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Comparative Assessment of Gate Leakage Mechanism of AlGaN/GaN HEMT With and Without AlN Spacer

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ABSTRACT: In this paper, a surface potential-based compact model on gate leakage mechanism is developed for AlGaN/GaN high electron mobility transistor. Comparative study on gate leakage current has been carried out without and with AlN spacer. The forward bias and reverse bias gate current of AlGaN/GaN HEMTs is decomposed into two distinct components, which are Poole-Frenkel (PE) emission and Thermionic emission (TE). In both sets of devices, an additional trap-assisted tunneling component of current is observed at low reverse bias. The developed model is in excellent agreement with experimental data.

KEYWORDS: Compact model, Gate leakage current,AlN, Poole-Frenkel (PF), emission, Thermionic emission**.**

I. INTRODUCTION

AlGaN/GaN HEMT devices have emerged as very promising candidates for high speed and high power application [1] owing to properties such as high breakdown voltage, high charge density, and high electron mobility[2]. Although GaN HEMTs has several features, the major factor that limits the performance and reliability of the device is relatively high gate leakage. The gate leakage current reduces the breakdown voltage and the power-added efficiency while increasing the noise figure. A large reverse bias is applied in the gate to turn OFF the device, when they are normally ON with high 2-DEG concentration, as it leads to high off-state power loss and many reliability problems. Hence, the gateleakage mechanism is very essential to understand the breakdown characteristics of the device. Accurate physics-based gate leakage model is useful in both digital and analog circuits as the noise associated with the gate current can affect the performance of the circuit.

Our gate current model uses Surface potential (SP) based compact model, and to calculate the current equations three gate leakage mechanisms such as PE, TE, and TAT has been considered. The Poole-Frenkel emission model mainly governs the medium to high reverse-bias gate current and trap-assisted tunneling current at low reverse bias, whereas thermionic emission plays a dominant role in the forward-bias region [5]. These three components together attribute the total gate leakage current at multiple drain voltages and temperatures.

In this work, AlN spacer has been introduced between barrier and channel. AlGaN/AlN/GaN HEMTS have some unique features such as high two-dimensional electron gas (2DEG), sheet carrier density, carriermobility and also have excellent DC and RF performance. Comparative assessment on gate leakage current for conventional AlGaN/GaN HEMT and AlGaN/AlN/GaN HEMT has been carried out.

II. GATE CURRENT MODEL FORMULATION

A. POOLE-FRENKEL MODEL

To understand the reverse leakage mechanism PF emission is considered. As trap plays important role in leakage current, the activation of carriers from trap state to the continuum of states due to thermal energy is the main reason for PF emission current.

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For PF conduction, the relation between current density (J_{PF}) and electric field (E) is given by

$$J_{PF} = C.E.\exp\left(\alpha + \beta\sqrt{E}\right) \quad (1)$$

Where $\alpha = -\emptyset_d/V_{th}$, $\beta = (q/\pi\epsilon_s)^{1/2}/V_{th}$

C stands for trap concentration, $\emptyset_d$ is the barrier height for the electron emission from trap state, $\varepsilon_s$is a permittivity of AlGaN for conventional HEMT, whereas for spacer based HEMT $\varepsilon_s\varepsilon_{AlN}$will be permittivity, and V_{th} is the thermal voltage. The electric field is calculated using the expression [3]

$$E = \frac{q\sigma_p - C_g(V_{g0} - \psi)}{\epsilon_s} \quad (2)$$

Where $V_{g0} = V_g - V_{OFF}$, C_g is the gate capacitance, σ_p is the sum of the piezoelectric polarization charge in the barrier and the difference between spontaneous polarization charge in the buffer and barrier, and q stands for electron charge.

