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DFT Aware Test Architecture for Communication ICs: ATPG- Based Fault Detection on Lower Technology Node

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Abstract

In this research, hafnium dioxide (HfO_2) and titanium dioxide (TiO_2) are investigated as advanced gate dielectrics for GaN-based MISHEMTs on diamond substrates. AlGaN/GaN MISHEMTs, incorporating HfO_2 and TiO_2 as gate dielectrics, have been rigorously analyzed and optimized for RF and DC performance through ATLAS TCAD simulations. The MISHEMTs with HfO_2 gate dielectrics exhibited impressive metrics: a high drain current density (I_{DS}) of 3.62 A/mm, a breakdown voltage (V_{BR}) of 998 V, a transconductance (g_m) of 1.09 S/mm, and a cutoff frequency (f_T) of 49 GHz. Conversely, the MISHEMTs utilizing TiO_2 as the passivation layer demonstrated even superior performance, achieving an I_{DS} of 3.7 A/mm, a V_B of 1168 V, a g_m of 1.13 S/mm, and an f_T of 48 GHz. Both dielectric materials contributed to a notably low on-resistance of 4.9 Ω·mm. The synergistic effect of the diamond substrate with high-performance HfO_2 or TiO_2 gate dielectrics positions these MISHEMTs as highly promising candidates for next-generation power switching and RF applications, due to their enhanced efficiency and robustness under high-power and high-frequency conditions. The proposed work improves the performance enhancement of Metal-Insulator-Semiconductor High Electron Mobility Transistors (MISHEMTs) with inclusion of diamond substrate. Diamond substrate to its wide energy bandgap ranges of 5.5 eV for used materials for both power electronics and RF applications electrical and Thermal properties are concerned in its high

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Introduction

GaN HEMT is a preferred choice in applications requiring high power density, high frequency and high voltage. But performance of GaN HEMT is still an issue, the most notable being current collapse. Current collapse refers to a considerable fall in the drain current when measured under high amplitude, high-frequency gate swings. It is one of the performance difficulties that GaN-based HEMTs still face. Typically, surface passivation is a preferred technique used to reduce surface state densities and mitigate drain current collapse. The passivation effects of several dielectrics, include SiNx, Silicon Dioxide (SiO), SiON, Aluminum oxide (Al2O3), Sc_2O_3, Aluminum Nitride (AlN) and Magnesium carbonate (MgCaO1) are analyzed in the literature. In this work SiO_2, Al_2O_3 and H_2F_3 are used for passivation dielectrics to reduce the current collapse and improve the break down voltage. To realize an enhancement mode transistor GaN HEMT with p-GaN gate and AlGaN back barrier is proposed and investigated. The transfer characteristics, transconductance, threshold voltage and breakdown voltage are analyzed. Results indicate that the device exhibits positive threshold voltage. It is observed that the p-GaN HEMT with AlGaN back barrier shows higher breakdown voltage compared to the p-GaN HEMT without AlGaN back barrier. In addition, the impact ambient on the transconductance and threshold voltage is analyzed. The threshold voltage linearly varies with the change in ambient temperature. High-power performance capabilities of AlGaN/GaN high-electron-mobility transistors (HEMTs) are currently of major interest.[1] However, current collapse is the main problem limiting power-switching performances in AlGaN/GaN HEMTs. This causes poor thermal dissipation as well as buffer related electron and surface trapping effect.

