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Frances Garcia, Samira Shamsir, Syed K. Islam

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A Compact Model and TCAD Simulation for GaN-Gate Injection Transistor (GIT)

Frances Garcia, Samira Shamsir, Syed K. Islam
Department of Electrical and Computer Engineering, The University of Tennessee,
Knoxville, TN 37996, USA

Abstract: Wide bandgap (WBG) semiconductor devices represent an attractive developing technology for power applications that is recently gaining commercial ground. GaN has advantages as one of the top contenders with high bandgap, high mobility, high saturation velocity, and high breakdown voltage. GaN enhancement-mode devices are favored over depletion-mode devices for power electronics applications and are only recently becoming commercially available. The enhancement-mode device investigated in this work is a GaN-gate injection transistor (GIT) in which the normally-off operation is achieved with an additional p -doped gate. This paper presents current-voltage (I-V) characteristics of GaN-GIT device using a physics based compact model as well as TCAD (Technology Computer-Aided Design) numerical simulation to predict and model the device behavior of the GIT. This paper presents a comparison of the TCAD simulation results with a compact model intended for low frequency applications in power electronics in the KHz to MHz range.

Keywords: GaN, GIT, HEMT, WBG, TCAD

1. Introduction

During the past few years, researchers have focused their attention on wide bandgap (WBG) materials for power electronics applications. Extensive research on GaN devices during the past decade has demonstrated the realization of these devices with superior on-resistance, higher breakdown voltage and smaller device sizes compared to conventional Si power devices. GaN is

particularly coveted for its high breakdown voltage, high mobility and high saturation velocity as illustrated in Table 1 [1].

Table 1: Properties of Wurtzite GaN

Symbol	Parameter	Quantity
E _g [eV]	Bandgap	3.4
E _{crit} [V/cm]	Breakdown Electric Field	5x10 ⁶
μ[cm ² /Vs]	mobility	≤1000
V _{sat}	Saturated electron velocity	2.6x10 ⁵
K _c [W/cm°C]	Thermal conductivity	1.3

Most of the GaN based transistors reported to date are typically lateral heterojunction field-effect transistor (HFET) or high electron mobility transistor (HEMT) due to the availability of two-dimensional electron gas (2DEG) created by spontaneous and piezoelectric polarization of AlGa_n/Ga_n heterojunction. The mechanical stress results in piezoelectric polarization which occurs in the same direction as the tensile strain formed by AlGa_n. Due to the presence of native 2DEG channel the device is inherently depletion-mode or normally-on which is undesirable for power electronic applications. An emerging device technology that achieves enhancement-mode operation of AlGa_n/Ga_n HEMT incorporates a *p*-doped Ga_n layer beneath the gate electrode. This type of configuration is termed as the gate injection transistor (GIT) [2-3]. This device structure has several advantages over the other enhancement-mode Ga_n HEMT structures due to its low on-resistance and high current density.

Currently, analytical models exist for depletion-mode HEMTs [4], but given the behavior of the GIT a new model is proposed for which there are only fitted empirical models for Ga_n power devices [5-6]. This paper presents a closed-form charge control model for two-

dimensional electron gas (2DEG) channel and the effect of the p -doped GaN in order to attain a positive threshold voltage in a GaN GIT device for switching application in power electronics typically in the KHz or MHz frequency range. This paper also presents a numerical simulation of the I-V characteristics with varying barrier layer thickness and barrier doping for comparison with the analytical model.

2. Device Structure

The typical structure of the GaN high electron mobility transistor (HEMT), shown in Fig. 1, consists of a heterojunction with dissimilar bandgaps of AlGaN and GaN. GaN is a piezoelectric material and the stress generated from the lattice structural differences results in piezoelectric and spontaneous polarization at the heterojunction [7-8].

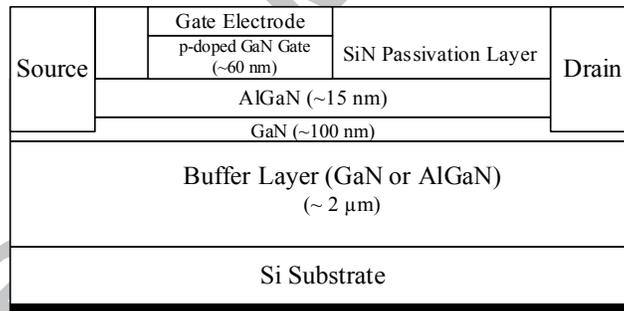


Fig. 1. Schematic illustration of the p -GaN GIT device. The buried channel of the device is formed at the AlGaN/GaN interface.