The current equation is obtained by integrating the current density along channel length from source to drain,

$$I_{PF} = \int_0^L J_{PF}.dx \quad (3)$$

The integration variable is changed from x to ψ using the expression [12]

$$dx = \frac{L(V_{g0} - \psi - V_{th})}{(V_{g0} - \psi_m - V_{th})(\psi_d - \psi_s)}d\psi = L.K(V_{g0} - \psi - V_{th})d\psi \quad (4)$$

Where $\psi_m=(\psi_s+\psi_d)/2$, ψ_d, $\psi_s$are the SP at source and drain side respectively, Lis the channel length. In PF current equations SP based model is used to obtain E interms of ψ. Derivative of electric field (2) with respect to x and (V_{go}-ψ) is obtained from (2) and the obtained equation is substituted in (4), we get,

$$\frac{dE}{dx} = \frac{C_g}{L\,\epsilon_s\,K.(V_{g0} - \psi + V_{th})} = \frac{C_g^2}{L(A - B.E)} \quad (5)$$

Where $A = \epsilon_s\,K(C_g V_{th} + q\sigma_P)$, $B = \epsilon_s^2.K$

By changing the integration variable from dx to dE (3)can be written as follows,

$$I_{PF} = WLCe^{\alpha}\int_{E_S}^{E_D} E.e^{\beta\sqrt{E}}.\frac{(A - B.E)}{C_g^2}dE \quad (6)$$

The total current is given by,

$$I_{PF} = \frac{WLC}{C_g^2}e^{\alpha}\left[\frac{2A}{\beta^4}e^{\beta\sqrt{E}}\left(\beta^3E^{1.5} - 3\beta^2E + 6\beta\sqrt{E} - 6\right) - \frac{2B}{\beta^6}e^{\beta\sqrt{E}}\left(\beta^5E^{2.5} - 5\beta^4E^2 + 20\beta^3E^{1.5} - 60\beta^2E + 120\beta\sqrt{E} - 120\right)\right]_{E=E_S}^{E=E_D} \quad (7)$$

B. THERMIONIC EMISSION MODEL:

TE plays a major role in the forward bias range, J-V characteristics of a schottky contact is given by [7]

$$J_{TE} = J_{TE0}\left[\exp\left(\frac{V}{\eta V_{th}}\right) - 1\right] \quad (8)$$

$$J_{TE0} = A^*T^2\exp\left(-\frac{\emptyset_b}{V_{th}}\right) \quad (9)$$

Where J_{TE0} is the reverse saturation current density, $A^*$is a Richardson's constant, $\emptyset_b$ is the schottky barrier height, η is the ideality factor and $V = V_g - \psi$.

For current equation, the current density is integrated along the channel length,

$$I_{TE} = \int_0^L J_{TE}.dx \quad (10)$$

We replace dx in terms of $d\psi$ and after integration we obtain TE current as

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$$I_{TE} = WLJ_{TE0}.K[\exp\left(\frac{V_g-\psi}{\eta V_{th}}\right)\eta V_{th}\left(\eta V_{th} - V_{th} - V_{g0} + \psi\right) - \psi\left(V_{th} + V_{g0}\right) + \frac{\psi^2}{2}]_{\psi=\psi_S}^{\psi=\psi_D} \quad (11)$$

C. TRAP ASSISTED TUNNELING CURRENT MODEL:

At zero bias the electric field across the barrier does not go to zero. The forward trap-assisted tunneling current flow from gate to the channel compensates the PF emission current from channel to gate near zero bias. Also, the TAT current and PF emission has same temperature dependence. The J_{TAT} is given by [5]

$$J_{TE} = J_{TE0}\left[\exp\left(\frac{V-V_0}{\eta_2 V_{th}}\right) - 1\right] \quad (12)$$

Where J_{TAT0} the reverse saturation current density obtained by equating J_{TAT} and J_{PF} at V_g=0.

The TAT current is obtained by integrating J_{TAT} in a similar fashion as described for TE. The I_{TAT} is given by,

$$I_{TAT} = WLJ_{TAT}.K[\exp\left(\frac{V_g-\psi-V_0}{\eta V_{th}}\right)\eta V_{th}(\psi - V_{g0}) + \psi(\frac{\psi}{2} - V_{th} - V_{g0}]_{\psi=\psi_S}^{\psi=\psi_D} \quad (13)$$

Based on the dependencies of gate length (L), gate width (W) and AlGaN layer thickness, the scalability of device is considered. In (2) vertical electric field relies on AlGaN layer thickness, as it depends on gate capacitance.

