Compact modeling of gate leakage phenomenon in GaN HEMTs

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TR2021-079 July 12, 2021

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In this paper, we provide a physical motivated compact model for AlGaN/GaN based High Electron Mobility Transistors (HEMTs). The device electrostatics and drain-source electron transport are modeled using previously published surface potential based I-V model for shortchannel III-Nitride HEMTs. The model presented here includes thermal emission (TE), trap-assisted tunneling (TAT), Poole Frenkel (PF) emission, and Fowler-Nordheim (FN) tunneling as the dominant sources of gate leakage. Excellent agreement between the model and fabricated AlGaN/GaN HEMTS with SiN passivation is demonstrated over a broad bias and temperature range between 298 K to 573 K.

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***Abstract*—In this paper, we provide a physical motivated compact model for AlGaN/GaN based High Electron Mobility Transistors (HEMTs). The device electrostatics and drain-source electron transport are modeled using previously published surface potential based I-V model for short-channel III-Nitride HEMTs. The model presented here includes thermal emission (TE), trap-assisted tunneling (TAT), Poole Frenkel (PF) emission, and Fowler-Nordheim (FN) tunneling as the dominant sources of gate leakage. Excellent agreement between the model and fabricated AlGaN/GaN HEMTS with SiN passivation is demonstrated over a broad bias and temperature range between 298 K to 573 K.**

***Keywords*—Compact model, GaN HEMTs, Gate leakage, Temperature**

I. Introduction

AlGaN/GaN-based high electron mobility transistor (HEMT) is an excellent device technology for high-frequency, high-power, and harsh environment applications, providing high polarization induced charge density (two-dimensional electron gas, 2DEG) in the channel, high mobility with reduced scattering effects, and high saturation velocity [1]. However, despite these advantages, the excessive gate leakage current is a limiting factor, in these devices, especially for devices operating under high-field and high-temperature environments. Under forward biasing, thermal emission (TE, I_{TE}) current increases exponentially with forward biasing voltage across the gate Schottky contact. Besides, in the case of GaN HEMTs, the tunneling current is assisted through localized traps that are present in the insulator (AlGaN) layer. This component of gate current is termed the trap-assisted tunneling (TAT, I_{TAT}) current. While in the reverse-biased mode, the dominant mechanisms of gate leakage are due to the Poole–Frenkel (PF, I_{PF}) emission and the Fowler–Nordheim (FN, I_{FN}) tunneling [2]. In order to optimize the device performance by reducing gate leakage current and enable accurate circuit simulation, various analytical models have been proposed to provide a physical explanation of gate leakage current in GaN HEMTs.

There are few reports on analytic and physical modeling of gate leakage in a compact manner. In Ref. [3], gate leakage is computed without including the effect of the drain bias and, therefore, is not applicable over a broad bias range. In [4], gate leakage in GaN HEMTs was studied for temperature less than 320 K. However, during nominal device operation in RF circuits, the channel temperature of GaN HEMTs could exceed 450K. Ref. [5] uses a simplified Schottky-diode theory to represent the gate-source and gate-drain leakage currents. In Ref. [6], the gate leakage current due to the existence of surface traps is reported to be the primary mechanism and is modeled physically by solving Poisson's and current density equations. However, the validity of these models in short-channel HEMTs with quasi-ballistic transport has not been established. In this work, a physically motivated model for gate leakage current in GaN HEMTs is proposed, the gate leakage current is solved self-consistently with the current-voltage characteristics of HEMTs with transport ranging from diffusive to quasi-ballistic regime, taking the current dependent voltage drop across the ungated access region, as well as self-heating effects of GaN HEMTs into account. The model is applicable for broad bias and a temperature range between 298 K to 573 K.

II. Modeling

A prototypical AlGaN/GaN HEMT device structure and its equivalent circuit model are shown in Fig. 1. As shown in Fig. 1, the Schottky diodes that exist between the gate metal and the source/drain are shown in the equivalent circuit model. This circuit also indicates the non-linear source and drain resistances, R_s and R_d, respectively, due to access regions in the HEMT. The intrinsic voltage at the source and drain nodes is given as V_{si} and V_{di}, respectively. The resistances of the access regions are current dependent, so as the voltage drop across the access regions [7]. Therefore, the intrinsic voltage drops from gate to source V_{gsi} (V_g-V_{si}) and gate to drain V_{gdi} (V_g-V_{di}) as the inputs to calculate gate leakage current have to be solved self-consistently with the drain-source current (I_{ds}). Here I_{ds} is modeled using a virtual-source-based approach for short-channel devices, previously published by the authors in Ref. [8]. The I-V model is surface potential based with surface potential, ψ_s defined at the highest potential point in the channel, which is also referred to as top-of-barrier (ToB).

