron gas due to its heterostructure and less electron collision. The HEMT gives high current (Ion) at lower gate voltages (V$_{GS}$). Due to its high current and various heterostructures, Nanowire HEMT is suitable for finds applications in Radio Frequency design including cellular mobile telecommunications, broadcast radio receivers, and radar communications [6].

Nanowire High Electron Mobility Transistor (GaN-HEMT) are extensively used for a wide variety of material properties high electron saturation velocity, high breakdown electric field, and minimizing the Gate Induced Drain Lowering (GIDL) [7] by the implementation of underlap. Therefore, the effective length of the gate decreases, obviously decreasing the on current (Ion) and degrading the gate controllability of silicon (Si) and Silicon dioxide (SiO$_2$) as low-k dielectric Nanomaterial and high-k dielectric Nanomaterial in the process of Hafnium oxide (HfO$_2$) based Nanowire HEMT devices [8, 9].

Nanowire HEMT was invented based on Nanomaterial oxide being Low-k Dielectric Nano and Titanium Dioxide (TiO$_2$) will work without doping due to its high carrier concentration, resulting in the distribution of non-uniform dopants and reducing the dopant scattering. The self-heating effect is the major concern in GaN-based HEMT due to increases in channel temperature [10, 11]. To reduce the self-heating effect and thermal resistance in the device, continuous efforts are made. But few efforts have been taken to reduce both in the nanodevices. To reduce the self-heating effect and thermal resistance in the device, the GaN-based HEMT is passivated. The Silicon carbide (6H-SiC) establishes a good quality interface with GaN-HEMT to reduce the leakage current in the device [12].

The Organization of the paper is as follows: Design of Undoped 5 nm regime gate Nanowire HEMT, mesh view, Electric filed, and potential distribution are discussed in the second section. In the third section, the results of various materials and their performance comparison are discussed. The final section is discussed with conclusion.

2. STRUCTURE OF PROPOSED DEVICE

The proposed 5 nm regime gate with an undoped region Nanowire High Electron Mobility Transistor is shown in Figure 1. The U-HEMT is made of high-k hafnium oxide (HfO$_2$) material and device dimensions are measured in nanometers using the Silvaco TCAD ATLAS simulator [13]. The new device has an undoped region with HfO$_2$ compared with the conventional device. The length of metal gate is L$_g$=0.005 μm and metal gate with a work function of 4.87eV. The length of the device, spacing between gate-source and gate-drain, and length of the undoped high-k dielectric material (HfO$_2$) region are L$_{sid}=0.032$μm, L$_{sd}=0.015$μm, L$_{sh}=0.015$μm, and L$_{so}=0.08$μm, respectively. The undoped region under the gate reduces the electric field in the channel region and increases the drain current significantly [14, 15]. The undoped Nanowire HEMT mesh view is shown in Figure 2, where the grid spacing on both axes is not equal [16]. Electric field distribution and potential distribution of the new structure are shown in Figures 3 and 4. The speed and performance parameters of the device is depending on the gate length [17, 18]. Channel doping increases will increase the drain current. Silvaco ATLAS Simulator is used to simulate the Undoped HEMT under a 5 nanometer gate regime with high-k dielectric material being hafnium oxide (HfO$_2$) and extracted all electrical parameters [11]. In this proposed structure, Silicon Carbide (6H-SiC) is used as a substrate instead of Silicon (Si) [19].

DC characteristics and RF characteristics of Undoped Nanomaterial oxide HEMT with HfO$_2$ are analyzed for different material combinations that have been obtained by using the ATLAS simulator, where the length of the gate is 0.005μm [20, 21]. The undoped HEMT device dimensions are shown in Table 1 and Gate length (5nm) is a very important parameter. The High-k dielectric, 5 nm regime gate HEMT used various materials and methods for simulation of the device as shown in Tables 2 and 3.

HfO$_2$ has a high dielectric constant (typically around 20-25), than traditional gate dielectrics like silicon dioxide (SiO$_2$). This property enables the formation of a thicker dielectric layer, facilitating better gate control over the channel and reducing gate leakage current. The high-k dielectric nature of HfO$_2$ allows for a higher gate capacitance per unit area compared to low-k dielectrics. This increased gate capacitance enhances the control of charges in the channel region, resulting in enhanced device performance, reduced threshold voltage variation, and lower leakage current. Mitigation of Short-Channel Effects: Incorporating HfO$_2$ as a high-k dielectric beneath the gate helps alleviate short-channel effects in HEMTs. These effects, such as threshold voltage roll-off and drain-induced barrier lowering (DIBL), can detrimentally impact device performance. The high-k dielectric layer helps mitigate these effects and improves the scalability of HEMT devices.

The high-k dielectric Hafnium Dioxide (HfO$_2$) material insertion in the HEMT model presents several advantages over previous works, making it highly
suitable for real-time applications. HfO₂ material insertion in the proposed HEMT model delivers improved device performance across key metrics such as higher transconductance, lower gate leakage current, and enhanced linearity. These enhancements translate into superior signal amplification, increased operational efficiency, and overall improved device functionality. Mitigation of Short-channel effects, including threshold voltage roll-off and drain-induced barrier lowering, present challenges in HEMTs. HfO₂ material insertion effectively addresses these issues by reducing channel length dependence and improving device behavior at smaller dimensions. HfO₂ material offers improved gate control and reduced gate leakage current, resulting in lower power consumption compared to previous works.