III. RESULTS AND DISCUSSION

The total gate current is obtained by adding the three components for a wide-bias range.

The gate current increases exponentially with applied gate voltage for forward bias region. But in logarithmic scale, straight line will be observed at high forward bias due to voltage drop across the gate resistance.

A.PARAMETER EXTRACTION:

The models for three component of gate current, namely PF current, TE current, and TAT current have their own set of parameters.

A.1. PF current parameters:

The parameters of PF component are C, $\emptyset_d$, β and σ_p. C is a trap concentration, $\emptyset_d$ is the barrier height. $\sigma_p$is obtained by summation of piezoelectric polarization charge in the barrier layer and the net spontaneous polarization charge in the barrier and buffer layer. β is given by $(q/\pi\varepsilon_s)^{1/2}/ V_{th}$.

Φ_d, β, and σ_p parameters have been slightly tuned their values to fit the current in high negative gate-bias range. $\sigma_p$provides the polarization electric field and determines the gate bias at zero net field. From (7) it seen that Φ_d is a reading parameter. β is used to modulate the slope of the current.

Parameter	Description	Default value
σ_p	Polarization charge density(cm^{-2})	$1.4e^{13}$
Φ_d	Barrier height for the electron emission from the trap state (eV)	0.3
β	Parameter dependent on AlGaN permittivity and hence Al mole fraction ($V^{-1/2}m^{1/2}$)	$1.39e^{-3}$
C	Trap concentration parameter($A/V_{m)}$	$1e^{-6}$
Φ_b	Schottky barrier height(eV)	1.17
η	Ideality factor for TE current	2.0
J_{TAT0}	Reverse saturation current density for TAT(Am^{-2})	$1e^{-3}$
η_2	Ideality Factor TAT current	2.0
V_0	Parameter to fit toatal gate current close to orgin(V)	-0.5

Table.1.Gate current parameters

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A.2.TE Parameters:

Two parameters in TE currents areΦ_b and η.Φ_b is the schottkybarrier height and η is the ideality factor.Φ_b is adjusted to make TE component has a minimumeffect for negative gate biases.At positive gate bias,slope of TE current is determined by η.

A.3.TAT current Parameter:

TAT components are modeled using J_{TAT0}, V_0 and η_2. J_{TAT0} is a very low value scaling parameter and hence, it does not affect the reverse bias current.V_0 is tuned to get sum of all three component zero at zero bias.$\eta_2$evaluates the slope of TAT current.

