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Modeling of Noise Power Spectral Density Analysis for GaN/AlGaN HEMT

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Abstract

Nano Technology is the branch of technology that deals with dimensions and tolerances in terms of nanometers. In this paper, the electrical characteristics analysis is determined for the Nano-GaN HEMT and Micro-GaN HEMT and also power spectrum density is determined for GaN Nano-HEMT by reducing the gate length Lg in nm range. The GaN Nano HEMT is producing high current comparing to Micro GaN HEMT. Accuracy of the proposed analytical model results is verified with simulation results.

Keywords

HEMT, GaN/AlGaN, 2DEG, Drain Current, Noise Power Spectrum Density

1. Introduction

High electron mobility transistors are made up of the GaAs semiconductor material, but the research on HEMT experts says that GaN has good characteristics than GaAs because of their good breakdown voltage, less power dissipation. It can operate at high temperature, and it is having more power density and can operate at high voltage compared to GaAs based HEMT for that purpose. We are talking about GaN/AlGaN HEMT here [1]-[3].

The Applications of GaN/AlGaN HEMT are used in Space applications, Radar and in satellites because they are considered to be very promising candidates for high-speed and high-power applications. These devices offer advantages such as high breakdown voltage, high charge density, and good electron mobility [1]. The formation of the 2-dimensional electron gas (2DEG) in these devices is the heart of the device operation and has been studied in great detail in the literature [4]-[6]. Many articles are present for HEMTs, but the dimension used for gate length is in micrometer range [7]-[9]. Thus, there is scope for developing a simple accurate analytical model for GaN HEMT

by considering the gate length dimension in nanometer range (100 nm).

In this paper, we developed electrical characteristics analytical model for the GaN/AlGaN HEMT. Using the dimensions and the parameters of developed HEMT, we have compared the I-V characteristics for the Nano meter gate length and Micro meter gate length GaN-HEMT, and we have determined the noise power spectrum density for Nano GaN HEMT using Matlab and the performance is compared with the simulation results.

2. Model Formation

We call High electron mobility transistor as a Heterostructure FET because it uses two different semiconductor materials. One semiconductor should have a higher energy band gap and another one should have a lower energy band gap for the conduction takes place. We also call it as a MODFET (Modulation doping FET) he term "modulation doping" refers to the fact that the dopants are spatially in a different region from the current carrying electrons.

The schematic cross-section of the AlGaN/GaN HEMT is shown in **Figure 1(a)**. GaN-based HEMTs employ two kinds of materials with different band gaps as the barrier and channel layer. The most popular one is AlGaN/GaN HEMTs. Due to the conduction band offset between AlGaN and GaN, an electron potential quantum well is formed at the hetero-interface between AlGaN and GaN. This heterojunction of different band-gap materials constitutes a triangular-like quantum well on the GaN side of the conduction band which allows electrons move freely parallel to the heterojunction plane without any impurity collision. This collection of high mobility electrons inside the quantum well is called two-dimensional electron gas (2DEG).

Figure 1(b) shows the 2DEG produced between GaN and AlGaN semiconductor materials. Fermi level of both the bands must be equal for the conduction takes place. This is known as the equilibrium state. When we give the gate voltage, the conduction band of AlGaN raises to communicate with the GaN conduction band and the conduction band of GaN material bends down to communicate with AlGaN material in between these two we will get the 2DEG it is like a channel in MOSFET where the electrons
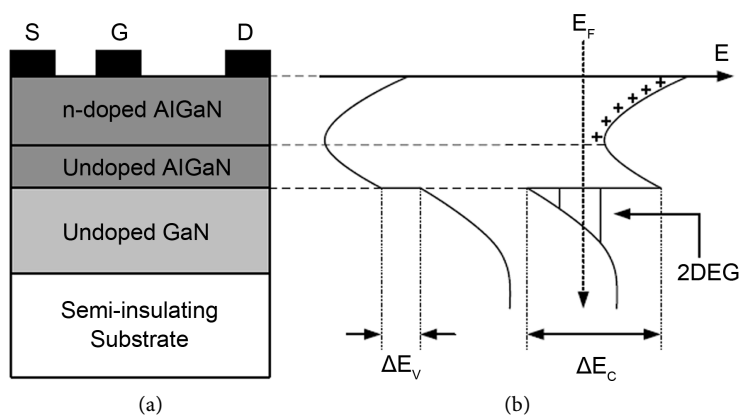
Figure 1. (a) Cross section and (b) band diagram of GaN HEMT structure.

are present and they start moving for the applied gate voltage and drain voltage. The electrons are confined in this potential well to form a 2DEG. The electrons transport in a two-dimensional way, which can largely improve the electron mobility.