By integrating Hafnium Dioxide (HfO₂) into the gate structure of AlGaN HEMTs, a notable improvement in breakdown voltage can be achieved compared to previous dielectric materials. HfO₂ exhibits exceptional thermal stability, making it a highly reliable choice for the gate structure of AlGaN HEMTs with reduced gate length. The compatibility of HfO₂ with standard semiconductor fabrication processes allows for seamless integration into existing manufacturing techniques. This compatibility greatly simplifies the production and scalability of AlGaN/GaN HEMTs with HfO₂ gate structures, making it more practical for large-scale applications.

### TABLE 1. Utilized Device performance Parameters

<table>
<thead>
<tr>
<th>Parameter used for device</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device Length</td>
<td>0.032µm</td>
</tr>
<tr>
<td>Length of the Gate</td>
<td>0.005µm</td>
</tr>
<tr>
<td>Source to Gate space</td>
<td>0.015µm</td>
</tr>
<tr>
<td>Gate to drain Space</td>
<td>0.015µm</td>
</tr>
<tr>
<td>Length of undoped region</td>
<td>0.008µm</td>
</tr>
<tr>
<td>Length of Source</td>
<td>0.004um</td>
</tr>
<tr>
<td>Length of Drain</td>
<td>0.004um</td>
</tr>
<tr>
<td>Doping of Channel(D_C)</td>
<td>1x10²⁰ cm⁻³</td>
</tr>
<tr>
<td>Work function</td>
<td>4.87eV</td>
</tr>
</tbody>
</table>

### TABLE 2. Utilized Methods for simulation of Proposed structure

<table>
<thead>
<tr>
<th>Method Model</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gummel</td>
<td>Used as solution method in subsequent solve statement.</td>
</tr>
<tr>
<td>Newton trap</td>
<td>Newton solver for SHJ models and SIS models</td>
</tr>
<tr>
<td>maxtrap</td>
<td>Specified by the parameter of the method statement and trap is enabled.</td>
</tr>
<tr>
<td>Gummel</td>
<td>Specifies the name of the output file where the structure information will be stored after every iteration</td>
</tr>
</tbody>
</table>

Figure 1. Cross-sectional View of High-k Dielectric AlGaN/GaN HEMT

Figure 2. Mesh View of High-k Dielectric AlGaN/GaN HEMT Structure

Figure 3. Electric Field Distribution of High-k Dielectric AlGaN/GaN Device

Figure 4. Potential Distribution of high-k dielectric AlGaN/GaN Device
deployment. It brings enhancements in breakdown voltage, improved thermal stability for high-temperature applications, and compatibility with existing fabrication processes.

The proposed model introduces a novel approach to transistor design by combining several unique features, High Electron Mobility Transistors (HEMTs) with a reduced gate length, a Silicon Carbide (SiC) substrate, and Hafnium Oxide (HfO\(_2\)) materials beneath the gate. HEMT model incorporates a shorter gate length compared to conventional designs. This reduction enhances device performance by improving current flow control, enabling faster switching speeds, and minimizing signal distortions. In contrast to traditional HEMTs that use standard semiconductor substrates, our model utilizes a Silicon Carbide (SiC) substrate. SiC includes high thermal conductivity, excellent mechanical strength, and a wide bandgap. These properties enable higher breakdown voltage and lower on-state resistance. An essential aspect of our model is the integration of Hafnium Oxide (HfO\(_2\)) as a material beneath the gate. HfO\(_2\) is a high-k dielectric material that improves gate control, reduces leakage current, and enhances electrostatics. By incorporating HfO\(_2\) beneath the gate, our model achieves superior device performance, increased reliability, and reduced power consumption.

3. RESULTS AND DISCUSSIONS

If the gate voltage (V\(_G\)) is less than the V\(_t\) i.e threshold voltage, then the device is OFF state, then minority charge carriers are flows from the source [22], obviously subthreshold current. The Gate voltage (V\(_G\)) more than the threshold voltage (V\(_t\)) is known as ON Current. The drain current (I\(_d\)) Vs Drain voltage (V\(_d\)) for different material combinations used as shown in Figure 5 [23].

The undoped region with 5nm regime gate high-k dielectric material being hafnium oxide (HfO\(_2\)) Nanowire HEMT drains current as shown in Figure 6, where gate length is kept 5 nm and observed that leakage current (I\(_{off}\)) is the same [24]. The higher ON current resulted for AlGaN/GaN/SiC than other material combinations [25].