In virtual gate concept the electrons fill in the surface traps with negative charge collected in the surface. Hence trapped electrons are not released instantaneously and thus drain current degradation and transient gate bias shifting are observed. Different types of techniques are discussed using surface passivation technique to suppress current collapse.[2] A wide range of passivation materials and techniques have been studied in order to create appropriate and robust passivation dielectrics for HEMTs. These include SiOx, SiNx and SiOxNy deposited by Plasma-Enhanced Chemical Vapor Deposition (PECVD), SixNy by reactive sputtering, Al_2O_3, AlN, HfO_2, SiO_2, and SixNy deposited by PECVD. Several methods have been published for the passivation of the AlGaN/GaN HEMTs. These methods include in-situ Metal-organic chemical vapor deposition (MOCVD), remote plasma chemical vapor deposition CVD, electron-cyclotron CVD, and catalytic CVD. The passivation layer plays the most important role of suppressing the electron trapping on the surface. Whenever heterostructure is grown, defects are found on the surface as pits. Removing the surface oxide is done by passivation and hence surface defects are minimized or the number of positive charges at epi-structure interface is increased. This neutralizes the AlGaN polarization charges which results in decreased surface-related depletion of 2DEG. SiN passivation is one of most popular solutions because it effectively suppresses the collapse current and provides high stability. This technique reduces the effect of surface induced current collapse. By modulating the electric field profile, it also mitigates buffer-induced current collapse[3] has developed bilayer SiNx passivation scheme using LPCVD which effectively suppresses the dispersive effects in AlGaN/GaN High-Electron-Mobility Transistors (HEMTs) for microwave power operation. MOCVD as in-situ SiNx passivation's and plasma-enhanced chemical vapor deposition as out-situ SiNx passivation's are used to compare the bilayer LPCVD passivation. These have the maximum power at output and low dynamic ON state resistance. Plasma and wet chemical treatments are typically used for ex-situ pretreatments. Plasma-based techniques are used mostly for in-situ pretreatments before the passivation layer is applied. [4] have discussed SiNx deposited passivation layers in GaN and AlGaN High Mobility Electron Transistors (HEMTs) without surface damage by chemical vapor deposition. They have obtained a low sheet resistance and high electron mobility.[5] have proposed to use SiNx surface passivation on top of the epitaxial stack in GaN HEMTs. During high voltage operation this technique modifies the charge stored in the carbon doped layer of GaN thus enabling the control of current collapse due to traps in the buffer. The current collapse that is suppressed by an enhanced vertical leakage at the top of the buffer is demonstrated using Substrate bias ramps. In addition, the epitaxial buffer's main carrier transport is changed as a result of modifications to the surface passivation.[6] proposed SiN as the surface passivation and gate dielectric for AlGaN/GaN. After the barrier growth of the GaN HEMT, they have fabricated an in-situ SiN gate dielectric. They have combined an in-situ SiN and SiN deposited by PECVD producing a bilayer passivation. They compared the gate pulse and DC Characteristics of GaN HEMT before and after the passivation and observed that current collapse in the device is reduced dramatically.[7] have used Si_3N_4/AlN as the passivation layer. The thin AIN layer passivates the surface states in the access region. The passivation increases the effective carrier mobility in normal off-channel when compared to conventional device with only Si3N4 passivation. Because of the passivation of surface states by the AlN layer, the degradation in dynamic ON-resistance is reduced, thus enhancing the dynamic and static performance of the device.[8] have increased the breakdown voltage by using double passivation layers with combination of high-k dielectric and SiN and single passivation layers of high-k dielectric or SiN. The double passivation layers effectively reduce the current collapse and increase the breakdown voltage when compared with single SiN passivation layer with the same insulator thickness. The double passivation layers with high k dielectric reduce the electric field at the drain edge of the gate, resulting in a higher breakdown voltage. However, the breakdown voltage is noticeably lower in the case of the double passivation with thin second layer as compared to a high-k single passivation layer. Furthermore, it has been demonstrated that for double passivation layers, as the relative permittivity of the second passivation layer rises and the SiN layer is thin, the breakdown voltage approaches the same as a high-k single passivation layer.[9] has proposed bilayer passivation of the Si-rich Si3N4/SiN and observed the suppressed current collapse. Between the conventional AlGaN layers and the SiN layer a Si-rich SiN interlayer is fabricated which has been effective in mitigating current collapse and surface leaking, improving RF power performance and sheet resistance. They also discovered that the interlayer of SiN prevents device degeneration in high-temperature environments. This interlayer also reduces power dissipation due to the heating effects, resulting in improved RF power output and efficiency.[10] has proposed using 3 types of SiNx passivation for microwave GaN and AlGaN HEMTs with CVD at low pressure under different conditions of degradation which reduces the trapping effect. Si-rich SiNx is the first layer, eliminating slow surface traps, and Si-poor SiNx is the second layer reducing gate leakage current. Large signal and small signal performances are analyzed to show a reduced current collapse. Results show mainly Si-rich SiNx eliminates AlGaN slow surface traps.[11] have suggested adding a SiN/Al passivation layer to AlGaN/GaN HEMTs reduces surface damage and blocks it. It has been demonstrated that SiN/Al passivation effectively suppresses current collapse as measured by Ids-Vds pulse measurements and reduces leakage current by 2 to 3 orders of magnitude. Additionally, various treatment surface techniques are suggested to enhance the passivation effect.[12] have proposed deposition of SiN film by a conventional Plasma-enhanced chemical vapor deposition (PECVD) for surface passivation. They also optimized the aluminum content and AlGaN thickness. They have achieved a good power output density with AlGaN thickness of 15µm and aluminum content of 30%.[13] has suggested a method that combines multi-cycle plasma-free ozone oxidation with wet surface treatment before passivation. Because of the removal of the imperfect surface layer and enhancement of the Si3N4 passivation effect, the Ids-Vds pulsed characteristic indicates that the device has improved immunity to current collapse.[14] have shown that post-passivation treatment of plasma reduces leakage of gate and drain current and suppresses the virtual gate effect. AlGaN/GaN HEMTs with post passivation plasma significantly reduces gate leakage compared to conventional devices while increasing drain current. Using post plasma passivation to reduce the surface trap in the access region the authors have suppressed the virtual gate effect shown an improvement in the DC characteristics of the device. GaN HEMT with AlN passivation demonstrate good dielectric constant, small lattice mismatch and high thermal conductivity devices thus reducing leakage current and trapping effects.[15] have used atomic layer epitaxy (ALE) for depositing layers of AlN. The SiNx along with 300°C films of AIN are deposited after gate metal deposition. HEMTs passivated using high crystalline AlN, shows improved 2DEG sheet density carrier, gate leakage current, off-state drain leakage current, breakdown voltage and subthreshold slope. In addition, dynamic on-resistance degradation during off-state pulse voltage switching stress is suppressed.[16] have deposited AlN polycrystalline by DC sputtering which acts a heat spreader over AlGaN/GaN HFETs. Thermal simulation results show that the thermal resistances of AIN passivation AlGaN/GaN HFETs are significantly lower than devices with SiN passivation. This shows that ON state resistance is decreased with the increase in drain current and current collapse is suppressed. Marginal increase in RF power output has also been confirmed.[17] have deposited AlN film using PEALD for GAN HEMT. Significant dynamic ON-resistance reduction and current collapse suppression are demonstrated in the AlN-PEALD passivated AlGaN/GaN HEMTs under high-drain-bias switching conditions.[18] has used TiO_2 for passivation in AlGaN/GaN HEMT. AlGaN/GaN HEMT passivated with SiN and TiO_2 exhibited a high breakdown voltage reduced gate leakage current.[18] have proposed Titanium dioxide (TiO_2) as a good passivating material for AlGaN/ GaN HEMT in high frequency applications. In this proposed method, TiO_2 and hafnium dioxide (HFO_2) are the used for passivation in AlGaN/GaN HEMTs. Large and small signal performance, DC performance is improved by TiO_2 passivation as compared to passivation using only HFO_2. An increase in power efficiency was demonstrated that allows GaN HEMTs to be employed in high power applications. Magnesium Fluoride (MgF_2) deposited using e-beam evaporator at room temperature is used as passivation layer as for AlGaN/GaN HEMTs by Oh et al. (2020). The negative effects of passivation deposition are excluded and the surface traps are effectively reduced by MgF_2. Results indicate gate forward leakage current is reduced and breakdown voltage is enhanced. Authors have shown that surface damage due to e-beam evaporator can be minimized.[19] have used Sc_2O_3 and MgO passivation for GaN devices by plasma assisted molecular-beam epitaxy. Results show that this technique reduces the effect of current collapse. It has used hydrogen peroxide along with sulfuric acid as passivation of GaN HEMTs. Pinch-off gate leakage current of the device is significantly reduced by the two chemical treatments. The oxidizing of the surface is done by sulfuric acid which has strong passivation effect on the gate leakage current. Reduction in trap density interface charge is also noted. After fabricating the full device, treatment of sulfuric acid under the gate along with SiNx passivation results in reduction interface trap density and mitigates the surface related current collapse.[20] USED A BILAYER OF

SiN/Al_2O_3 for passivation in GaN HEMT. When Al_2O_3 is inserted between SiN and AlGaN/GaN, the surface leakage current of GaN HEMTs has reduced compared to only SiN passivation. For all ranges of samples, two-dimensional variable hopping is thought to be the mechanism of surface conduction. With SiN/Al_2O_3 bilayer passivation, the leakage current in the buffer layer was substantially less than SiN passivation. The pulse measurement demonstrates the effect of surface state and trapping effects can be significantly reduced by SiN/Al2O3 bilayer passivation technique.

