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Effect of ZrO_2 Dielectric over the DC Characteristics and Leakage Suppression in AlGaN/InGaN/GaN DH MOS-HEMT

V. Sandeep, J. Charles Pravin*

Kalasalingam Academy of Research and Education, Virudhunagar, Tamil Nadu, India

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The device performance of AlGaN/InGaN/GaN Double Heterostructure Metal-Oxide-Semiconductor High Electron Mobility Transistor (DH MOS-HEMT) upon using 10 nm thick Zirconium Dioxide (ZrO_2) as dielectric is studied here. Oxide dielectrics play an important role in forming Two-Dimensional Electron Gas (2DEG). An analytical model is proposed for evaluating the charge density, carrier concentration, drain current, transconductance, and gate capacitance of the device. ZrO_2 based DH MOS-HEMTs display exceptional performances such as maximum drain current density ($I_{D\max}$) and transconductance ($g_{m\max}$) in comparison to InGaN based HEMTs. Due to the high-quality 2DEG ace between ZrO_2 and the AlGaN barrier layer, the MOS-HEMT demonstrates excellent carrier concentrations and gate capacitances. Also, electrostatic analysis at various interfaces is carried out and the impact of InGaN layer thickness over the 2DEG enhancement is investigated. An exceptional agreement is formed between the experimental results from the literature and the produced outputs. Incorporating a strong high-*k* dielectric material like ZrO_2 results in an effective leakage suppression in the range of 10^{-7} mA/mm. The results show that the device could be a feasible solution for both high-power switching and microwave applications.

Keywords: AlGaN/GaN, Double heterostructure, MOS-HEMT, InGaN, ZrO_2, Capacitance, Threshold voltage.

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1. INTRODUCTION

Silicon material poses a threat to the microelectronics revolution by keeping the device from performing at high frequencies while scaling down further. Attention turns over to a more diverse group of materials that approaches the problem of group III-V semiconductors [1]. Gallium nitride (GaN) is one of the best alternatives for silicon that could be used for high power switching and high frequency applications [2]. High electron mobility transistors (HEMTs) can be built using GaN materials, which have an improved breakdown voltage (VBR) than other low power devices and could withstand conductivity to a higher extent [3]. AlGaN/GaN based HEMTs have found intense popularity in the early years due to their capability to form polarization induced charge densities of the order of 10^{13} cm^{-2} inside the triangular potential well [4]. They could also operate at gigahertz frequencies with increased output power density and analyze different levels of traps at the interface [5].

AlGaN/GaN HEMTs also benefit from low gate leakages and low switching losses, which proves the device possible potential in millimeter-wave applications [6]. When dielectrics are used for insulation, the threshold voltage of the MOS-HEMT tends to shift negatively. There are traps grown in AlGaN/GaN HEMTs which provoke a negative shift in the pinch-off voltage and cause the occurrence of parasitic effects in the device [7]. InGaN back-barriers are used to eliminate parasitic effects in AlGaN/GaN devices [8]. Using InGaN as a notch layer, the buffer leakage current is reduced as well as the quality of 2DEG mobility is improved [9, 10]. Confining 2DEGs in InGaN/GaN quantum wells determines the polarization-induced electric fields and interface charges [11]. There have been multiple quantum wells implemented using InGaN material, thereby increasing the current drives and confining electrons near the 2DEG [12]. There was still an issue arising regarding the gate leakage effects in the device. MOS-HEMT devices were used to overcome this issue by using an oxide or dielectric layer near the metal region. A high-*k* material could considerably reduce the gate leakage and power dissipation of the device and also enhance the gain and output resistance [13]. A high-*k* passivation used for AlGaN/GaN heterostructure helped to increase its breakdown voltage and enhance its frequency of operation to about 10 GHz [14]. Earlier HEMT devices used SiO_2 as a MOS-gate [15]. HfO_2 is another high-*k* dielectric material that can be used as an oxide basically for AlGaN/GaN MOS-HEMTs, which could thereby provide high current drives and transconductance [16]. However, due to the difficulty arising in the fabrication stages, this material is prone to less consideration. ZrO_2 is also a prominent dielectric material that can be used as a gate oxide for MOS-HEMT devices [17]. Low gate leakage is obtained upon employing ZrO_2 as a gate dielectric in AlGaN/GaN devices [18].