Table 1 shows the properties of different semiconductor materials. We can see GaN semiconductor material has a good property compared to the Si, GaAs and SIC semiconductor materials. Hence we are discussing about GaN HEMT here.

3. Drain Current Characteristics and Noise Power Spectrum Densities of GaN HEMT

3.1. I_d Characteristics of GaN HEMT

If assumed a constant mobility, then for low values of V_{ds} (drain to source voltage), the drain current I_d in the linear region is given by [10],

$$I_d = \varepsilon_N \mu \frac{\omega}{2L(d+\Delta d)}\left[2\left(V_{gs}-V_{off}\right)V_{ds}-V_{ds}^2\right], \text{ for } V_{ds} \leq V_{gs} - V_{off} \tag{1}$$

V_{ds} is further increased, then the carrier reaches the saturation voltage and the saturated drain current Drain current becomes,

$$I_d = \varepsilon_N \mu \frac{\omega}{2L(d+\Delta d)}\left(V_{gs}-V_{off}\right)^2, \text{ for } V_{ds} \geq V_{gs} - V_{off} \tag{2}$$

where,

ε_N -permittivity of the substrate material in HEMT;

V_{gs} -The gate to source voltage;

V_{off} -Offset voltage.

The offset voltage V_{off} can be calculated by the formula [10],

$$V_{off} = \phi_B - \frac{\Delta E_C}{q} - V_{P2} \tag{3}$$

V_{p2} can be calculated by using formula [10],

$$V_{p2} = \frac{qN_{dd}^2}{2\varepsilon_N} \tag{4}$$

Table 1. Material properties of semiconductors at 300 K.

Property	Material				
	GaN AlGaN/GaN	SiC	Diamond	Si	GaAs/AlGaAs, InGaAs
Band gap energy, Eg (MV/cm)	3.44 eV	3.26 eV	5.45 eV	1.12 eV	1.43 eV
Electric breakdown field, Ec (MV/cm)	3	3	10	0.3	0.4
Saturated (Peak) Velocity electronics, Vsat (VPeak) ($\times 10^7$ cm/s)	2.5	2.0	2.7	1.0	1.0
Electron mobility, μ_s (cm^2/V·s)	900	700	4800	1500	8500
2DEG density, n_s ($\times 10^{13}$ cm^{-2})	1.0	N.A	N.A	N.A	<0.2
Thermal conductivity (W/cm·K)	1.3 - 2.1	3.7 - 4.5	22	1.5	0.5
Relative Permittivity ε_r	9.0	10.1	5.5	11.8	1.8

3.2. Noise Power Spectrum Densities

Noise power spectral densities (PSD) can be described as superposition of flicker noise, thermal noise and several generation-recombination (G-R) noise components.

- (G-R) Noise: The temperature dependence of the (G-R) noise arising from the traps was used to deduce the thermal activation energies and cross sections. The present results are compared to those of the literature to identify the Physica-chemical nature of traps responsible of the G-R noise.
- Flicker Noise: Flicker noise is found in all active devices as well as passive elements. Flicker noise dominates noise at low frequencies. The noise spectral density has a 1/f frequency dependence and hence the name "1/f" noise. This noise source is most significant at low frequencies, although in devices exhibiting high flicker noise.
- Thermal noise: This is directly proportional to the absolute temperature (T) and as T approaches zero, the thermal noise also approaches zero. The thermal noise spectral density is also independent of the frequency and thus thermal noise can also classified as white noise.

