IJE TRANSACTIONS C: Aspects Vol. 36 No. 09, (September 2023) 1652-1658

International Journal of Engineering

Journal Homepage: www.ije.ir

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

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PAPER INFO

Paper history:
Received 12 June 2023
Received in revised form 24 June 2023
Accepted 05 July 2023

Keywords:
Silicon Dioxide
Radio Frequency
Transconductance
High Conductivity
High Electron Mobility Transistor

ABSTRACT

We have designed and simulated a 10-nanometer regime gate High Electron Mobility Transistor (HEMT) with an undoped region (UR) under the gate with high k dielectric as hafnium oxide (HfO2). The thickness of metal gate(G) and undoped regions are equal but length of channel(C) is not equivalent. The proposed Undoped under the gate dielectric High Electron Mobility Transistor reduces the maximum electric field(V) in the channel region and increases the drain current significantly. The High-K dielectric High Electron Mobility Transistor structure obtained a saturated Ion current of 60% higher than the conventional structure. For High critical Power and High-frequency Power transmission Amplifiers utilizes the AlGaN/GaN/SiC-based High Electron Mobility Transistor with an undoped region under the gate with High-K Hafnium oxide. The Proposed advanced High Electron Mobility Transistor Produces a higher Drain current (Id), 54% high transconductance (Gm) with Low On-Resistance (Ron), and High conductivity in comparison to typical High Electron Mobility Transistor. In Addition to these improved characteristics, the Electric field along the Y direction is also observed. The proposed structure formed by Low-k Dielectric materials in the process of Silicon Dioxide(SiO_2) and High-k dielectric being Titanium Dioxide (TiO_2) and Hafnium Oxide (HfO_2) created more opportunities in Power electronics and radio frequency operations.

***doi**: 10.5829/ije.2023.36.09c.09*

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 SiO_2 and High-K dielectric material being hafnium oxide represented as HfO_2 and Titanium Dioxide (TiO_2) [3]. Due to its heterostructure undoped channel is possible in Nanowire HEMT and

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Please cite this article as: E. Radhamma, D. Vemana Chary, A. Krishnamurthy, D. Venkatarami Reddy, D. Sreenivasa Rao, Y. Gowthami, B. Balaji, Performance Analysis of High-K Dielectric Heterojunction High Electron Mobility Transistor for RF Applications, ***International Journal of Engineering, Transactions C: Aspects***, Vol. 36, No. 09, (2023), 1652-1658

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_d=0.032µm, L_{gs}=0.015µm, L_{ds}=0.015µm, and L_u=0.08µm, 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