However, incorporating oxide layers above the $Al_xGa_{1-x}N$ barrier layer creates trap densities at the interface between the oxide and AlGaN. Hence, this work concentrates on evaluating the DC characteristics of the AlGaN/InGaN/GaN heterostructure by employing ZrO_2 as the dielectric layer. The interface charges between the dielectric and semiconductor (ZrO_2/AlGaN), and semiconductor layers (AlGaN/InGaN) and (InGaN/GaN) have also been evaluated.

The rest of the manuscript is organized as follows. Section II discusses the structure of the proposed device and the model formation. Section III reports the results analyzed for the proposed structure. Finally, section IV draws the conclusions of the article.

2. MODEL FORMULATION

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* jcharlespravin@gmail.com

The cross-sectional illustration of the proposed DH MOS-HEMT structure is shown in Fig. 1. AlGaN is used as the silicon-doped barrier having a thickness of 15 nm, and GaN is the undoped buffer layer. There is an *n*-type doped InGaN interlayer between AlGaN and GaN layers, which could be used as a channel. Both the barrier and interlayers are doped with *n*-type bulk concentrations of 2×10^{17} cm^{-3} and 1×10^{18} cm^{-3}, respectively. ZrO_2 is used as the oxide/dielectric region. The gate region ($L_G = 100$ nm) has aluminum metal stacking since it has low contact resistance. Since the device is of low dimension, Short Channel Effects (SCE) occur and create imperfect confinement of electrons near the 2DEG, causing a large pinch-off in the device. The confinement problems in the device can be eliminated, and the concentration of holes can also be increased by using the InGaN layer.

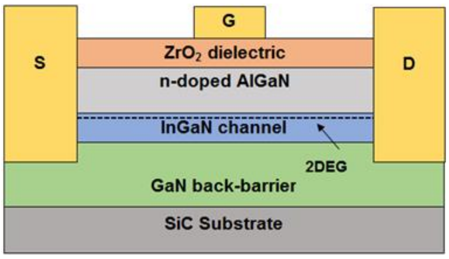


Fig. 1 – The cross-sectional diagrammatic illustration of the proposed DH MOS-HEMT structure

2.1 2DEG Charge Density Model

Deriving an expression for the density in the 2DEG area requires discussion of the dependence of the Fermi level E_F on the carrier concentration n_S. The electrostatic analysis leads to this formation:

$$q\Phi_B - F_1 t_{AlGaN} - \Delta E_C + E_F = 0, \qquad (1)$$

F_1 is the electric field in the AlGaN layer. The continuity of displacement action at the AlGaN/InGaN interface results in the following equations:

$$\varepsilon F_1 = q t_{AlGaN} - q n_S, \qquad (2)$$

$$\varepsilon F_2 = q t_{InGaN}, \qquad (3)$$

F_2 represents the electric field in the InGaN layer, ε is reported as the average dielectric constant between the AlGaN, InGaN and GaN layers.

The polarization vector along the *c*-axis directed from nitrogen towards gallium forms an internal electric field in the opposite direction to that of the electron wave offset, which is called spontaneous polarization. Evaluation of the total carrier concentration requires the contribution of both piezoelectric and spontaneous polarizations.

σ_{tot} is the total polarization charge density at the 2DEG area. Eventually, the total carrier concentration (n_s) is simplified as:

$$n_S = \frac{\sigma_{tot} + \frac{\varepsilon}{qt_1}\left(\gamma(\phi_M - \chi_1) + (1-\gamma)\phi_0 - \frac{\gamma q N_D t_1}{C_{ox}} + E_F - \Delta E_C\right)}{1 + \frac{\varepsilon}{qt_1}\left(\frac{1}{n_0} + \frac{1}{D}\right)}, \qquad (4)$$

D is the effective density of states of electrons.

The dependence of the 2DEG concentration on the channel thickness cannot be easily predicted due to the progressive formation of 2DHG as the InGaN/GaN interface. This occurs when the thickness of InGaN channel is increased without varying the AlGaN thickness. This leads to the electrons passing through two different sources: i) through 2DHG at the InGaN/GaN interface and ii) through the surface donor states in the AlGaN layer, provided by n_0 and E_d. The expression occurring at the InGaN/GaN interface can be formulated as follows:

$$\varepsilon F_2 = q\sigma_2 - qD_h(F_2 t_1 - E_F - E_G), \qquad (5)$$

F_2 is the electric field in the InGaN layer, D_h is the density of hole states at the InGaN/GaN interface, and E_G is the energy band gap.