The Noise power spectrum Density analysis of Nano-HEMT using GaN material can obtain by drain current. After obtaining the drain current of GaN Nano-HEMT and GaN Micro-HEMT, the noise PSD can be calculated by following the Hooge's expression [11].

$$S_{id} = \frac{I_d^2 \alpha_H}{f^N} \tag{5}$$

where,

S_{id} = Noise power spectrum density;

I_d = Drain current;

f = operating frequency;

N = Total no of electrons in the conduction Band;

α_H = Hooge's parameter of GaN.

Hooge's Parameter is the dimensionless parameter. Very recently, a mobility fluctuation noise theory was proposed by Musha and Tacano, suggests that energy partition among weakly coupled harmonic oscillators in an equilibrium system is subjected to 1/f fluctuations.

4. Results and Discussion

The accuracy of the proposed model is validated using the commercially available TCAD Sentaurus device simulator. The set of parameters used for simulation are shown in Table 2.

The Drain current characteristics plotted for GaN HEMT for Lg in 1 micrometer is shown in Figure 2 and for Lg in 100 nanometer is shown in Figure 3. From the figures it is observed that um gate length GaN HEMT produces less Drain current compared to the Nano GaN HEMT. The Drain current of GaN Nano-HEMT is hundred times more than that of GaN HEMT is observed in Figure 2 and Figure 3.

**Table 2.** List of parameters used in equations and their values that are used to obtain results.

Symbol	Description	Value/unit
W	Gate width	1 μm
L	Gate Length	100 nm
N_d	Donor level concentration	1×10^{19} cm^{-3}
K	Boltzmann's Constant	1.38×10^{-23} J/K
T	Operating temperature	300 K
Q	Electronic charge	1.6×10^{-19} C
D_d	Thickness of doped layer in Nano-HEMT	90 nm
D_i	Thickness of undoped layer in Nano-HEMT	80 nm
$\Delta d = d_d + d_i$	Correction factor	170 nm
Φ_b	Schottky barrier Height	0.697
M	Mobility	900 cm^2/Vs
E_g	Band gap energy of GaAs	3.44 eV
N_v	Density of state in valance band	9×10^{18} cm^{-3}
N_c	Density of state in conduction band	4.7×10^{17} cm^{-3}
ϵ_s	Semiconductor Permittivity	$12.9 \times 8.85 \times 10^{-14}$ F/cm
V_{p2}	Pinch-off voltage in doped layer	1.75 V
F	Operating Frequency	1 GHz
N	No. of conduction Electrons	10^{18}
α_H	Hooge's Parameter	2×10^3
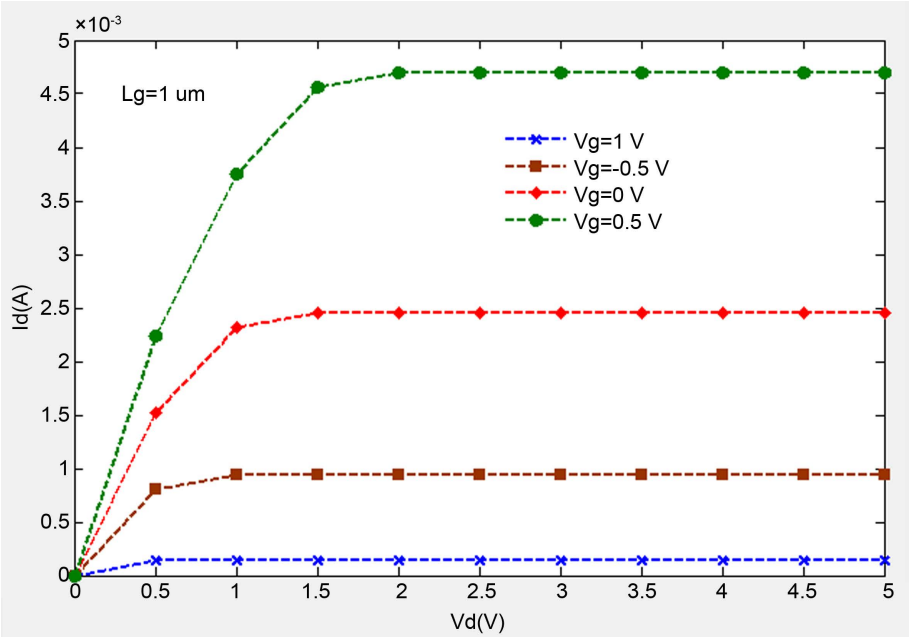
Figure 2. Id vs. Vd characteristics for Lg = 1 um, Vd = (0 V to 5 V) with step size = 0.5 V for various Vg.