Proposed work

In Figure 1 is illustrated with the enhancement-mode HEMT on a diamond substrate with multiple epitaxial layers. A 25-nanometer thickness of Al0.05Ga0.65N layer, a 10-nanometer of thickness of Al0.10Ga0.75N layer, and a Al0.15Ga0.85N cap layer thickness of 10-nanometer. gate dielectric of 3-nanometer, consists of TiO2 and HfO2, is used for higher breakdown voltage to minimize the gate leakage current. The Enhancement-mode is attained by the heterostructure of Al0.05Ga0.65N/ Al0.10Ga0.75N, MISHEMT of the conjunction with a metal-insulator-semiconductor recessed gate type HEMT. The Al0.15Ga0.85N cap layer is managed to disperse and decrease the access resistance, with their thickness and support the functionality. The aluminium concentration for AlGaN barrier layer plays an important role, as it influences the spontaneous polarization (PSP) of the barrier. In the AlGaN layer, both piezoelectric and spontaneous polarization effects are considered to enhance performance, while only spontaneous polarization is taken into account for the GaN layer. This careful consideration of material composition and layer structure is essential in achieving the desired electrical characteristics, ensuring that the E-mode HEMT delivers high efficiency and reliability in high-power and high-frequency applications. The combined effects of the heterostructure, gate dielectric, and cap layer contribute to the overall performance of the device, making it a promising solution for advanced semiconductor applications. The total polarization (PT) is calculated by ATLAS TCAD software using a specific equation (1).

$$P_T = P_{SP} + P_{PZ} \tag{1}$$

where, P_{PZ} and P_{SP} are piezo-electric polarization and spontaneous polarization

$$P_{PZ} = 2\,\frac{1 - 0}{0}\left(\epsilon_{31} - \frac{13}{33}\epsilon_{33}\right) \tag{2}$$

where the a_0 is the lattice constant and a_1 is the lattice constant. The parameters and are elastic constants. The piezoelectric constants are and . In both spontaneous and piezoelectric models, negative and positive charges accumulate on the top and bottom surfaces of the AlGaN barrier, respectively. This charge distribution results in the formation of positive charges at the bottom of the AlGaN layer, which in turn induces a two-dimensional electron gas (2DEG). The 2DEG acts as the channel in an AlGaN-MISHEMT device. The gate is established using a Schottky contact with a work function of 5.2 eV, while the source and drain are secured with ohmic contacts, characterized by a work function of 3.93 eV. These contacts ensure efficient current flow in the device. Table 2 provides the material parameters utilized in the simulation to achieve accurate modeling of the device's behavior. The careful consideration of these parameters is crucial for optimizing the performance of the AlGaN-MISHEMT, particularly in high-frequency and high-power applications.

$$\mu_n = \frac{\mu_0 + v\left(F^{a-1}/F_c^a\right)}{1 + c\left(\frac{F}{F_c}\right)^b + \left(\frac{F}{F_c}\right)^a} \tag{3}$$

where electric field, mobility field, and electric field with critical are represented as F, , and respectively. The user-defined parameters, labeled as a, b, and c, are detailed in Table 1. The simulation employs physics-based models to solve equations, utilizing the Newton method for iterative computation. To accurately model the MISHEMT device, the structure is divided into small triangular regions through a process known as meshing. This approach allows for detailed analysis of the device's behavior. In the simulation, precise meshing was achieved through a trial-and-error method, ensuring that the device was accurately represented without encountering conversion issues. It was determined that fine meshing, particularly along the channel and at the gate edge, provided the most accurate results. This fine meshing was critical for capturing the intricate details of the device's operation. To extract the terminal current, transport and continuity equations were solved using the Newton technique, ensuring a precise calculation of current flow within the device. This careful attention to meshing and the use of advanced numerical methods were essential for optimizing the simulation's accuracy and reliability. The result is a highly detailed and accurate model that closely replicates the real-world behavior of the MISHEMT device, making it a valuable tool for design and analysis.

The enhancement-mode high-electron-mobility transistor (HEMT) on a diamond substrate, illustrated in Figure 1(a) and figure 1(b), is engineered with a layered epitaxial structure. This structure comprises a 25-nanometer Al0.05Ga0.95N layer, a 10-nanometer Al0.Ga0.75N layer,

Table 1 TCAD Parameters of Mobility Model

Parameter	Values
(kV/cm)	220.89
(10^7cm/s)	1.9094
	7.2044
	0.7857
	6.1973

and a 10-nanometer Al0.15Ga0.85N cap layer. To ensure high breakdown voltage and minimal gate leakage current, a 3-nanometer gate dielectric layer made of TiO2/HfO2 is incorporated. The E-mode operation of the transistor is enabled by the Al0.05Ga0.65N/Al0.10Ga0.75N heterostructure, combined with a recessed gate metal-insulator-semiconductor HEMT (MISHEMT) design. The Al0.15Ga0.85N cap layer is specifically engineered to control dispersion and reduce access resistance, with its thickness and aluminium mole fraction optimized for effective E-mode performance. Figure 1(c) indicates the aluminium content in the AlGaN barrier layer is crucial, as it significantly influences the spontaneous polarization (PSP) of the barrier. This careful adjustment of the aluminium concentration directly impacts the device's electrical characteristics, affecting performance metrics such as breakdown voltage and efficiency. The combination of these materials and structural elements is key to achieving the desired high-performance characteristics of the HEMT, making it well-suited for applications requiring high power handling and efficiency.