Unfortunately, the heterojunction structure typically results in a depletion-mode device, which is less than optimal for power applications [9]. Although several GaN device structures have been proposed to achieve enhancement-mode operation, the GIT is emerging commercially and consequently motivates the interest for a comprehensive understanding of the device behavior.

Underneath the gate electrode of a GIT device, there is a p -type doped GaN layer which raises the conduction band of the AlGa_N barrier layer above the Fermi level turning the device normally-off. When the gate voltage is increased, the conduction band is lowered forming 2DEG and as the voltage further increases holes are injected into the channel inducing a large number of electrons via conductivity modulation [2]. The conductivity modulation makes the GIT behaviorally different from a recessed enhancement mode HEMT because it allows a higher current density. The electrons flow from the source to the drain in response to the drain bias while the holes stay close to the gate electrode due to their lower mobility.

The thickness of the barrier layer, the doping levels of different layers, and the mole fraction of AlGa_N affect the threshold voltage as discussed later. The substrate usually consists of Si or SiC, which are superior to GaN in terms of thermal conductivity allowing for a smaller die size by eliminating the need for a heat sink. Although Si is less expensive than SiC, the latter has a lower thermal expansion coefficient mismatch and a better lattice matching relative to GaN than Si keeping the undesired strain to a minimum [10].

3. Analytical Model

In a GaN HEMT, a 2DEG channel is formed at the heterojunction between AlGa_N and GaN layers. The same applies to the GIT device, but the conduction band is raised by the offset of the p -Ga_N underneath the gate electrode. For this reason, the existing GaN HEMT model needs to be modified by including the impact of the p -doped GaN on the threshold voltage. In addition, due to this p -doped GaN, the GaN GIT device shows a significant difference in the charge control model of the drain current due to the device operation discussed in the previous section.

Thus, a more appropriate model for this particular device structure is necessary to predict the device behavior.

3.1. Threshold Voltage

Previously reported threshold voltage models for depletion- mode and enhancement-mode recessed-GaN HEMT are based on the energy band diagram of the heterostructure [11]. GIT GaN devices have an extra layer of *p*-type GaN/AlGaIn below the gate electrode as shown in Fig. 1. This creates a conduction band offset at the heterojunction between the *p*-doped region and the *n*-doped AlGaIn barrier layer. This offset in the conduction band raises the conduction band above the Fermi level forcing the device to be normally-off or enhancement-mode. Fig. 2 shows the band diagram of the GaN GIT device with *p*-GaN cap layer. The threshold voltage was determined based on the energy band analysis at zero gate bias or $V_a = 0$.

An approach similar to [11] was used to derive (1) following the band diagram of GaN/AlGaIn heterostructure to develop the threshold voltage for the GIT device. The band offset is assumed to be equivalent at both heterojunctions. The gate electrode along with the *p*-GaN material is treated as a Schottky diode so that at zero gate bias there is a built-in potential at the Schottky junction [12]. However, the applied voltage to the gate electrode can change the built-in voltage similar to a Schottky diode [13]. The heterojunction at the *p*-GaN/AlGaIn interface is treated as a *pn*-heterojunction diode in which doping quantities affect the built-in potential as well as the position of the conduction band [13], [14] as,

$$V_{th} = \phi + (V_{BI1} - V_a) - V_{BI3} \quad (1)$$

where, ϕ is the Schottky barrier height and V_{BI1} is the built-in potential for a Schottky gate diode structure as expressed by Eq. (2), N_D is the doping density of AlGaIn barrier layer, d is the

thickness of barrier layer, V_{BI3} is expressed by (4), σ is the net polarization induced sheet charge density at AlGa_xN/GaN interface and V_a is the voltage applied to the gate electrode. The built-in potential between the gate electrode and the *p*-Ga_{1-x}N, V_{BI1} , is expressed as the difference between the Fermi energy of the metal and that of the semiconductor and is simplified to [14],