2.2 Threshold Voltage

Originally there are continuous energy states present at the oxide/AlGaN interface, having a neutral state in the center. States above this are acceptor states devoid of any electrons, and those below are termed donor states, i.e., occupied with electrons. The interface charge (Q_{it}) is evaluated by taking into consideration the ionized states present between the Fermi level and E_0.

Thus, the threshold voltage is given as:

$$V_T = \frac{\phi_{MS} - \frac{t_{ox}(Q_{ox} + Q_{it})}{\varepsilon_{ox}} - \frac{q\sigma_{tot} t_1}{\varepsilon_1}}{1 + \frac{t_{ox} q D_{it}}{\varepsilon_{ox}}}, \qquad (6)$$

where ΔE_C is the conduction band offset, t_{AlGaN} is the thickness of the AlGaN barrier layer.

The drain current for the proposed heterostructure when operating in the linear region is evaluated using the threshold voltage by the following equation:

$$I_D = \frac{\mu(E) C_{eq}}{2}\left(\frac{W}{L_{SD}}\right)\left[(V_{GS} - V_T)V_{DS} - V_{DS}^2\right]. \qquad (7)$$

Here, I_D is the drain current, V_{GS} is the gate-source voltage, V_{DS} is the drain-source voltage, L_{SD} is the distance from the source to the drain, and *W* is the width of the channel.

3. RESULTS AND DISCUSSION

A model has been evaluated to find the DC characteristics and gate capacitances of the proposed ZrO_2/AlGaN/InGaN/GaN double heterostructure. Due to the InGaN layer, having an opposite piezoelectric polarization to the AlGaN barrier, an increase in the conduction band edge at the GaN/InGaN interface is detected, and a crisp potential barrier is formed near the 2DEG. A barrier with such dimensions can confine electrons better and enhance the buffer isolation. With increasing thickness of the AlGaN barrier from 1 to 10 nm, the sheet carrier concentration raises from 3.8×10^{10} to 9.8×10^{12} cm^{-2} for a fixed Al mole concentration value of 0.13. Fig. 2 depicts the variation of carrier concentration over the barrier thickness. Compared to a DH-HEMT structure, upon incorporating ZrO_2 as an oxide/dielectric layer, the concentration increases almost threefold.

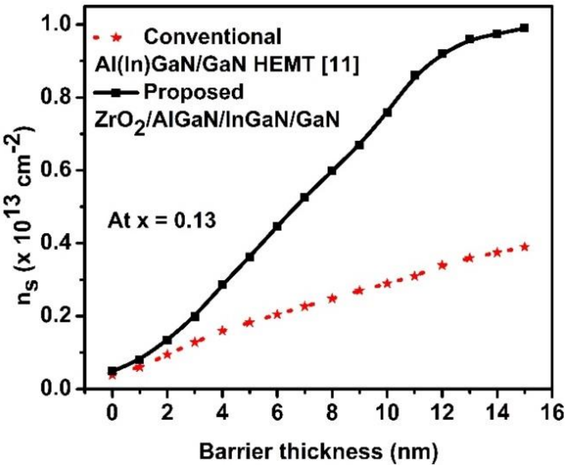


Fig. 2 – Carrier concentration for ZrO$_2$/AlGaN/InGaN/GaN DH MOS-HEMT

A barrier with very low thickness often leads to high leakage current, which is a crucial problem for high power devices. The surface of the transistor ought to be passivated with a particular oxide or dielectric layer to reduce leakage. Hence, we have used ZrO$_2$ as the dielectric to take care of the leakage problem and also to increase the transconductance. The barrier layer thickness causes a significant variation in the electron concentration in the 2DEG. The threshold voltage of the device is affected by both the barrier and dielectric layers.

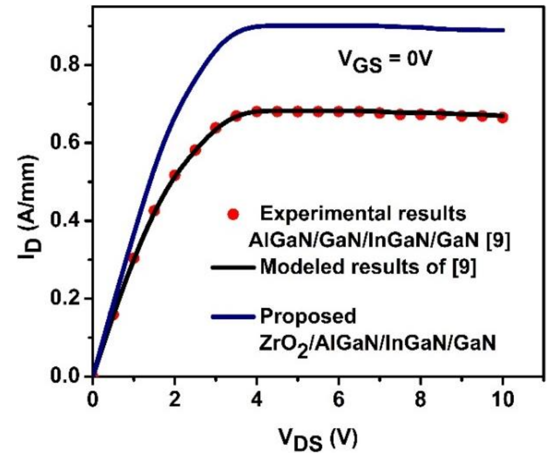
The DC characteristics for AlGaN/GaN/InGaN/GaN HEMT are shown in Fig. 3a. J. Liu et al. experimented on the AlGaN/GaN/InGaN/GaN HEMT heterostructure using a double heterojunction with reduced buffer leakage. A maximum saturation drain current of 680 mA/mm was achieved for a gate bias of 0 V. A InGaN notch layer of 3 nm was used here. The above-mentioned experimental data have been given in Fig. 4 along with their corresponding modeled outputs from the proposed model, showing excellent agreement.