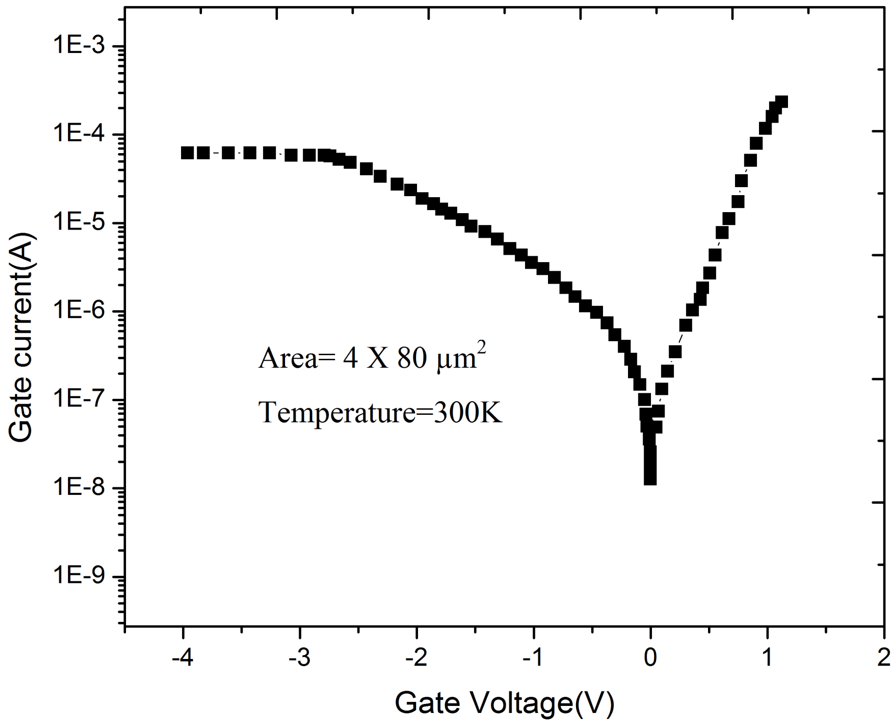

Fig.1. I_gVs V_g for conventional HEMT

The proposed gate current model of AlGaN/GaN HEMT devices is shown in Fig.1.The Al composition of 0.3 is used for AlGaN barrier with 24nm thickness.V_g ranges from -4to2V.In forward bias region,current will be increased exponentially with gate voltage whereas in log scale,there will be straight line.

Fig.2. shows the temperature dependence of the gate current model for wide range of temperature and bias voltage.

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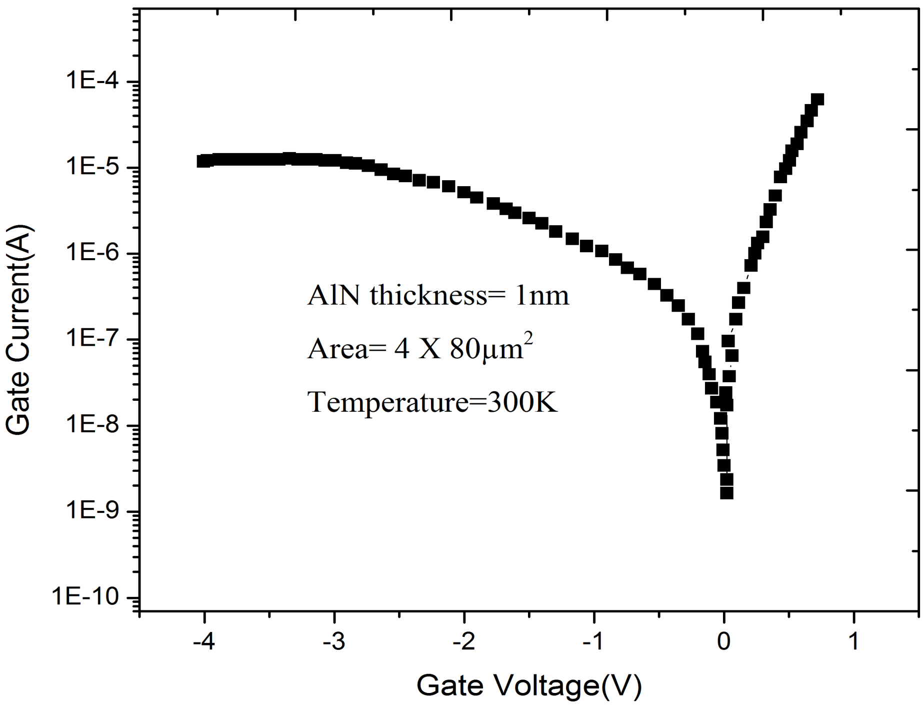

Fig.2. I_g - V_g for AlN spacer based HEMT

The gate leakage current for AlGaN|AlN|GaN HEMT shown in Fig.3.It is clear that withAlN insertion the leakage current is reduced compared to conventional HEMT. Due to wider bandgapAlN, there will be increased potential barrier and better confinement in channel.Thus improvement in drain current and mobility leads todecreased leakage current.