Figure 4 and Figure 5 show the I-V characteristics for Micro and Nano GaN HEMT. In this case we have kept Vd as constant value and for the variation of Vg. Even in this case if Lg = 100 nm in Figure 5, the drain current is hundred times greater than the device which has Lg = 1 um in Figure 4. From the figures (Figures 2-5), it is observed that the drain current is higher for nanometer GaN HEMT with increasing gate voltage and/or drain voltage compare to micrometer GaN HEMT.
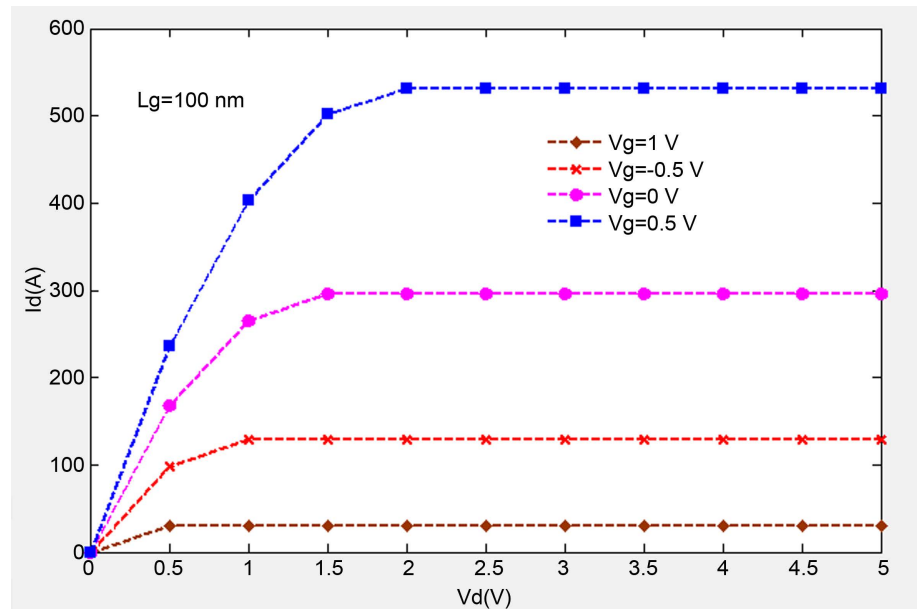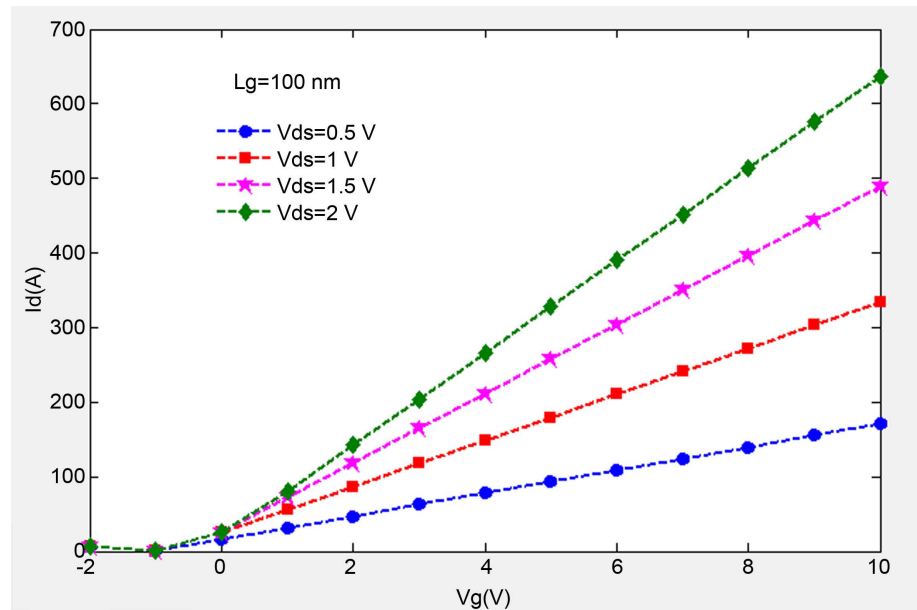