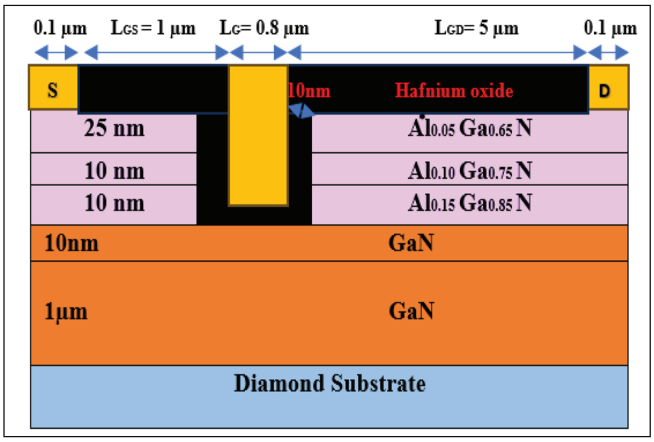

Fig.1(a): Device schematic for hafnium oxide dielectric

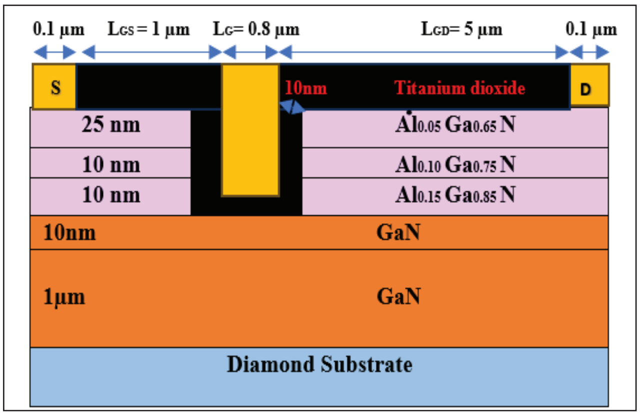

Fig. 1(b): Device schematic for titanium oxide dielectric

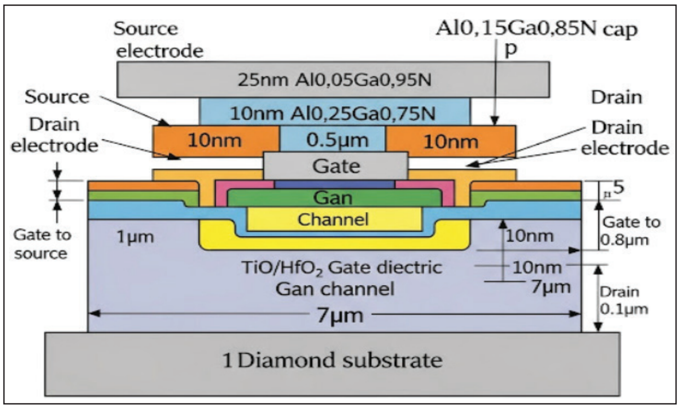

Fig. 1(c): modeling for TiO_2/HFO_2 Dielectric

Table 2. Physical parameter for TCAD simulation

Parameter	AIN	InN	GaN	Diamond
Dielectric constant (□0)	8.2	13.9	10.6	5.5
Electron mobility (µn) (cm^2/Vs)	298	3178	1498	2250
Breakdown field (V/cm)	12.1x106	0.9x105	2.8x106	10x106
Electron saturation velocity (vsat (m/s))	1.59 × 107	2.4x107	1.89x107	2.5 × 10^7
Band gap (Eg) (eV)	6.19	0.59	3.99	5.5

Figure 2 presents the simulation results for an enhancement-mode MISHEMT using TiO_2, compared with experimental data. The properties of various semiconductor materials are analyzed using Silvaco TCAD simulations. The device physics-based models utilized in this study accurately replicate the experimental results, demonstrating the effectiveness of the simulation approach in predicting device performance The device simulations were carried out using Silvaco

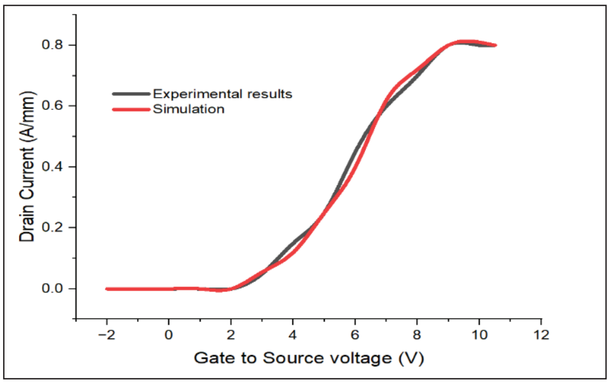

Fig. 2: Silvaco - TCAD Simulation comparing experimental and simulation

TCAD tools, specifically leveraging ATLAS, Deck Build, and TonyPlot. The MISHEMT structure was defined with layers including diamond substrate, GaN buffer, AlGaN barrier, high-κ dielectric (HfO_2/TiO_2), and metal gate. Material models incorporated bandgap narrowing (BGN), polarization effects, and mobility models like Doping and High Field Recombination mechanisms such as SRH, Auger, and Radiative were enabled. Boundary conditions included ohmic contacts at source/drain and Schottky or MIS contact at the gate. Neumann conditions were applied on symmetry edges. non-uniform meshing with fine refinement near the AlGaN/GaN interface and gate dielectric region ensured accuracy. Simulations involved DC bias sweeps and V DS solved using Gummel iterations and Newton-Raphson methods with tight convergence criteria. Thermal effects were initially ignored by applying isothermal conditions. The simulated RON values under stress makes the data to use various designs of AlGaN/GaN MISHEMT. This analysis used to identify the alteration of semiconductor technologies, mentioned in Figure 3.