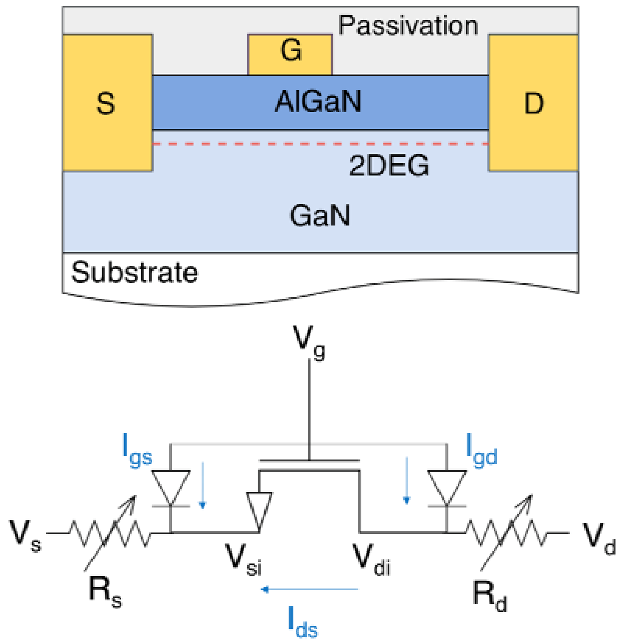


Figure 1Illustration of the cross-section of a prototypical AlGaN-GaN HEMT. Below is the equivalent circuit diagram of the GaN HEMT. The gate-source leakage is I_{gs}, gate-drain leakage is I_{gd}, nonlinear source/drain resistances are represented as R_s and R_d. The voltages at the intrinsic source and drain nodes are represented as V_{si} and V_{di}, respectively.

With the definition that x-axis is the direction from the gate to the substrate, and the y-axis is along channel direction. The band bending diagram in the x direction is illustrated in Fig. 2. The band bending increases with increased reverse bias with lower carrier confinement in the channel as indicated by wavefunction (dash line). In this work, we consider that only the first quantized energy sub-band in the channel is occupied with electrons.

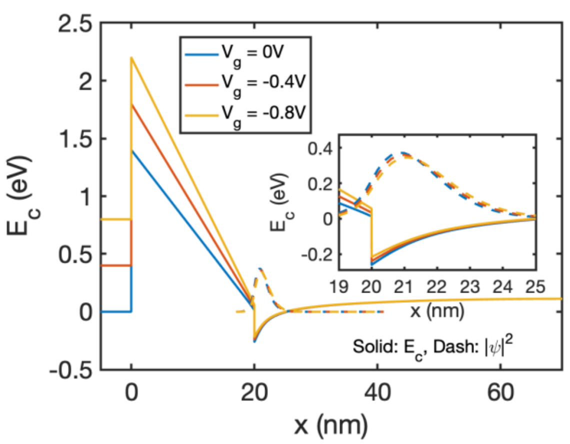


Figure 2 Band bending from the gate to the substrate without gate leakage obtained for Al0.22Ga0.78N insulator layer. Inset is a zoomed in view of the band bending in the channel.

As shown in Fig. 3 and 4, different mechanisms dominate the gate leakage current under forward and reverse biasing region.

The definitions of model parameters are summarized in Table I. And key equations that applied to model the gate leakage current are summarized in Table II.

The total gate current I_g in the forward biasing region is the sum of gate-source (I_{gs}) and gate-drain (I_{gd}) components. In the reverse biasing region, the channel potential is almost constant throughout the channel region. The I_g in the reverse biasing region is estimated by assuming uniform current density over the gated area. The electric field crosses the insulator layer is calculated according to $E = (V_{gsi} - \psi_s)/T_{ins}$, with surface potential ψ_s extracted from the I_{ds} model, and T_{ins} is the thickness of the insulator layer.