The output characteristics of the proposed AlGaN/InGaN/GaN heterostructure have been plotted in Fig. 3b. The drain current is evaluated at different gate voltages varying from 1 V to – 3 V. The proposed MOS-HEMT device exhibits excellent current drive and pinch-off characteristics. There is a significant enhancement in the pinch-off quality of the ZrO$_2$ device at a V_{GS} of – 3 V. The steady oxide/barrier interface renders high gate bias. Due to this effect, there is a large current being able to flow through the channel. A maximum drain current density of 1.16 A/mm was delivered for the ZrO$_2$-based DH MOS-HEMT with a gate bias of 1 V.

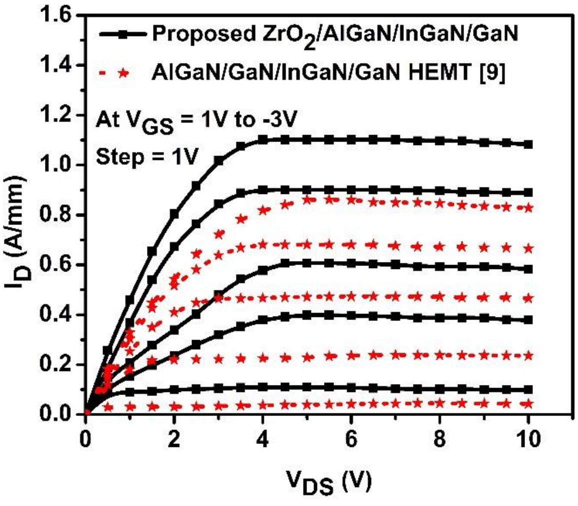
The positive shift of the pinch-off voltage in the conventional HEMT device is due to the sign of the polarization field in InGaN, which is opposite for AlGaN. There is an improvement in the pinch-off quality for ZrO$_2$-based MOS-HEMT, which leads to suppression in Drain Induced Barrier Lowering (DIBL).

Fig. 4a represents the transfer characteristics of AlGaN/InGaN/GaN MOS-HEMT devices with both gate dielectrics for a fixed gate length of 100 nm. ZrO$_2$-based DH MOS-HEMT device displays an excellent current drive of 0.983 A/mm for a drain source bias of 3 V. The devices have comparable ON-state characteristics. The threshold voltage of the device is derived from the linear region of the I_D-V_{DS} curve at low drain bias, i.e., 1 V, and the shift is consistent with the I_D-V_{GS} curve. Since ZrO$_2$ MOS-HEMT is known to exhibit current collapse, the effect causes the threshold value of the device to remain more negative than that of a conventional HEMT device. The change in transconductance (g_m) with gate voltage is shown in Fig. 4b. Since the dimensions used for the barrier and oxide layers are low, the gate to channel distance is reduced. There is a negative shift in the threshold voltage for the proposed device due to the use of a dielectric/oxide layer. A peak transconductance value of 248 mS/mm is measured for the proposed DH MOS-HEMT device at a V_{GS} of 3 V.

Capacitance-voltage measurements were carried out on the proposed structure. Electrons flow (or) diffuse from the AlGaN barrier and the capacitance converges towards the gate capacitance near the dielectric layer. Various parameters such as AlGaN and GaN thickness, dielectric thickness, doping concentration, work function difference between metals, and electron affinity of the barrier influence the shape of the C-V curve.