$$V_{BI1} = \phi - \frac{kT}{q} \ln\left(\frac{N_v}{N_a}\right) \quad (2)$$

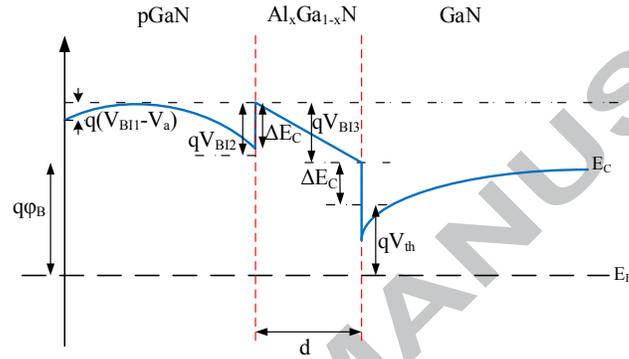


Fig. 2. Energy band diagram for a GIT device with *p*-Ga_{1-x}N cap layer.

The conduction band offset, ΔE_C is assumed to be cancelled out as the offset exists on either side of the AlGa_xN barrier layer. Treating the junction as a *pn* heterojunction diode, qV_{BI2} as shown in the simulated band diagram in Fig. 2, can be expressed as,

$$qV_{BI2} = \frac{\Delta E_c - \Delta E_v}{2} + kT \ln\left(\frac{N_d N_a}{n_{i,n} n_{i,p}}\right) + \frac{kT}{2} \ln\left(\frac{N_{v,n} N_{c,p}}{N_{c,n} N_{v,p}}\right) \quad (3)$$

V_{BI2} is described as the built-in potential in a *pn* heterostructure where the *n*-type material has a larger band gap [14]. Due to the lack of experimental values for specific mole fractions of AlGa_xN, V_{BI2} was not calculated. However, within normal doping levels, V_{BI2} is negligible and only significant for heavy doping due to the lowering of the conduction band as is seen in the simulation results. The model calculation excludes V_{BI2} , since moderate level of AlGa_xN doping is

expected. V_{BI3} is the potential drop across the AlGaN barrier for the depletion-mode device [15] and is expressed as,

$$V_{BI3} = \frac{qN_D d^2}{2\varepsilon_{AlGaN}} - \frac{\sigma}{\varepsilon_{AlGaN}} d \quad (4)$$

where the polarization is downwards as is typical for GaN/AlGaN and is,

$$\sigma = P_{spont}(AlGaN) - P_{spont}(GaN) + P_{piezo}(AlGaN) \quad (5)$$

Here $P_{spont}(GaN)$ is -0.029 and $P_{spont}(AlGaN) = -0.052m - 0.029$. $P_{piezo}(AlGaN)$ is negligible and m is the mole fraction of AlGaN [15]. Since the GIT becomes enhancement mode through the p -GaN layer by introducing the ΔE_c parameter there is negligible effect on the threshold voltage either in calculation or simulation from the p -doping since the heterojunction potential well remains undisturbed.

3.2 Charge Control Model for I-V Characteristics

From the model described above, the value of the threshold voltage is dependent on the applied gate voltage. Once the gate voltage surpasses the threshold voltage and the conduction band is lowered, the device behaves as a traditional depletion-mode device where the charge present in the channel depends on a virtual threshold voltage that is described by the threshold voltage model for a depletion-mode device.

To derive an analytical model of the DC characteristics of the GIT structure the traditional depletion-mode device model is initially considered without the addition of the p -GaN. This threshold voltage is being referred to as *virtual threshold* voltage, V_{vir} , which is different from the actual GIT threshold voltage given by [15],

$$V_{vir} = \varphi - \Delta E_c - \frac{qN_D d^2}{2\varepsilon_{AlGaN}} - \frac{\sigma}{\varepsilon_{AlGaN}} d \quad (6)$$

With the addition of the proposed GIT threshold voltage V_{th} , which is dependent on the applied voltage at the gate electrode, the conduction band drops as the gate voltage is increased. The charge control model proposed for this case is given by,

$$n_s(x) = \frac{\varepsilon}{qd}(V_{GS} - v(x) - V_{vir} + (V_{GS} - V_{th})) \quad (7)$$

where, $v(x)$ is the potential with respect to channel, ε is the dielectric constant of AlGaIn, d is the thickness of the AlGaIn layer and V_{GS} is the applied gate-to-source voltage.