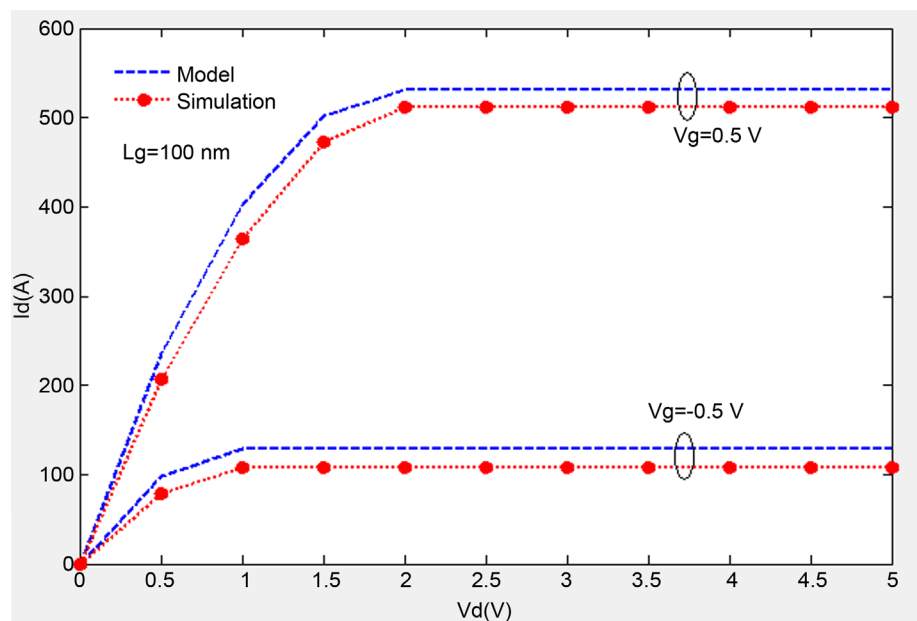**Figure 3.** Id vs. Vd characteristics for Lg = 100 nm, Vd = (0 V to 5 V) with step size = 0.5 V for various Vg.
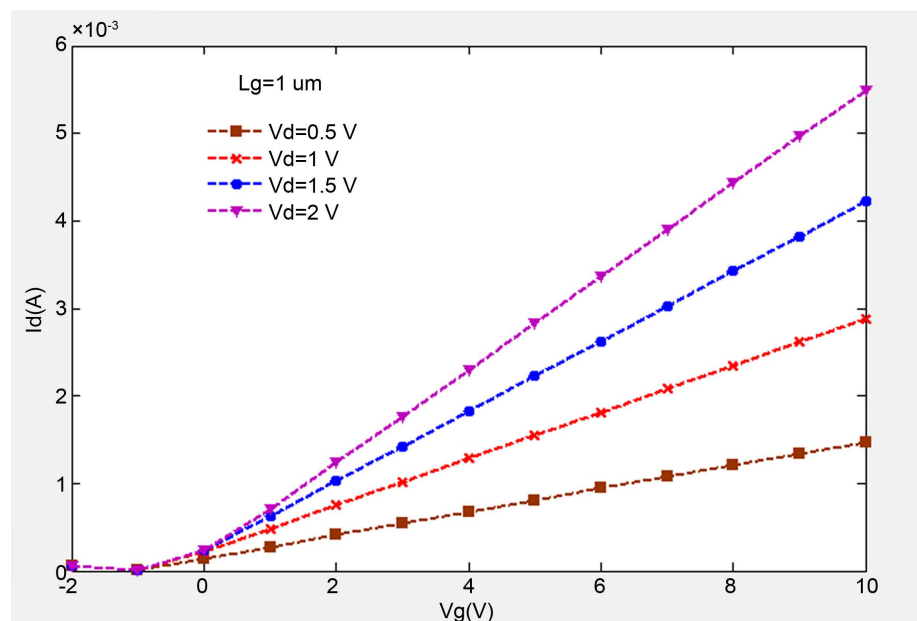
Figure 4. Id vs. Vg characteristics for Lg = 1 um, Vg = (−2 V to 10 V) with step size = 1 V for various Vd.