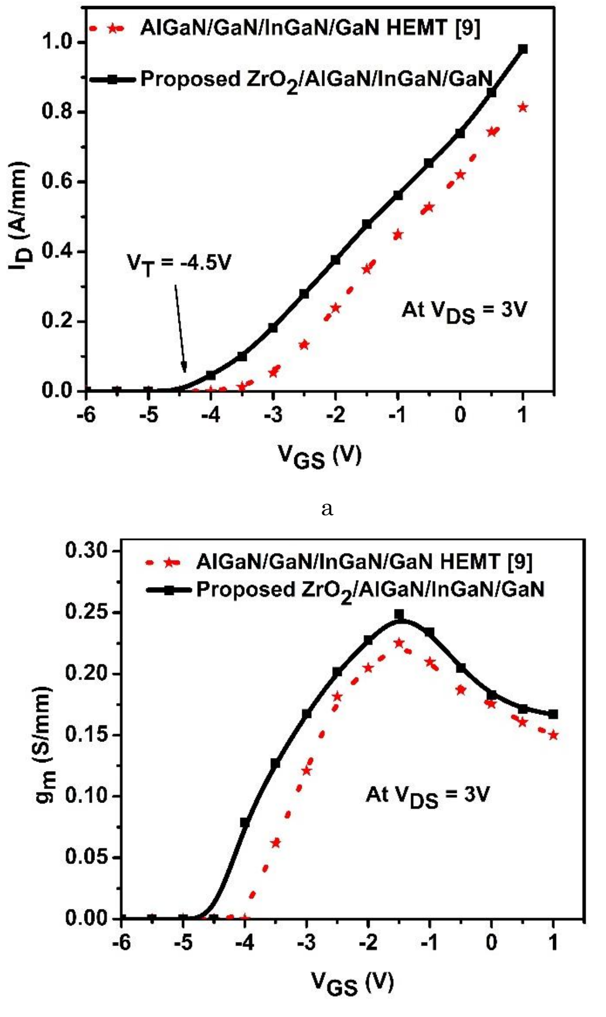


a



b

Fig. 3 – a) I-V characteristics of the experimental results shown in [9] evaluated using the proposed model; b) output characteristics of the proposed MOS-HEMT



a

b

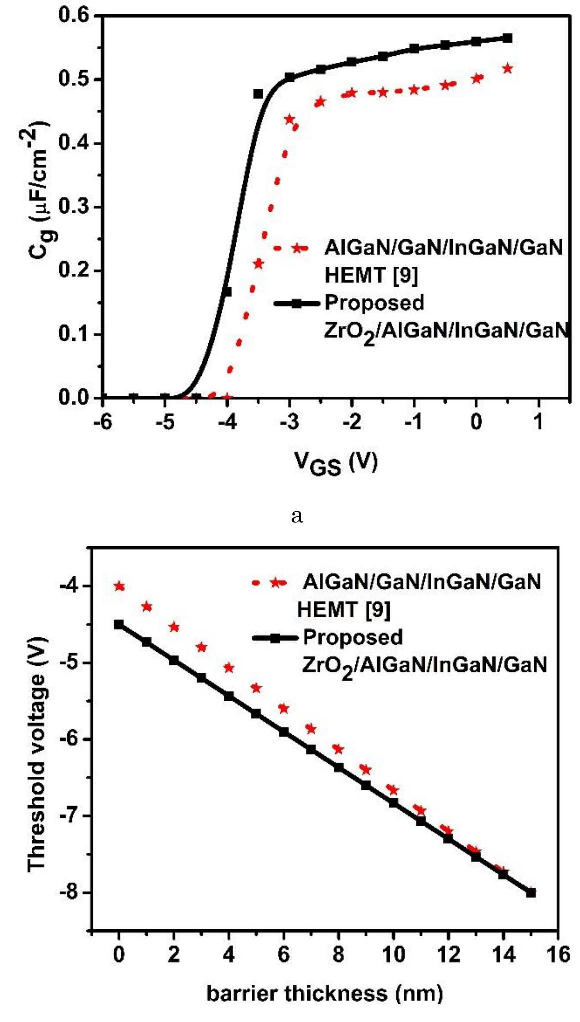
Fig. 4 – a) Transfer characteristics of the proposed MOS-HEMT with constant drain-source voltage of 3V; b) dependence of transconductance (g_m) on gate-source voltage for AlGaN/InGaN/GaN MOS-HEMT with ZrO_2 dielectric

The comparison of the gate capacitance for both the proposed DH MOS-HEMT structure and the conventional HEMT structure is shown in Fig. 5a.