The channel current is modeled by considering drift and diffusion to get,

$$I_{DS} = qZn_s(x)u(x) \quad (8)$$

where, Z is the gate width and $u(x) = \frac{\mu_0 E(x)}{1 + \frac{E(x)}{E_{crit}}}$ where, μ_0 is low field mobility simplifying to,

$$I_{DS} = C(V_{GS} - v(x) - V_{vir} + (V_{GS} - V_{th})) \frac{E(x)}{1 + KE(x)} \quad (9)$$

and recalling $E(x) = \frac{dV(x)}{dx}$ where, $C = \frac{\varepsilon_{AlGaIn}\mu_0}{d}$ and $K = \frac{1}{E_{crit}}$ the following is expression of the drain current is obtained,

$$I_{DS} \left(1 + K \frac{dV(x)}{dx} \right) = C(V_{GS} - v(x) - V_{vir} + (V_{GS} - V_{th})) \left(\frac{dV(x)}{dx} \right) \quad (10)$$

Integrating both sides and ignoring the resistive voltage losses at the source and the drain, and for $V_{GS} > V_{th}$ and $V_{GS} < V_{DSSab}$ for the linear region we get,

$$I_{DSLIn} = \frac{C(V_{GS} - V_{vir} + (V_{GS} - V_{th}))V_{DS} - 0.5V_{DS}^2}{KV_{DS} + L} \quad (11)$$

To derive the saturation current, the channel conductance is zero so that,

$$g_d = \frac{\partial I_D}{\partial V_{DS}} = \frac{C}{(KV_{DS} - L)^2} \{2V_{GS}L - 0.5KV_{DS}^2 - L(V_{th} + V_{vir} + V_{DS})\} \quad (12)$$

When solved for saturation voltage,

$$V_{DSsat} = \left(\frac{\sqrt{4V_{GS}KL - 2KLV_{th} - 2KLV_{vir} + L^2} - L}{K} \right) \quad (13)$$

Such that the drain current in saturation becomes,

$$I_{DSsat} = \frac{C(V_{GS} - v(x) - V_{vir} + (V_{GS} - V_{th}))V_{DSsat} - 0.5V_{DSsat}^2}{KV_{DSsat} + L} \quad (14)$$

3.3 Self-Heating Consideration

GaN devices additionally experience self-heating effect due to the high current passing through the device, which degrades the drain current value as a function of the drain-to-source voltage in the saturation region. This is mainly due to the conductivity of materials that tends to be nonlinear depending on the junction temperature. Many self-heating models are incorporated as empirical models [16-18]. The gate voltage correlates to an increase in self-heating. Unique to this structure, the simulated gate voltage and the lattice temperature was extracted from the TCAD simulation and is described by,

$$T = -3.089V_G^3 + 31.2V_G^2 - 54.25V_G + 309 \quad (14)$$

Using the empirically based mobility model from [16] the mobility was calculated for different gate voltages. The mobility was assumed to decrease linearly along with the drain-to-source voltage.

4. Simulation Results

Table 2: Calculation and Simulation Parameters

Symbol	Parameter	Quantity
ϕ [eV]	Schottky Barrier Height	0.6
m	Mole fraction	0.2
D [m]	Thickness of AlGaN	15×10^{-9}
ε [F/m]	Dielectric constant	$9.3\varepsilon_0$
N_d [cm ⁻³]	n-AlGaN concentration	1×10^{18}
N_a [cm ⁻³]	p-GaN concentration	3×10^{17}
L [m]	Length of GIT	15×10^{-6}
Z [m]	Width of GIT	5×10^{-5}
μ [m ² /(Vs)]	mobility	0.04
E_g [eV]	Bandgap of GaN	3.4
E_{crit} [V/m]	Critical Electric Field	160×10^5

The device simulation for the GaN GIT device has been performed using TCAD Sentaurus. The Sentaurus library provides a sample structure based on an existing GIT device [19-20] for which it compares the GIT experimental IV curves to the simulation example. This serves as a verification of the simulation from which parameters and structure were manipulated for comparison to the proposed compact model. The calculation and the simulation parameters used are shown in Table 2 along with structure dimensions from Fig. 1.