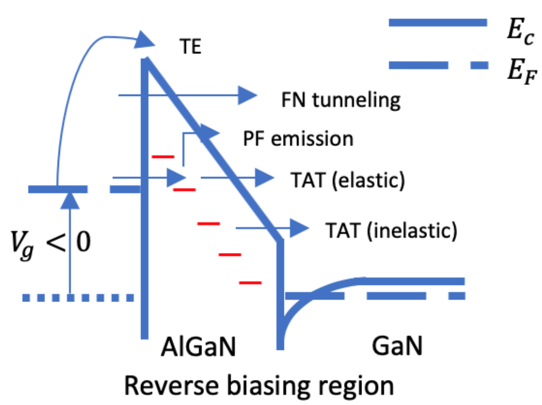


Figure 3Illustration of gate leakage mechanisms in reverse biasing region. Vg is the gate voltage. TE: thermionic emission, PF: Poole-Frenkel emission; TAT: trap-assisted tunneling; FN: Fowler Nordheim tunneling.

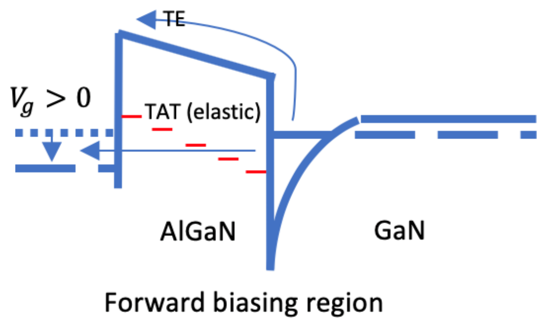


Figure 4Illustration of gate leakage mechanisms in forward biased regimes. Vg is the gate voltage. TE: thermionic emission, TAT: trap-assisted tunneling.

The effects of environmental temperature as well as temperature rising due to self-heating effects is incorporated in the model parameters.

III. Results

A device fabricated with 20-nm thick $Al_{0.22}Ga_{0.78}N$ on top of 900 nm unintentionally doped GaN channel followed by 300 nm GaN buffer (Fig. 5) is applied for model calibration. The model fits the measurement data of the device is shown in Fig. 6. The gate-leakage model is temperature-and bias-dependent and faithfully represents the essential physics pertinent to high-frequency and high-power GaN HEMTs, and physical insight into the process flow optimization.

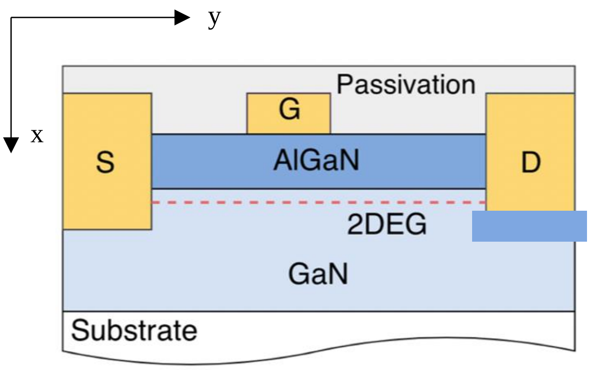
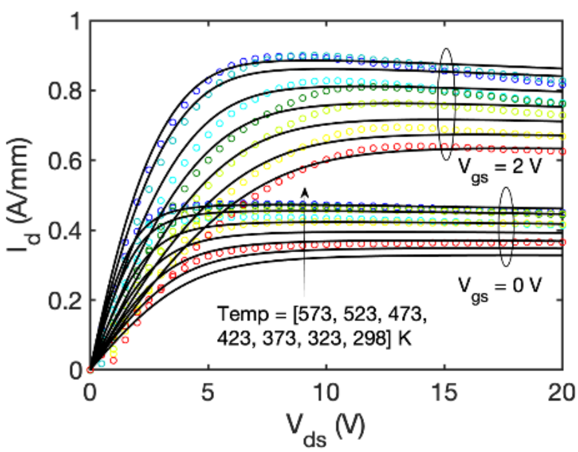
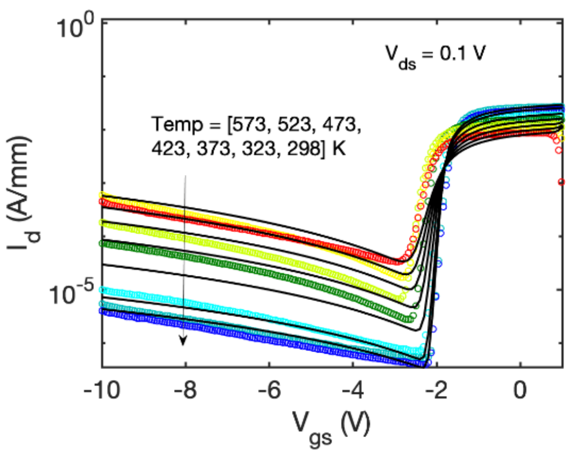