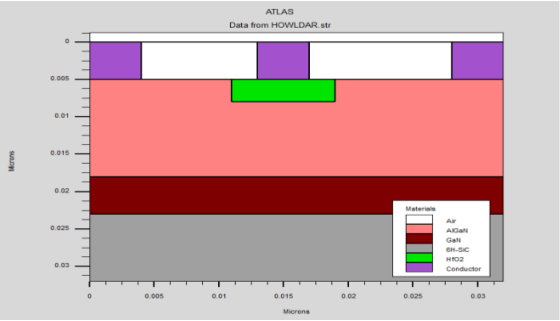

Figure 1. Cross-sectional View of High-k Dielectric AlGaN/GaN HEMT

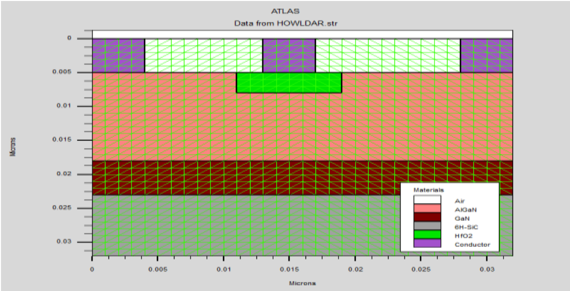

Figure 2. Mesh View of High-k Dielectric AlGaN/GaN HEMT Structure

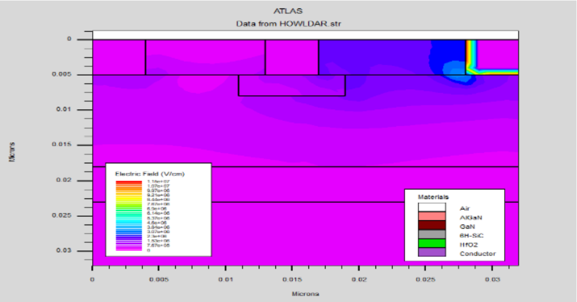

Figure 3. Electric Field Distribution of High-k Dielectric AlGaN/GaN Device

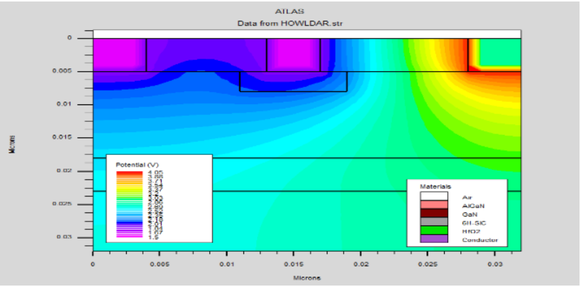

Figure 4. Potential Distribution of high-k dielectric AlGaN/GaN Device

suitable for real-time applications. HfO_2 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.HfO_2 material insertion effectively addresses these issues by reducing channel length dependence and improving device behavior at smaller dimensions. HfO_2 material offers improved gate control and reduced gate leakage current, resulting in lower power consumption compared to previous works.

By integrating Hafnium Dioxide (HfO_2) into the gate structure of AlGaN HEMTs, a notable improvement in breakdown voltage can be achieved compared to previous dielectric materials. HfO_2 exhibits exceptional thermal stability, making it a highly reliable choice for the gate structure of AlGaN HEMTs with reduced gate length. The compatibility of HfO_2 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 HfO_2 gate structures, making it more practical for large-scale

TABLE 1. Utilized Device performance Parameters

Parameter used for device	Value
Device Length	0.032μm
Length of the Gate	0.005μm
Source to Gate space	0.015μm
Gate to drain Space	0.015μm
Length of undoped region	0.008μm
Length of Source	0.004um
Length of Drain	0.004um
Doping of Channel(D_C)	$1x10^{20}$ cm^{-3}
Work function =4.87eV	

TABLE 2. Utilized Methods for simulation of Proposed structure

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

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 Vt 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 (Id) 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 (Ioff) 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].

TABLE 3. Utilized Models for simulation of Proposed structure

Material Model	Description
conmob	Concentration Dependent
srh	Uses fixed minority carrier lifetimes
Auger	Used as high current densities
fldmob	Parallel Electric Field Dependence

$$Drain\ Conductance(G_d) = \frac{\delta I_{ds}}{\delta V_{ds}} \tag{1}$$

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

$$Transconductance(G_m) = \frac{\delta I_{ds}}{\delta V_{gs}} \tag{2}$$

The simulated on-resistance (Ron) Vs drain voltage (V_d) as shown in Figure 9. As drain conductance

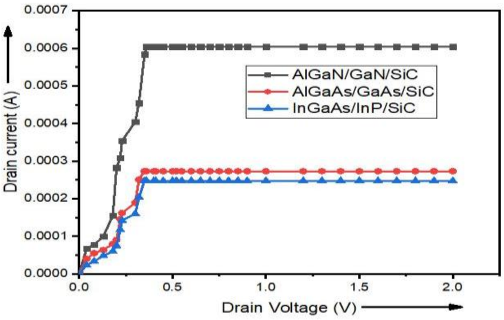

Figure 5. Variation of Drain current Vs Drain voltage for different hetro combination material