The I-V characteristics were simulated by varying AlGaN doping, and barrier thickness including the band diagrams for the varying parameters. Without the application of the gate voltage the variation of the AlGaN barrier thickness shows a relationship where the thicker barrier layer corresponds to a depletion-mode device as shown in Fig. 3. This can also be seen from the potential, V_{BI3} as described in (4) which increases with thickness, d , until the drop is large enough to plunge the conduction band below the Fermi level. The thinning of the barrier layer thus corresponds to the enhancement-mode operation, which is the same logic behind the enhancement-mode operation of a recessed gate GaN HEMT [21]. The energy band diagrams

show a lowering of the conduction band in the p -GaN cap also shown in Fig. 4. The thickness of the AlGaN layer was also varied in the model for the threshold voltage and was compared with the TCAD simulation results as shown in Fig. 5.

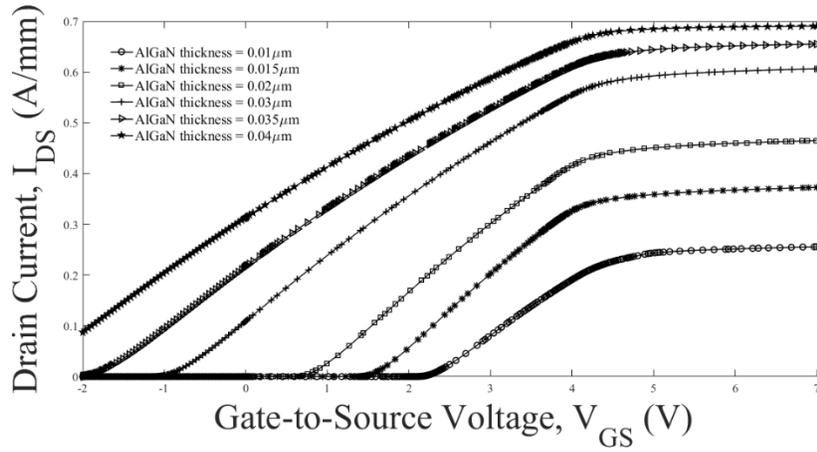


Fig. 3. Transfer curves for varying AlGaN thickness.

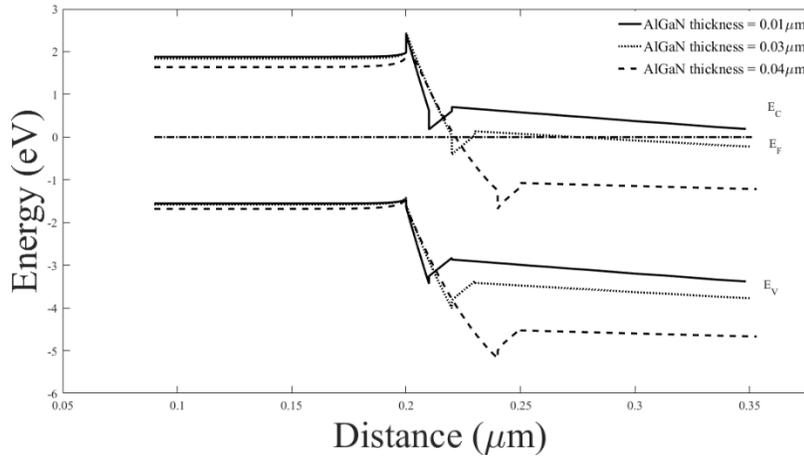


Fig. 4. Band diagram for varying AlGaN thickness.