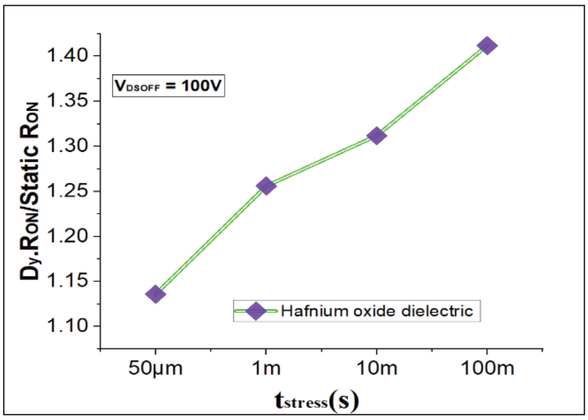

Fig. 3: Simulated RON with t stress of VDSOFF = 50 V (Dielectric HFO_2)

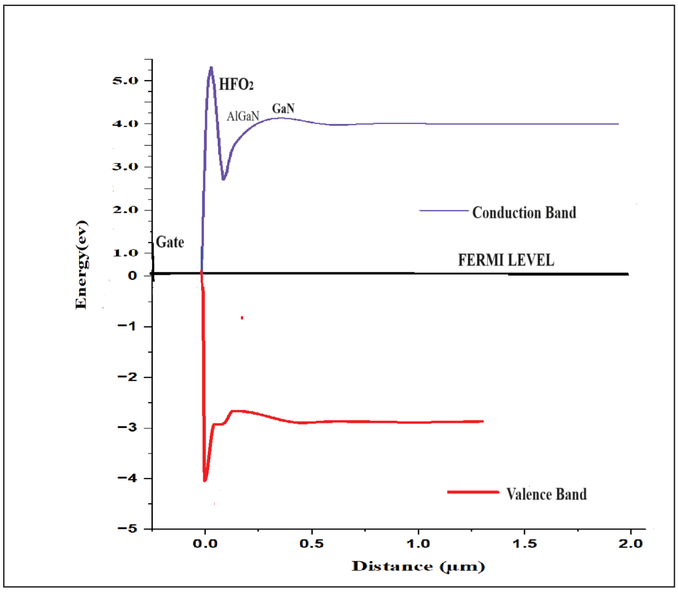

Fig. 4(a): Band diagram - E-Mode for HFO_2 dielectric MISHEMTs

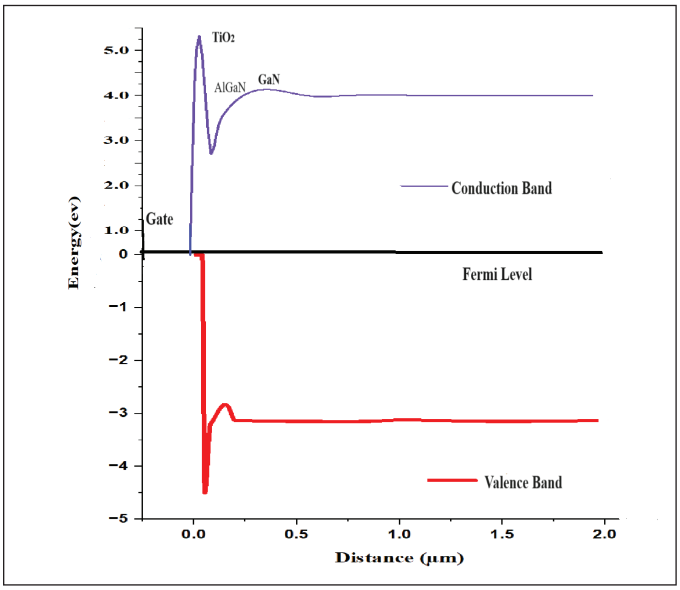

Figure 4(b): Band diagram - enhancement-mode (E-Mode) MISHEMTs TiO_2 dielectric

In enhancement-mode Metal-Insulator-Semiconductor High Electron Mobility Transistors (MISHEMTs), the choice of gate dielectric significantly impacts device performance, including gate leakage current, breakdown voltage, and overall reliability. This performance is closely linked to how well the dielectric material aligns with the semiconductor layers in the device, affecting the band diagrams and electric field distribution. In this discussion, we examine the effects of high-k dielectrics, specifically hafnium dioxide (HfO_2) and titanium dioxide (TiO_2), on the performance of MISHEMTs. Figures 4a and 4b present band diagrams showing the alignment of valence and conduction bands, as well as the Fermi level, for these dielectrics. Additionally, Figure 5 illustrates the electric field distribution within the devices as determined by TCAD simulations. Hafnium dioxide (HfO_2) is a high-k dielectric material with a dielectric constant of approximately 25. The band diagram of a MISHEMT using HfO_2 shows that its conduction band is positioned significantly higher than that of the AlGaN layer. This creates a substantial potential barrier, which has two primary effects: it reduces gate leakage current and enhances the breakdown voltage of the device. The high potential barrier formed by the HfO_2 conduction band is crucial for suppressing unwanted leakage currents, thereby improving the efficiency and reliability of the transistor under high-voltage conditions. Moreover, the valence band of HfO_2 is well-aligned with the AlGaN valence band, which is essential for regulating the flow of charge carriers. This alignment ensures that the carrier transport through the channel is controlled effectively, contributing to the transistor's overall performance. Its dielectric properties work in conjunction with HfO_2 to ensure an even distribution of the electric field across the gate dielectric and the underlying GaN channel. This helps in maintaining device stability, especially under high-frequency operation and significant power loads. The combined effect of HfO_2 and TiO_2 in smoothing the electric field distribution enhances the device's ability to perform reliably in various operating conditions. In addition to the choice of gate dielectric, the substrate material also plays a crucial role in device performance. Diamond, with its exceptional thermal conductivity, offers significant advantages in electric field management. The high thermal conductivity of diamond aids in dissipating the heat generated by the electric field, which helps prevent the formation of hot spots that could lead to thermal breakdown. This is particularly important for devices operating under high power conditions where heat management is critical for maintaining performance and reliability. Furthermore, diamond's wide bandgap supports higher breakdown voltages, allowing the device to handle more substantial electric fields without compromising performance. The ability of diamond to withstand high electric fields and temperatures make it an ideal substrate for high-power and high-frequency applications. The combination of diamond with high-k dielectrics like HfO_2 and TiO_2 results in a robust and efficient device capable of meeting the demanding requirements of modern electronics. Figure 5 provides a detailed visualization of the electric field distribution in MISHEMTs with TiO_2 and HfO_2 dielectrics, as determined by TCAD simulations. These simulations offer valuable insights into how the electric field behaves within the device, highlighting the differences between the two dielectric materials. The visualizations show how the electric field is influenced by the choice of dielectric material, providing a clearer understanding of its impact on device performance. The TCAD simulations reveal that HfO_2 contributes to a more uniform electric field distribution, which helps in reducing high-field regions and improving overall device reliability.