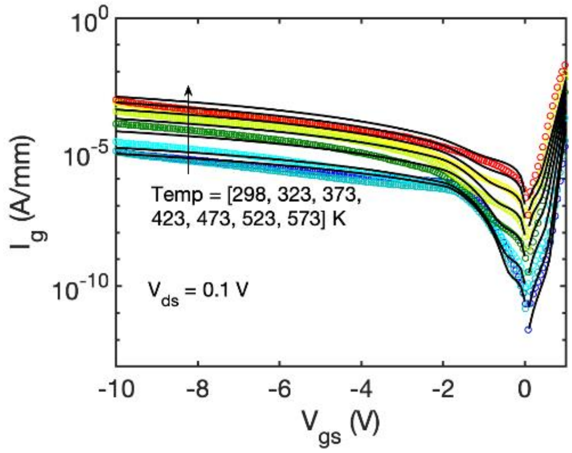
Figure 5 Cross-section of the fabricated device, with SiN passivation.



(a) Model fit to IdVd data of fabricated device with structure shown in Fig.5.



(b) Model fit to IdVg data of fabricated device with structure shown in Fig.5.



(c) Model fit to IgVg data of fabricated device with structure shown in Fig.5.

Figure 6 Model fit to (a) I_dV_d, (b) I_dV_g, (c) I_gV_g of fabricated device set. Symbols refer to measurements, while solid lines are model fit. Different colors refer to measurement taken under temperature varies from 298 to 573K.

TABLE I. PARAMETER DEFINATION IN GATE LEAKAGE MODEL

Symbol	Meaning
$\phi_{TE,TAT,PF}$	Potential barrier for TE, TAT, PF
$\eta_{TE,TAT}$	Non-ideality factor of TE, TAT
$\gamma_{TE,TAT,A,B}$	Temperature dependency of barrier height
A_{300}, B_{300}:	Constant model parameter for FN at 300 K
ϕ_t	Thermal voltage
L_{eff}	Effective channel length (set to gate length)
T	Temperature
C	Constant fitting parameter for PF
$I_{TE0,TAT0}$	Effective Richardson's constant
W	Channel width

IV. SUMMARY

In this work, a physical motivated compact model is proposed for gate leakage current in short-channel GaN based HEMTs as an extension of previously published I-V model. The model parameters as introduced here have its physical meaning, and easy to be extracted based on material and geometry properties. With temperature dependency correctly incorporated, the model shows good matching with experimental data measured in the temperature range varying from 298 to 573K.

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TABLE II. KEY EQUATIONS APPLIED IN MODELING GATE LEAKAGE CURRENT

$I_{gs}^{TE} = I_{TE0}T^2 \exp\frac{-\phi_{TE}}{\phi_t}\left[\exp\frac{V_{gsi}}{\eta_{TE}\phi_t} - 1\right], I_{gd}^{TE} = I_{TE0}T^2 \exp\frac{-\phi_{TE}}{\phi_t}\left[\exp\frac{V_{gdi}}{\eta_{TE}\phi_t} - 1\right]$
$I_{gs}^{TAT} = I_{TAT0}T^2 \exp\frac{-\phi_{TAT}}{\phi_t}\left[\exp\frac{V_{gsi}}{\eta_{TAT}\phi_t} - 1\right], I_{gd}^{TAT} = I_{TAT0}T^2 \exp\frac{-\phi_{TAT}}{\phi_t}\left[\exp\frac{V_{gdi}}{\eta_{TAT}\phi_t} - 1\right]$
$\phi_{TE} = \phi_{TE,300} + \gamma_{TE}(T - 300), \phi_{TAT} = \phi_{TAT,300} + \gamma_{TAT}(T - 300)$
$I_g^{FN} = L_{eff}WAE^2 \exp\frac{-B}{E}, A = A_{300} + \gamma_A(T - 300)^2, B = B_{300} + \gamma_B(T - 300)$
$I_g^{PF} = L_{eff}WCE \exp\left[\frac{\phi_{PF} - \sqrt{E}\sqrt{q/\pi\epsilon_i}}{\phi_t}\right]$

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