The nano GaN HEMT drain current characteristics are compared with the simulation results are shown in **Figure 6** and **Figure 7** for Id versus Vd and Id versus Vg respectively.

The noise generated inside this device is due to drain current fluctuation caused due to material or crystal defects in GaN HEMTs. This noise power spectral density analysis stresses on the power spectral density of noise due to the drain currents are analyzed in
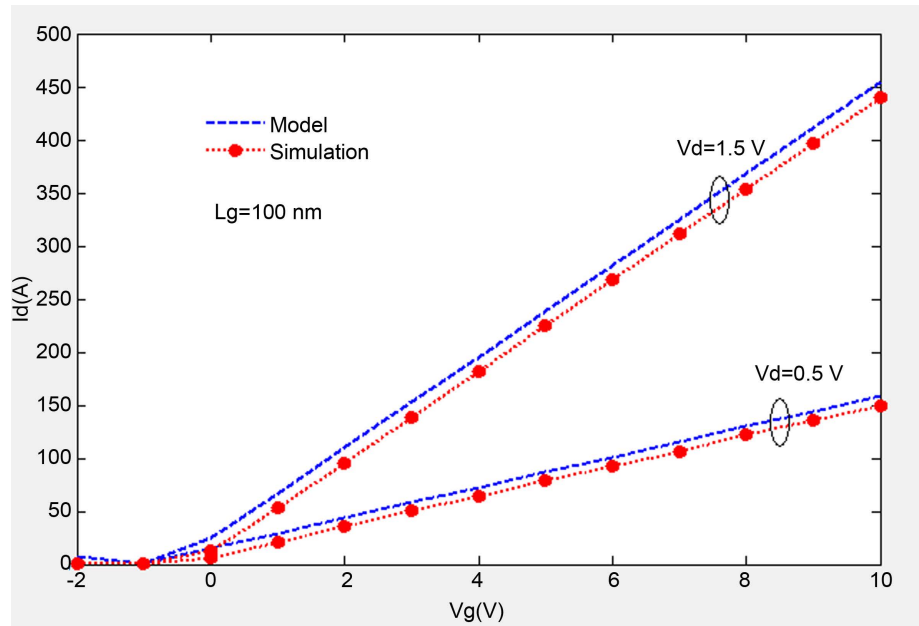

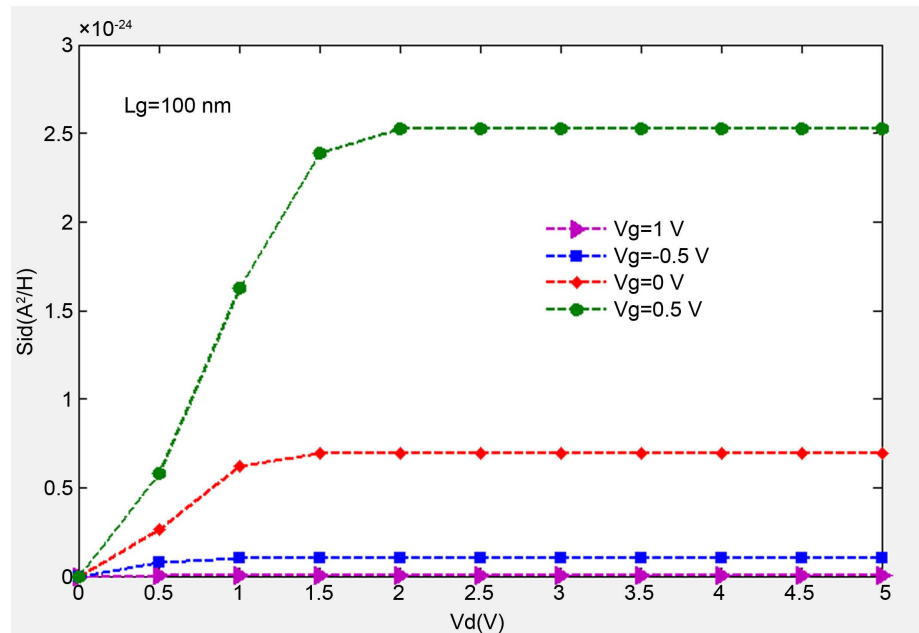**Figure 5.** Id vs. Vg characteristics for Lg = 100 nm, Vg = (−2 V to 10 V) with step size = 1 V for various Vd.