In figure 7 indicates the bandgap alignment, interface trap density, leakage current analysis, and breakdown voltage for both HfO_2 and TiOs. In high-power electronic applications, the breakdown voltage of Metal-Insulator-Semiconductor High Electron Mobility Transistors (MISHEMTs) is a critical parameter that defines the maximum voltage the device can handle before failing. For AlGaN/GaN MISHEMTs, enhancing breakdown voltage is essential to improve performance and reliability. The integration of high-k dielectrics like hafnium dioxide (HfO_2) and titanium dioxide (TiO_2), alongside the use of a diamond substrate, plays a pivotal role in achieving higher breakdown voltages. This combination optimizes

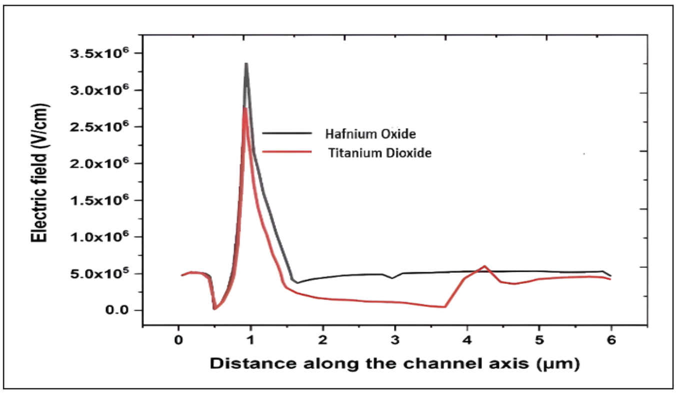

Fig. 5 Electric field distribution in MISHEMTs with TiO_2 and HfO_2 dielectric

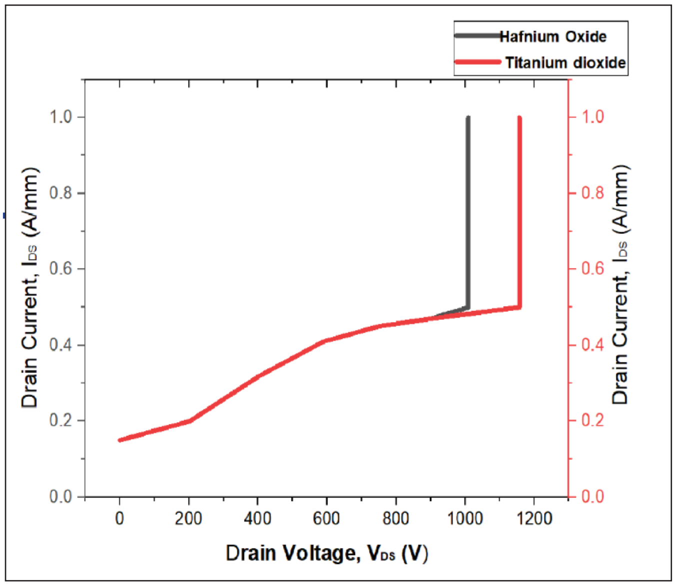

Fig. 6: breakdown characteristics - OFF-state for MISHEMTs- HFO_2 and TiO_2

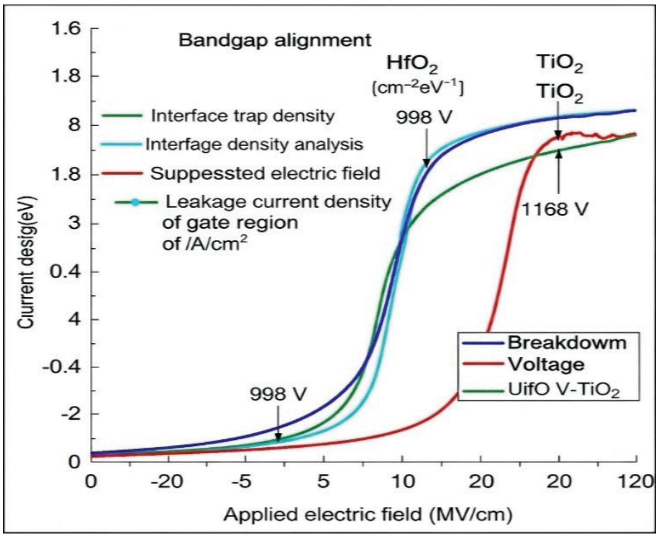

Fig. 7 Bandgap alignment, interface trap density, leakage current analysis, and breakdown voltage for both HfO_2 and TiOs

electric field distribution and mitigates issues related to thermal degradation. High-k dielectrics are materials with a high dielectric constant, which significantly affect the electric field distribution within MISHEMTs. HfO_2 and TiO_2 are two such high-k dielectrics that are known for their beneficial properties. HfO_2 has a dielectric constant of around 25, which is substantially higher than traditional silicon dioxide (SiO_2). This high-k material improves gate control over the channel and helps in reducing leakage currents. However, despite its advantages, devices with HfO_2 as the gate dielectric tend to show high electric fields around the gate region. This characteristic can lead to earlier breakdown under high-voltage conditions, as the electric field concentration increases the likelihood of device failure. TiO_2, with an even higher dielectric constant ranging from 80 to 100, aligns its conduction band closer to that of the AlGaN layer. This close alignment enhances gate control and transconductance, leading to better performance in high-frequency applications. TiO_2's dielectric properties help distribute the electric field more uniformly, reducing peak fields that contribute to premature breakdown. As a result, TiO_2-based MISHEMTs tend to exhibit higher breakdown voltages compared to those using HfO_2. Diamond is used as a substrate material in MISHEMTs due to its exceptional properties. The breakdown characteristics of MISHEMTs are analyzed in the OFF state of drain voltage versus drain current curves. Figure 6 illustrates the characteristics representation The breakdown voltage is identified by either a sudden increase in drain current or a sharp drop in drain voltage. For MISHEMTs constructed with an ultra-wide bandgap diamond substrate, the observed breakdown voltages are 998 V for devices with HfO_2 and 1168 V for those with TiO_2 as the gate dielectric. The difference in breakdown voltages can be attributed to the dielectric