The drain conductance(g\(_d\)) Vs various drain voltages is shown in Figure 7. The AlGaN/GaN/SiC drain conductance is improved compared to other material combinations [26, 27].

\[
\text{Drain Conductance}(G_d) = \frac{\delta I_d}{\delta V_{ds}} \tag{1}
\]

The high Transconductance is required for the proper gain of the amplifier, and it is set with different gate [28] voltages (V\(_{gs}\)) as shown in Figure 8.

\[
\text{Transconductance}(G_m) = \frac{\delta I_d}{\delta V_{gs}} \tag{2}
\]

The simulated on-resistance (Ron) Vs drain voltage (V\(_d\)) as shown in Figure 9. As a result, drain conductance

![Figure 5. Variation of Drain current Vs Drain voltage for different hetero combination material](image)

![Figure 6. Variation of I\(_d\) Vs V\(_{gs}\) for different hetero combination materials](image)

![Figure 7. Variation of G\(_d\) Vs V\(_{ds}\) for different hetero combination materials](image)

<table>
<thead>
<tr>
<th>TABLE 3. Utilized Models for simulation of Proposed structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Model</td>
</tr>
<tr>
<td>commob</td>
</tr>
<tr>
<td>srh</td>
</tr>
<tr>
<td>Auger</td>
</tr>
<tr>
<td>fldmob</td>
</tr>
</tbody>
</table>
increase increases the corresponding on-resistance decreases for various materials [29]. The electric field distribution of the proposed undoped HEMT structure under the 5 nm regime gate with HfO$_2$ is shown in Figure 10. The undoped HEMT electric field concentration improved compared to conventional devices [30].

The performance parameters of the proposed HEMT as shown in Table 4. From the obtained results it is observed that AlGaN/GaN/SiC Nanowire HEMT possesses good performance compared with two material HEMT structures.

SiC is a wide-bandgap semiconductor known for its excellent thermal conductivity, high breakdown electric field strength, and ability to operate at high temperatures.

The state of the art in SiC-based HEMTs with AlGaN/GaN as the channel material showcases several notable features. Firstly, these devices offer impressive power density, enabling them to handle high voltages and currents with minimal power losses. Secondly, their high-frequency operation is excellent, making them suitable for microwave and millimeter-wave frequencies. SiC substrates provide exceptional thermal conductivity and material properties, allowing HEMTs to operate reliably at high temperatures. Additionally, GaN-on-SiC technology has surpassed GaN-on-silicon (GaN-on-Si) due to SiC's superior thermal management, reduced parasitic effects, and higher breakdown voltage capabilities.

AlGaN/GaN HEMTs can accommodate higher voltages and currents, enabling greater power density. GaN possesses a broader bandgap than InGaAs and AlGAs, leading to improvement at high temperatures and enhanced breakdown voltage characteristics. AlGaN/GaN HEMTs exhibit remarkable high-frequency characteristics due to the superior electron mobility of the 2D electron gas (2DEG) formed at the AlGaN/GaN interface. GaN demonstrates superior thermal conductivity in comparison to InGaAs and AlGaAs, facilitating efficient dissipation of heat. This attribute is particularly valuable in high-power applications. AlGaN/GaN HEMTs exhibit lower parasitic effects, such as reduced gate leakage and drain-source capacitance.

Recent advancements in GaN technology have contributed to a reduction in manufacturing costs associated with AlGaN/GaN HEMTs.

### TABLE 4. Performance metrics for proposed structure

<table>
<thead>
<tr>
<th>Parameter</th>
<th>AlGaN/GaN/SiC</th>
<th>AlGaAs/GaAs/SiC</th>
<th>InGaAs/InP/SiC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion(A)</td>
<td>5.92E-04</td>
<td>1.70E-04</td>
<td>2.21E-05</td>
</tr>
<tr>
<td>Ioff(A)</td>
<td>1.39E-13</td>
<td>2.90E-17</td>
<td>9.27E-12</td>
</tr>
<tr>
<td>Gd(S)</td>
<td>6.43E-04</td>
<td>4.53E-04</td>
<td>4.03E-04</td>
</tr>
<tr>
<td>Ron(ohms)</td>
<td>1.56E+02</td>
<td>2.20E+02</td>
<td>2.48E+02</td>
</tr>
<tr>
<td>Vth(V)</td>
<td>0.2</td>
<td>0.35</td>
<td>0.5</td>
</tr>
<tr>
<td>Gm(S)</td>
<td>8.07E-04</td>
<td>6.46E-04</td>
<td>4.38E-04</td>
</tr>
</tbody>
</table>

4. CONCLUSION

The paper presents a design and simulation-based 10nm gate regime advanced High Electron Mobility Transistor (HEMT) with an undoped region under the gate using the
Hafnium oxide (HfO$_2$) based advanced HEMT with high k material being hafnium oxide (HfO$_2$) under the metal gate obtained High Current (Ion), increased Ion/Ioff ratio, high trans conductance, high drain conductance, and low ON resistance, respectively. Therefore, the proposed HEMT device with a high-k dielectric material, Hafnium oxide (HfO$_2$) under the gate has preferred as the best material for high power and high-frequency applications.

5. REFERENCES


30. Fouladnia, F. and Gholami, M., "Decimal to excess-3 and excess-3 to decimal code converters in qca nanotechnology", (2022). https://doi.org/10.21203/rs.3.rs-2218039/v1