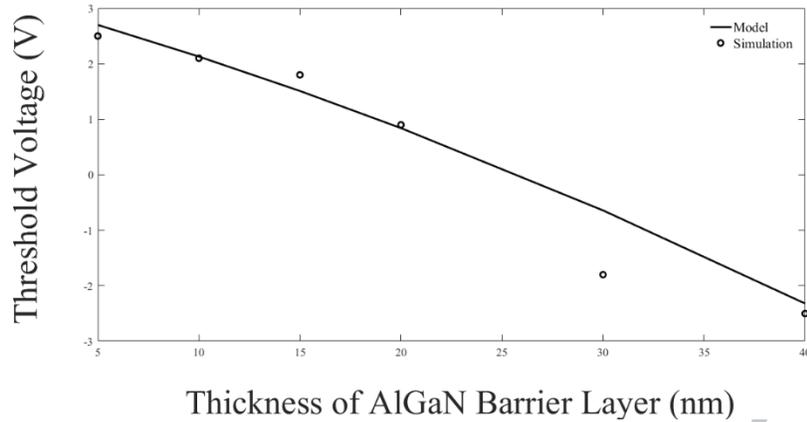


Fig. 5. Threshold voltage values from simulation and model for varying AlGaIn barrier layer thickness. There is good agreement between the simulation trend and the compact model. The linearity of the simulation may be improved with finer meshing but at the cost of much longer simulation time. The doping level has also been adjusted in the barrier layer as shown in Fig. 6. The higher the doping concentration the lower is the threshold voltage required to turn on the device. Fig. 6 and 8 below also show a significant decrease in the threshold voltage after a high doping is reached. The degenerate n -type layer has a Fermi level that begins to penetrate the conduction band turning the device on. At some threshold, the offset created by the p -GaIn cannot compensate for the channel formation forcing the device into depletion-mode operation. V_{BI2} , as expressed earlier, becomes significant when there is heavy doping as seen in Fig. 6 and 7. The simulation results show the effect of this conduction band lowering in Fig. 7 and was also labeled as qV_{BI2} from the band diagram of Fig. 2. From (1), it is obvious that V_{BI3} determines the threshold voltage as it linearly increases with respect to the n -doping.

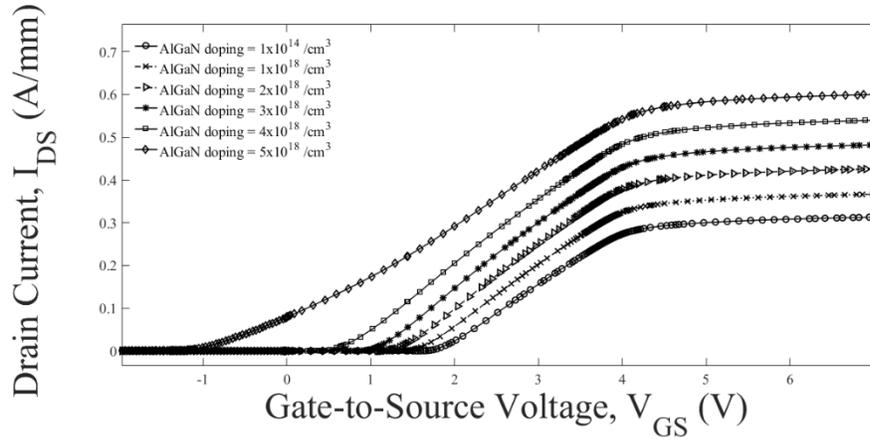


Fig. 6. Drain current response on gate voltage for varying AlGaIn doping.

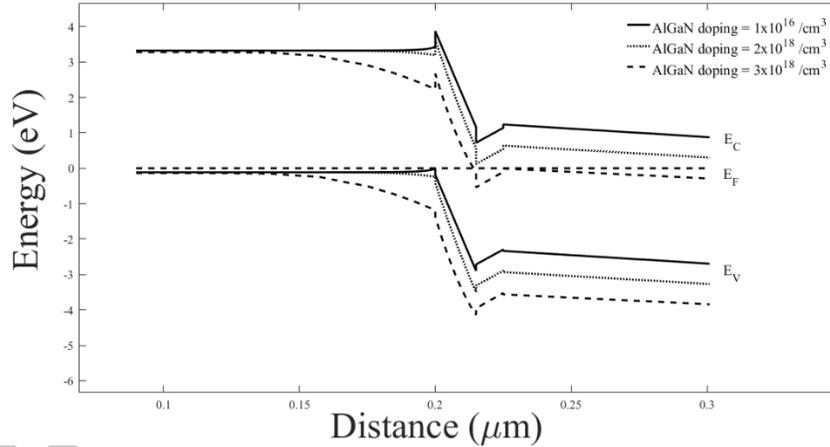


Fig. 7. Band diagram for varying AlGaIn doping.

The TCAD simulation results and the compact model for threshold voltage as a function of the barrier doping are compared in Fig. 8. The drain current for the linear and the saturation regions of operation are derived from the proposed control charge model and are adjusted for self-heating effects following (14). The I-V characteristics obtained from both the TCAD simulation

and the compact model with and without the self-heating fitting parameter are compared in Fig. 9.