At low V_{GS}, the value of the gate capacitance is very low and nearly zero, and mainly depends on the parasitic capacitance. However, it starts increasing with an increase in the value of V_{GS}. The maximum gate capacitance of 0.57 μF/cm^{-2} is achieved for the proposed ZrO_2/AlGaN/InGaN/GaN DH MOS-HEMT device across the gate beyond V_T. The gate capacitance is very small below V_T, since there is minimal sheet charge density in that region. Fig. 5b displays the variation of threshold voltage at different barrier thicknesses.

The proposed model depicts a decrease in V_T with an increase in AlGaN thickness. A negative threshold voltage shift is observed for the proposed DH MOS-HEMT device due to the use of the dielectric layer.

Gate leakage in the MOS-HEMT device is depicted in Fig. 6. The reduction in gate leakage strongly demonstrates the enhancement in buffer isolation by the potential barrier between the channel and GaN buffer.



a

b

Fig. 5 – a) Comparison of gate capacitance for the proposed MOS-HEMT with ZrO_2 dielectric layer; b) threshold voltage for the proposed MOS-HEMT device compared to the conventional DH-HEMT device [9]

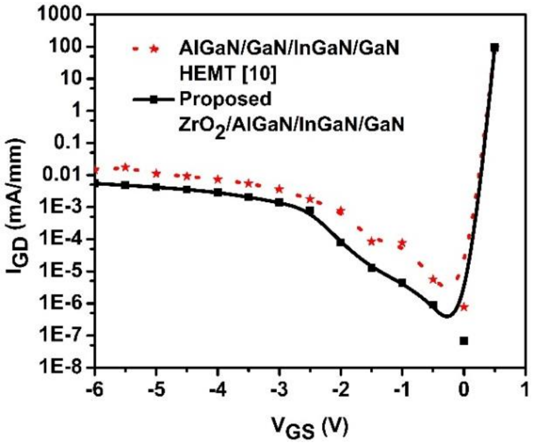


Fig. 6 – I_G-V_{GS} characteristics showing the gate leakage effects in both devices

Effective gate leakage suppression was achieved using this device in the range of 10^{-7} mA/mm. The extracted model parameters have been summarized in Table 1.

Table 1 – Extracted model parameters summarized

Parameter	Value
μ_{max}	153 cm/Vs
L_G	100 nm
t_{ox}	15 nm
σ_{tot}	3.75×10^{13} cm^{-2}
n_S	9.8×10^{12} cm^{-2}
I_{Dmax}	1.16 A/mm
g_{mmax}	248 mS/mm
C_{Gmax}	0.57 µF/cm^{-2}
V_T	– 4.5 V

4. CONCLUSIONS

The authors have attempted to establish an analytical model for predicting the DC characteristics of the proposed AlGaN/InGaN/GaN double heterostructure (DH) MOS-HEMT. The charge concentration, drain current density and gate capacitances were evaluated by performing a theoretical investigation of the device. Effective gate leakage suppression was achieved by using ZrO$_2$ as the dielectric. The proposed device produced about 27 % improvement in the drain current density and a higher gate capacitance due to the oxide/dielectric layer used. The thicknesses of InGaN and AlGaN layers led to higher carrier concentration in the 2DEG area. These results provide an opportunity for developing more MOS-HEMT structures with high-*k* dielectrics and are evidence that this device could be a potential solution for high power applications.