Figure 6. Model and simulation Id vs. Vd characteristics for Lg = 100 nm for Vg = 0.5 V and −0.5 V.

GaN material plotted with temperature is shown in **Figure 9**. Also the noise power spectral density model is compared with simulation results in **Figure 10**.

5. Conclusion

The model simulation for all the plots regarding Nano and Micro meter GaN HEMTs shows the comparative analysis for drain current characteristics. PSD analysis is done
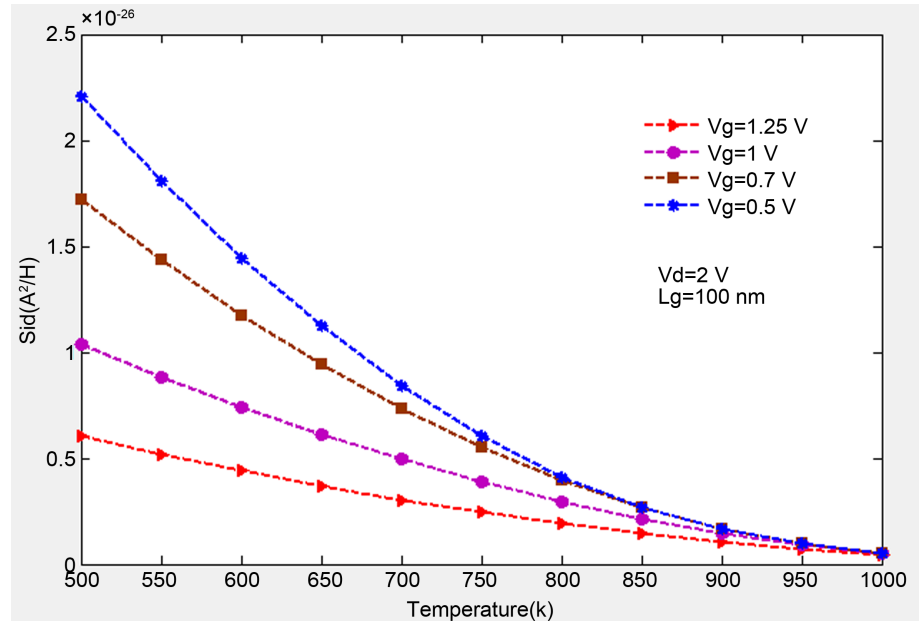
Figure 9. Temperature vs. Sid of GaN nano HEMT with Lg = 100 nm for various gate voltage.
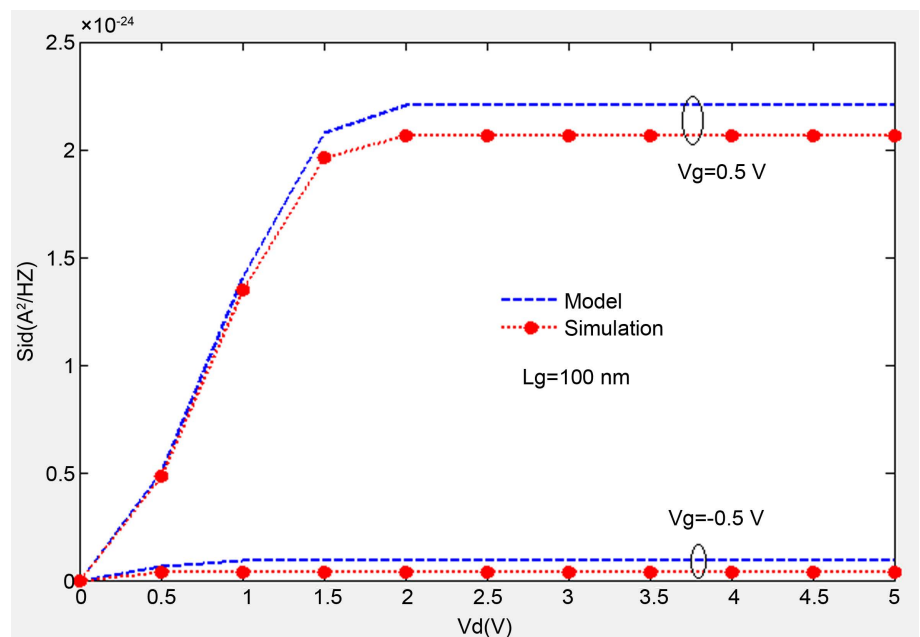
Figure 10. Model and simulation of Vds-Sid characteristics of GaN nano HEMT with Lg = 100 nm for Vg = 0.5 V and −0.5 V.