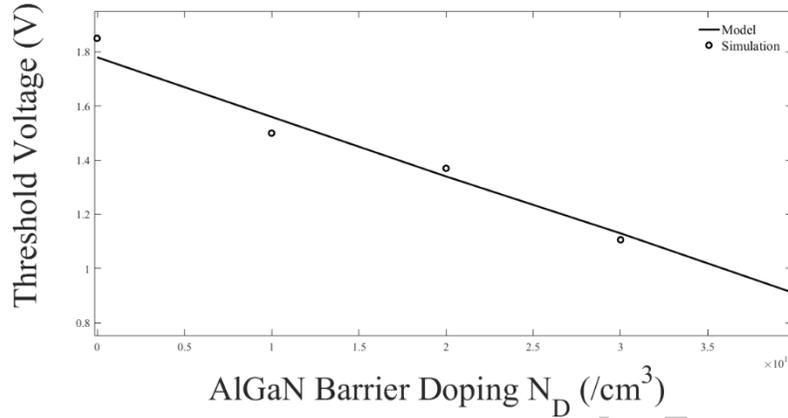


Fig. 8. Threshold voltage values for simulation and model for varying AlGaN doping.

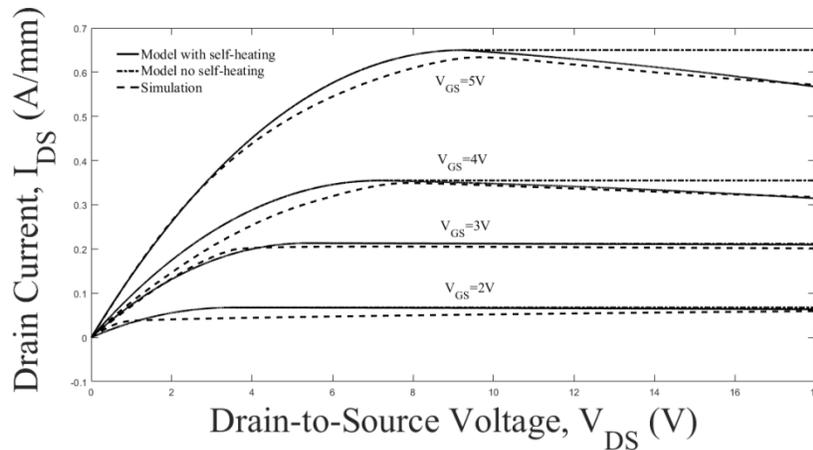


Fig. 9. DC output characteristics at various gate voltages.

5. Conclusion

Enhancement-mode transistors are important for power electronic applications and the GaN-GIT devices represent a potential device structure for commercial realization of wide bandgap (WBG) semiconductor technology for these applications. However, proper device characterization and modeling are very important for utilizing the full potential of this WBG device for high power applications. The proposed preliminary model correlates well with the

TCAD simulated values. Physical characteristics unique to the GIT operation are highlighted in the proposed model enabling a better understanding of the device technology and its limitations in power electronics applications. Future work will include the addition of a CV analytical model for power applications.

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Frances D. Garcia received her B.Sc. degree in physics from University of Tennessee, Knoxville, TN, USA. She is currently working on her Master Sc. Degree in electrical engineering under supervision of Dr. Syed Kamrul Islam. She is a DOE Wideband Gap Trainee Fellow at the University of Tennessee.

Her research interests include semiconductor device modeling and characterization and power electronics.



Samira Shamsir received her B.Sc. degree in electrical and electronic engineering from Bangladesh University of Engineering and Technology (BUET) in 2015. She is currently working towards her Ph.D. degree under the supervision of Dr. Syed Kamrul Islam. She is a Min H. Kao Fellow and

Graduate Research Assistant at the University of Tennessee, Knoxville. Her research interest includes semiconductor device modeling and characterization for high power application.



Syed Kamrul Islam (S'91–M'99) received his B.Sc. degree in electrical and electronic engineering from Bangladesh University of Engineering and Technology (BUET), Dhaka, and the M.S. and Ph.D. degrees in electrical and systems engineering from the University of Connecticut, Storrs. He is presently

a Professor in the Department of Electrical Engineering and Computer Science, University of Tennessee, Knoxville. His research interests are molecular scale electronics and nanotechnology, bio-microelectronics and monolithic sensors.