REFERENCES

1. J.A. Del Alamo, *Nature* **479**, 317 (2011).
2. H.W. Hou, Z. Liu, J.H. Teng, T. Palacios, S.J. Chua, *Sci. Rep.* **7**, 46664 (2017).
3. S.M. Razavi, S.H. Zahiri, S.E. Hosseini, *Physica E: Low Dimens. Syst. Nanostruct.* **54**, 24 (2013).
4. O. Ambacher, B. Foutz, J. Smart, J.R. Shealy, N.G. Weimann, K. Chu, M. Murphy, A.J. Seirakowstki, W.J. Schaff, L.F. Eastman, R. Dimitrov, L. Wittmer, M. Stutzmann, *J. Appl. Phys.* **87**, 334 (2000).
5. A. Brannick, N.A. Zakhleniuk, B.K. Ridley, L.F. Eastman, J.R. Shealy, W.J. Schaff, *Microelectron. J.* **40**, 410 (2009).
6. L. Arivazhagan, D. Nirmal, D. Godfrey, J. Ajayan, P. Prajoon, A.S. Fletcher, A. Amir Anton Jone, J.S. Raj Kumar, *Int. J. Electron. Commun.* **108**, 189 (2019).
7. I. Jabbari, M. Baira, H. Maaref, R. Mghaieth, *Physica E: Low Dimens. Syst. Nanostruct.* **104**, 216 (2018).
8. T. Palacios, A. Chakraborty, S. Heikman, S. Keller, S.P. DenBaars, U.K. Mishra, *IEEE Electron Dev. Lett.* **27**, 13 (2005).
9. J. Liu, Y. Zhou, J. Zhu, Y. Cai, K.M. Lau, K.J. Chen, *IEEE Trans. Electron Dev.* **54**, 2 (2006).
10. J. Liu, Y.G. Zhou, J. Zhu, K.M. Lau, K.J. Chen, *phys. status solidi c* **3**, 2312 (2006).
11. O. Ambacher, J. Majewski, C. Miskys, A. Link, M. Hermann, M. Eickhoff, M. Stutzmann, F. Bernardini, V. Fiorentini, V. Tilak, B. Schaff, *J. Phys. Condens. Matter* **14**, 3399 (2002).
12. K.H. Lee, P.C. Chang, S.J. Chang, *Microelectron. Eng.* **104**, 105 (2013).
13. J.C. Pravin, D. Nirmal, P. Prajoon, J. Ajayan, *Physica E: Low Dimens. Syst. Nanostruct.* **83**, 95 (2016).
14. B.K. Jebalin, A.S. Rekh, P. Prajoon, N.M. Kumar, D. Nirmal, *Microelectron. J.* **46**, 1387 (2015).
15. G. Simin, A. Koudymov, H. Fatima, J. Zhang, J. Yang, M.A. Khan, X. Hu, A. Tarakji, R. Gaska, M.S. Shur, *IEEE Electron Dev. Lett.* **23**, 458 (2002).
16. V. Sandeep, J.C. Pravin, A.R. Babu, P. Prajoon, *IEEE Trans Electron Dev.* **67**, 3558 (2020).
17. H. Jiang, C. Liu, K.W. Ng, C.W. Tang, K.M. Lau, *IEEE Trans Electron Dev.* **65**, 5337 (2018).
18. S. Rai, V. Adivarahan, N. Tipirneni, A. Koudymov, J. Yang, G. Simin, M.A. Khan, *Jpn. J. Appl. Phys.* **45**, 4985 (2006).
19. A. Nakajima, Y. Sumida, M.H. Dhyani, H. Kawai, E.S. Narayanan, *Appl. Phys. Exp.* **3**, 121004 (2010).

Вплив діелектрика ZrO$_2$ на характеристики постійного струму і пригнічення витоку в транзисторі DH MOS-HEMT на основі AlGaN/InGaN/GaN

V. Sandeep, J. Charles Pravin

Kalasalingam Academy of Research and Education, Virudhunagar, Tamil Nadu, India

У роботі вивчаються характеристики транзистора DH MOS-HEMT (Double Heterostructure Metal-Oxide-Semiconductor High Electron Mobility Transistor) на основі AlGaN/InGaN/GaN при використанні діоксиду цирконію (ZrO$_2$) товщиною 10 нм як діелектрика. Оксидні діелектрики відіграють важливу роль у формуванні двовимірного електронного газу (2DEG). Запропоновано аналітичну модель для оцінки густини зарядів, концентрації носіїв, струму стоку, провідності та ємності затвора. Транзистори DH MOS-HEMTs на основі ZrO$_2$ продемонстрували виняткові характеристики, а саме максимальну густину струму стоку (I_{Dmax}) та провідність (g_{mmax}) у порівнянні з транзисторами HEMTs на основі InGaN. Завдяки високоякісній межі розділу між ZrO$_2$ та бар'єрним шаром AlGaN, транзистор MOS-HEMT продемонстрував чудові концентрації носіїв та ємності затвора. Також проведено електростатичний аналіз на різних межах розділу та досліджено вплив товщини шару InGaN на покращення 2DEG. Отримані результати винятково узгоджуються з опублікованими експериментальними даними. Включення міцного high-*k* діелектричного матеріалу, такого як ZrO$_2$, призвело до ефективного пригнічення витоку в діапазоні 10^{-7} мА/мм. Результати показують, що транзистор може бути ефективним рішенням як для потужних комутуючих пристроїв, так і для мікрохвильових додатків.

Ключові слова: AlGaN/GaN, Подвійна гетероструктура, MOS-HEMT, InGaN, ZrO$_2$, Ємність, Порогова напруга.