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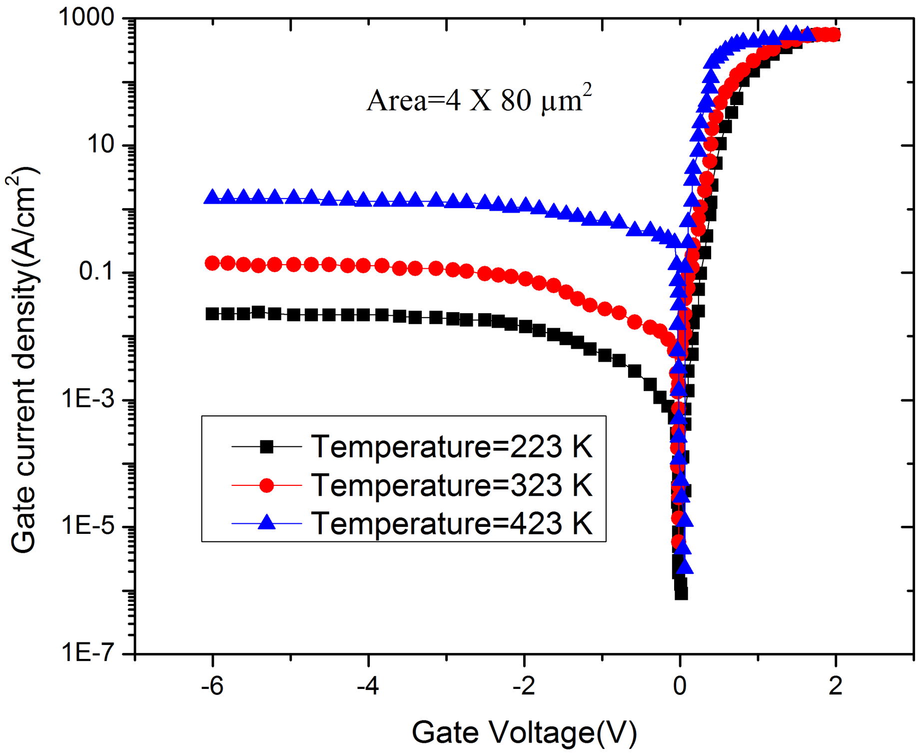

Fig.3. Plot of gate current density – voltage characteristics measured at three different temperature (223K, 323K, and 423 K) for AlGaN/GaN HEMT is shown.

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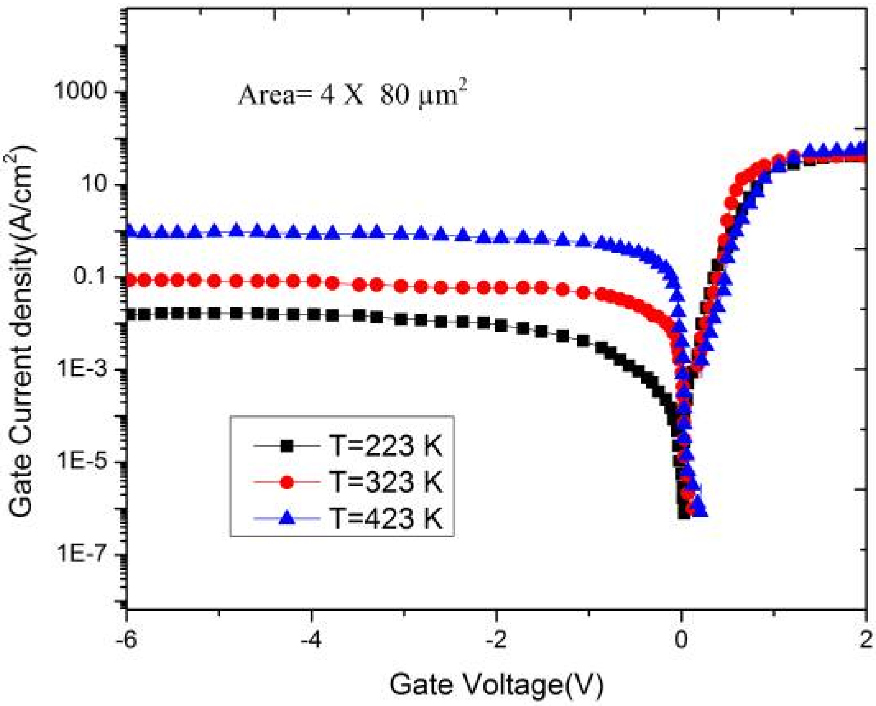

Fig.4. Variation of gate current density with gate voltage for AlGaN/AlN/GaN with 1nm AlN thickness is shown.