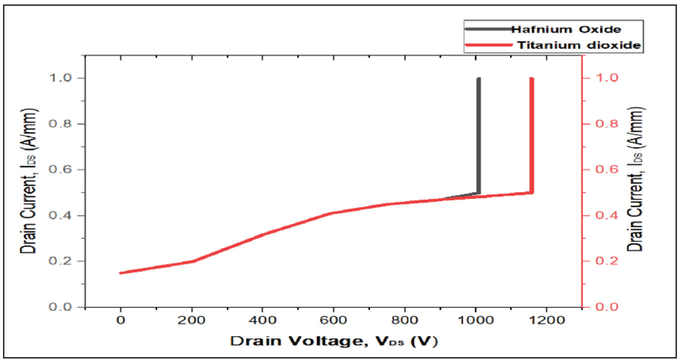

Fig. 8: breakdown characteristics in OFF-state MISHEMTs- HFO_2 and TiO_2

properties of the gate materials. MISHEMTs with HfO_2 as the gate dielectric tend to show higher electric fields around the gate region. This increased field intensity contributes to an earlier breakdown of the device, which can be observed in the breakdown characteristics. The electric field concentration around the gate in HfO_2-based devices leads to a relatively lower breakdown voltage of 998 V. In contrast, MISHEMTs with TiO_2 as the gate dielectric exhibit a more favorable electric field distribution. The high dielectric constant of TiO_2 results in a suppressed electric field near the gate region, which helps in achieving a higher breakdown voltage of 1168 V. This suppression of peak fields contributes to improved performance and reliability, particularly at compliance currents of 0.5 A. The compliance current level of 0.5 A is chosen for evaluating breakdown characteristics. wide bandgap and thermal conductivity are good for diamond substrate and also it supports the high-voltage operation and also it prevents reliability of device and thermal degradation. Figure 8 illustrates the breakdown voltage to achieve the materials with high breakdown voltages and overall performance of power and Figure 9(a) and 9b (b) represent the transconductance breakdown characteristics of the Hafnium and titanium diode dielectric MISHEMTs. Transconductance of 1.13 S/mm for titanium diode and Transconductance of 1.09 S/mm for HfO_2 insulator is achieve. Several factors considered for the transconductance, it includes substrate quality, gate length (LG), dislocation density, sheet carrier density (ns) barrier thickness and electron mobility (μ), The MISHEMTs on diamond substrates have high transconductance compared with different substrates used in HEMTs.

The cutoff gain frequency is a important parameter for AlGaN/GaN Metal-Insulator-Semiconductor High Electron Mobility Transistors Usage of High-k gates dielectric and advanced substrates will increase the fT values. High-k dielectrics like titanium oxide (TiO_2) and hafnium dioxide (HfO_2), play an important role in increasing of cutoff frequency. Dielectric materials like like titanium oxide (TiO_2) and hafnium dioxide (HfO_2)

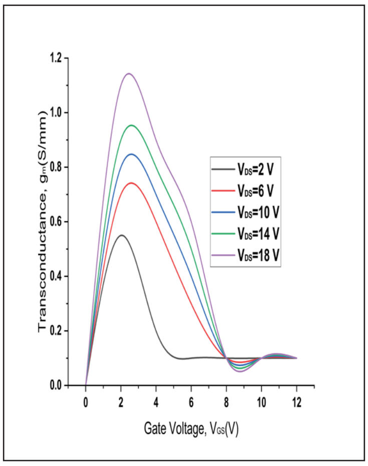

Figure 9(a): Transconductance - AlGaN/GaN MISHEMTs- Hafnium dioxide dielectric

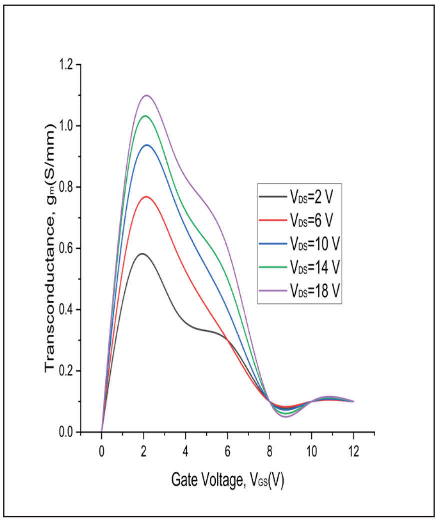

Figure9(b): Transconductance - AlGaN/GaN MISHEMTs- Titanium oxide dielectric

improves the gate control by increasing the dielectric constant, which decreasing the parasitic capacitances otherwise the reduce the transistor's speed. Thermal conductivity is high in diamond substrate used for AlGaN/GaN MISHEMTs. High thermal management makes the diamond to dissipates the heat effectively, thereby prevents the thermal degradation impact on negative performance with high frequencies. This thermal stability makes the device to maintains high-frequency performance and attain a maximum cutoff gain frequency. Figure 10 (a) and (b) indicates the cutoff frequency characteristics of both dielectric materials. TiO_2 dielectric MISHEMT on diamond substrate achieves an cutoff frequency (fT) of 49 GHz. HFO2 dielectric MISHEMTs with a cutoff frequency of 48 GHz. Thermal management, these advancements enable MISHEMTs to operate efficiently at high speeds and frequencies, making them well-suited for high-speed and high-frequency applications. The Johnson Figure of Merit (JFoM), calculated as JFoM = fT×VBR , is an essential measure for assessing the performance of AlGaN/GaN MISHEMTs, particularly when utilizing diamond substrates is as shown in figure 9. This metric combines two critical parameters: the cutoff frequency (fT) and the breakdown voltage (VBR). The cutoff frequency indicates the maximum frequency at which the transistor can operate effectively, while the breakdown voltage represents the maximum voltage the device can withstand before failure. Together, they reflect both the speed and the power-handling capability of the transistor. Diamond substrates offer significant advantages in this context due to their high thermal