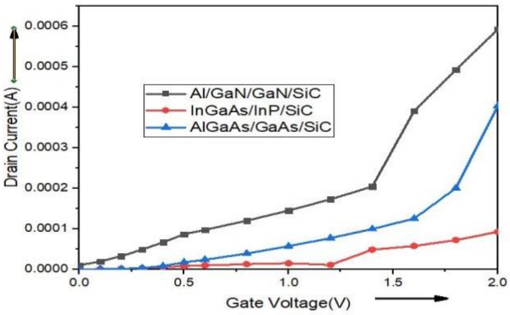

Figure 6. Variation of I_d Vs V_{gs} for different hetro combination materials

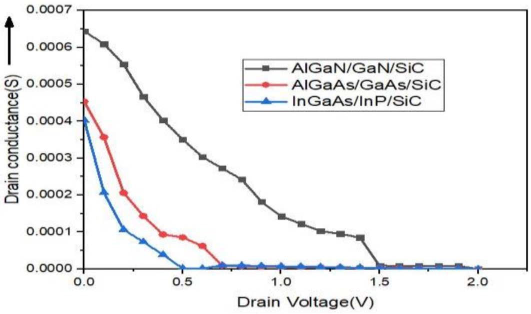

Figure 7. Variation of G_d Vs V_{ds} for different hetro combination materials

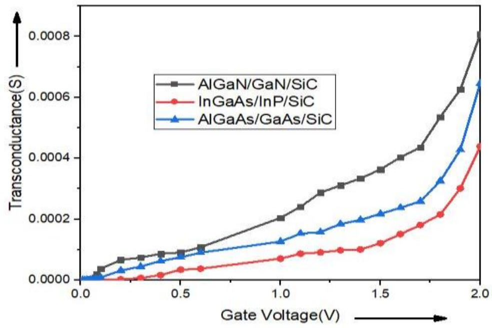

Figure 8. Variation of G_m Vs V_{gs} for different hetro combination materials

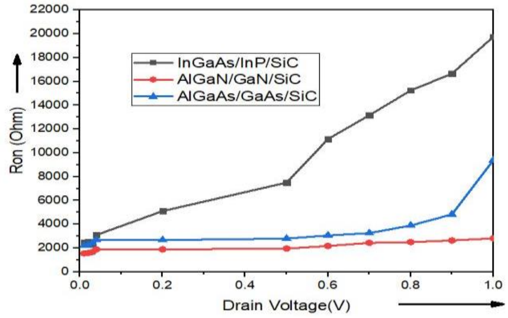

Figure 9. Variation of R_{on} Vs V_{ds} for different hetro combination materials

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.

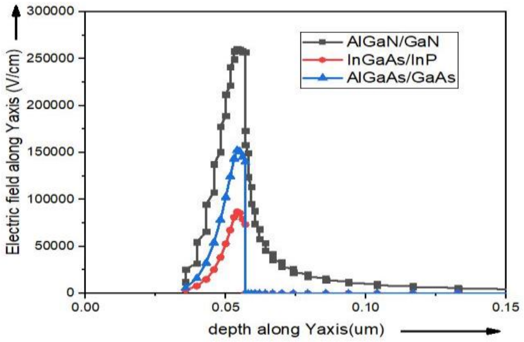

Figure 10. Electric Field Along Y-axis for different hetro combination materials

TABLE 4. Performance metrics for proposed structure

Parameter	AlGaN/GaN/ SiC	AlGaAs/ GaAs/SiC	InGaAs/InP/SiC
Ion(A)	5.92E-04	1.70E-04	2.21E-05
Ioff(A)	1.39E-13	2.90E-17	9.27E-12
Ion/Ioff	4.20E+09	5.80E+12	2.30E+06
Gd(S)	6.43E-04	4.53E-04	4.03E-04
Ron(ohms)	1.56E+02	2.20E+02	2.48E+02
Vth(V)	0.2	0.35	0.5
Gm(S)	8.07E-04	6.46E-04	4.38E-04

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 AlGaAs, leading to improve operation 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.

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

Silvaco TCAD simulator. The undoped region of the new HEMT structure made of high k material as hafnium oxide (HfO_2) material with AlGaN as channel, and silicon carbide (SiC) as the substrate. The GaN material-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.

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Persian Abstract

چکیده

ما یک گیت رژیم 10 نانومتری ترانزیستور تحرک الکترونی بالا (HEMT) را با یک منطقه خنثی (UR) در زیر دروازه با مواد دی الکتریک با k بالا که اکسید هافنیوم (HfO_2)است، طراحی و شبیه سازی کرده ایم .ضخامت دروازه و مناطق undoped برابر است اما طول کانال برابر نیست .ترانزیستور تحرک الکترونی بالا در زیر دی الکتریک گیت، حداکثر میدان الکتریکی (V) را در منطقه کانال کاهش می دهد و جریان تخلیه را به طور قابل توجهی افزایش می دهد .ساختار ترانزیستور تحرک الکترونی بالا دی الکتریک High-K جریان یون اشباع شده60 ٪ بالاتر از ساختار معمولی را به دست اورد .برای قدرت بحرانی بالا و فرکانس بالا تقویت کننده های انتقال قدرت با استفاده از AlGaN / GaN / SiC مبتنی بر ترانزیستور تحرک الکترون بالا با یک منطقه undoped زیر دروازه با مواد دی الکتریک بالا K به عنوان اکسید هافنیوم .ترانزیستور پیشرفته تحرک الکترون بالا پیشنهادی جریان تخلیه بالاتر(Id) ، ترانسرسانانس بالا54 ٪ (Gm) با مقاومت کم (Ron) و هدایت بالا در مقایسه با ترانزیستور تحرک الکترون بالا معمولی تولید می کند .علاوه بر این ویژگی های بهبود یافته، میدان الکتریکی در امتداد جهت Y نیز مشاهده می شود .ساختار پیشنهادی تشکیل شده توسط مواد دی الکتریک کم k در فرایند سیلیکون دی اکسید (SiO_2) و مواد دی الکتریک با کیفیت بالا مانند دی اکسید تیتانیوم (TiO_2) و اکسید هافنیوم (HfO_2) فرصت های بیشتری را در زمینه های الکترونیک قدرت و فرکانس رادیویی VLSI ایجاد کرده است.