It is clear fromFig.4.that the reverse leakage characteristics are nearly similar for AlGaN/GaN and AlGaN|AlN|GaN HEMT due to same barrier height for both devices.On the other hand,for forward leakage current,band discontinuity at the interface between the barrier and channel layer.Thus,forward current is apparently suppressed due to insertion of AlN spacer layer as it has high band discontinuity than the one without spacer.

IV. CONCLUSION

The forward and reverse gate leakage current is modeled and implemented in SP-based GaN HEMTs compact model.The gate leakage current of AlGaN/GaN HEMT with and without spacer is analyzed.Finally, we revealed that the insertion of AlN spacer layer,suppresses the forward gate leakage currentcompared to conventional HEMT.

REFERENCES

[1] Mishra UK, Shen L, Kazior TE, Wu Yi-Feng."GaN-based RF power devices andamplifiers". Proc IEEE 2008;96(2):287–305.
[2] Trew RJ. "SiC and GaN transistors – is there one winner for microwave power applications?" Proc IEEE 2002;90:1032–47.
[3] D. Yan, H. Lu, D. Cao, D. Chen, R. Zhang, and Y. Zheng,
"On the reverse gate leakage current of AlGaN/GaN high electronmobility transistors," *Appl. Phys. Lett.*, vol. 97, no. 15,pp. 153503-1–153503-3, Oct. 2010.
[4] P. D. Ye *et al.*, "GaN metal–oxide–semiconductor high-electronmobility- transistor with atomic layer deposited Al2O3 as gate dielectric," *Appl. Phys. Lett.*, vol. 86, no. 6, p. 063501, Jan. 2005.
[5] S. Turuvekere, N. Karumuri, A. A. Rahman, A. Bhattacharya,A. DasGupta, and N. DasGupta, "Gate leakage mechanisms in AlGaN/GaN and AlInN/GaN HEMTs: Comparison and modeling," *IEEE Trans. Electron Devices*, vol. 60, no. 10, pp. 3157–3165, Oct. 2013.
[6] S. Khandelwal, Y. S. Chauhan, and T. A. Fjeldly, "Analytical modeling of surface-potential and intrinsic charges in AlGaN/GaN HEMT devices," *IEEE Trans. Electron Devices*, vol. 59, no. 10, pp. 2856–2860, Oct. 2012.
[7] S. M. Sze, "MIS diode and charge-coupled devices," in *Physics of Semiconductor Devices*, 2nd ed. New York, NY, USA: Wiley, 2001,pp. 402–407.

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ISSN (Online): 2278 – 8875

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[8] KANJALOCHAN JENA,1,2 RAGHUNANDAN SWAIN,1 and T.R. LENKA1, "Impact of AlN Spacer on Analog Performance of Lattice-Matched AlInN/AlN/GaN MOSHEMT", Journal of ELECTRONIC MATERIALS,DOI:10.1007/s11664-015-4296-1_ 2012 The Minerals, Metals & Materials Society.
[9] S. Pandey, D. Cavalcoli, B. Fraboni, A. Cavallini, T. Brazzini, and F. Calle," Role of surface trap states on two-dimensional electron gas density in InAlN/AlN/GaNheterostructures" Appl. Phys. Lett. 100, 152116 (2012).
[10] T. Nanjo, T. Motoya, A. Imai, Y. Suzuki, K. ShiozawaM.Suita, T. Oishi, Y. Abe, E. Yagyu, K. Yoshiara, and Y. Tokuda, Jpn. J. Appl. Phys. 50, 064101 (2011).