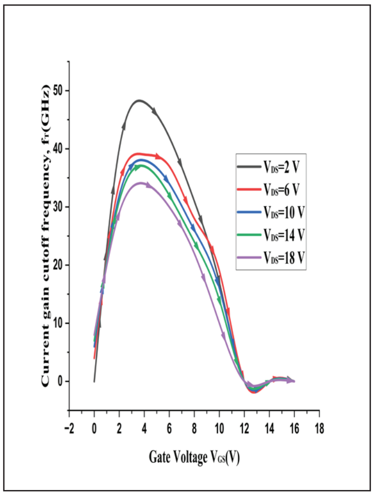

Figure 10(a): Current gain cutoff frequency for Hafnium dioxide dielectric

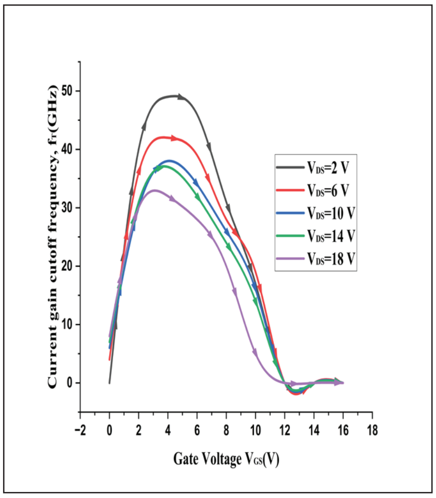

Figure 10(b): Current gain cutoff frequency for Hafnium dioxide dielectric

Table 3: comparison with existing MISHEMT technologies.

Number	Ref. no. year	Heterostructure details	Lg (μm)	Lgd (μm)	Ids (A/mm)	gm (mS/mm)	VBR (V)
1.	16, 2023	AlGaN/GaN with recessed gate on Si substrate	1	2	0.3	750	-
2.	17, 2021	Al_2O_3/AlGaN/GaN on Si substrate	2.1	12	0.22	10	-
3.	18, 2021	AlGaN/GaN with recessed gate SiC substrate.	0.3	3.5	1.2	-	-
4.	19, 2020	p-GaN/AlGaN/GaN on β-Ga_2O_3 substrate	0.9	4	0.94	501	826
5.	20, 20	HfO_2/AlGaN/GaN on sapphire substrate	0.51	1.5	0.1	254	43
6.	21, 2024	SiO_2/AlGaN/GaN on Si substrate	1	3	0.5	80	-
7.	22, 2024	p-GaN/AlGaN/GaN on SiC substrate	0.46	1.9	1.1	149	64
8.	23, 2023	SiO2/AlGaN/GaN on Si substrate	2	12	0.49	56.4	-
9.	This work	HFO2/TiO_2 on Diamond substrate	0.8	5	3.6	1130	998/1168

conductivity and excellent electrical properties. The high thermal conductivity of diamond helps manage heat efficiently, which is crucial for maintaining high performance at elevated frequencies. This enhanced thermal management contributes to higher Ft values, making diamond substrates suitable for high-speed applications. Moreover, diamond's superior dielectric strength enhances the breakdown voltage. The high breakdown voltage of devices on diamond substrates means they can operate reliably under extreme conditions without experiencing premature failure. This high breakdown voltage is particularly important for high-power applications, where managing power dissipation and maintaining device integrity is critical. As a result of these benefits, AlGaN/GaN MISHEMTs on diamond substrates often achieve a higher JFoM compared to those on traditional substrates. This improved JFoM reflects the combination of enhanced speed and power-handling capability, positioning diamond as an excellent choice for advanced high-frequency and high-power applications. Looking ahead, ongoing research and development in this area are expected to further enhance the JFoM for AlGaN/GaN MISHEMTs on diamond substrates. Advances in material processing and device engineering are likely to push the boundaries of performance, paving the way for next-generation devices with even greater capabilities. This progress will be instrumental in driving innovations across various high-performance fields, from telecommunications to power electronics. Diamond's unparalleled thermal conductivity ensures optimal heat dissipation, which is crucial for maintaining performance

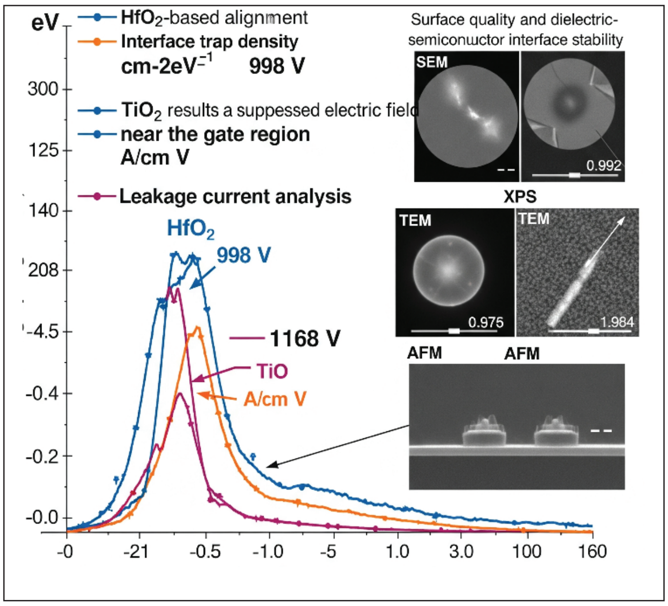

Fig. 11: TEM, SEM, AFM, and XPS data - validate the interface stability and surface quality.

in high-power applications. Integrating MISHEMTs RF-VLSI platforms is attainable but have to faces more key challenges. Thermal management is important for diamond substrates; it achieves interfacial resistance. Process integration makes sure dielectric compatibility and contamination-free fabrication. figure 11 illustrates the information taken HfO_2-based devices attained breakdown voltage of 998 V, iO_2 with a breakdown voltage of 1168 V. Additionally, the image includes TEM, XPS, SEM and AFM data this makes to validate the interface stability and surface quality.

Conclusion

AlGaN/GaN MISHEMTs with diamond substrates make the device transformative enhancement and significantly improve their performance metrics. Diamond's higher thermal conductivity makes higher heat dissipation an important factor in maintaining stability in high-power applications and RF applications. Additionally, high breakdown voltage for diamonds makes enhanced electron mobility and improved device efficiency and reliability. advances semiconductor technology by integrating the high-k gate dielectrics, such as titanium oxide (TiO_2) and hafnium dioxide (HfO_2). High-k materials improve the device performance of transconductance, gate control, and higher breakdown voltages by changing the leakage currents and peak electric fields to minimise. The diamond substrate makes thermal management and ensures performance under the need for frequency conditions and high power. This research mainly focuses on integrating these advanced MISHEMTs into practical circuits and systems, evaluating their performance and durability in real-world high-frequency and high-power environments.

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