by considering reduced gate length in nanometer range of GaN HEMT. Also, it is observed that the amount of drain current generated by GaN Nano-HEMT is greater than normal GaN HEMT, but the former lacks in maintaining low noise PSD with higher frequency range, which is very poor as compared to GaN HEMT.

References

[1]   Mishra, U.K., Parikh, P. and Wu, Y.F. (2002) AlGaN/GaN HEMTs—An Overview of Device Operation and Applications. *Proceedings of the IEEE*, **90**, 1022-1031.
http://dx.doi.org/10.1109/JPROC.2002.1021567

[2]   Khan, M.A., Bhattarai, A., Kuznia, J.N. and Olson, D.T. (1993) High Electron Mobility Transistors Based on a GaN/AlGaN Heterojunction. *Applied Physics Letter*, **63**, 1214-1215.
http://dx.doi.org/10.1063/1.109775

[3]   Chen, C.-H., Keller, S., Haberer, E., Zhang, L.D., DenBaars, S.P., Hu, E.L., Mishra, U.K. and Wu, Y.F. (1999) Cl2 Reactive Ion Etching for Gate Recessing of AlGaN/GaN Field-Effect Transistors. *Journal of Vacuum Science & Technology B: Microelectronics Processing,* **17**, 2755-2758. http://dx.doi.org/10.1116/1.591058

[4]   Cai, Y., Zhou, Y.G., Chen, K.J. and Lau, K.M. (2005) High-Performance Enhancement-Mode AlGaN/GaN HEMTs Using Fluoride-Based Plasma Treatment. *IEEE Electron Device Letters*, **26**, 435-437. http://dx.doi.org/10.1109/LED.2005.851122

[5]   Chang, C.Y., Pearton, S.J., Lo, C.F., Ren, F., Kravchenko, I.I.M., Dabiran, A., Wowchak, A.M., Cui, B. and Chow, P.P. (2009) Development of Enhancement Mode AlN/GaN High Electron Mobility Transistors. *Applied Physics Letters*, **94**, Article ID: 263505.
http://dx.doi.org/10.1063/1.3168648

[6]   Uemoto, Y., Hikita, M., Ueno, H., Matsuo, H., Ishida, H., Yanagihara, M., Ueda, T., Tanaka, T. and Ueda, D. (2007) Gate Injection Transistor (GIT)—A Normally-Off AlGaN/GaN Power Transistor Using Conductivity Modulation. *IEEE Transactions on Electron Devices,* **54**, 3393-3399. http://dx.doi.org/10.1109/TED.2007.908601

[7]   Kuroda, M., Ueda, T. and Tanaka, T. (2010) Nonpolar AlGaN/GaN Metalinsulator-Semiconductor Heterojunction Field-Effect Transistors with a Normally-Off Operation. *IEEE Transactions on Electron Devices,* **57**, 368-372.
http://dx.doi.org/10.1109/TED.2009.2037458

[8]   Ghaffari, M. and Orouji, A.A. (2015) Operational Improvement of AlGaN/GaN HEMT on SiC Substrate with the Amended Depletion Region. *Physica E: Low-Dimensional Systems and Nanostructures*, **74**, 303-309. http://dx.doi.org/10.1016/j.physe.2015.07.016

[9]   Aamir Ahsan, S., Ghosh, S., Sharma, K., Dasgupta, A., Khandelwal, S. and Chauhan, Y.S. (2016) Capacitance Modeling in Dual Field-Plate Power GaN HEMT for Accurate Switching Behavior. *IEEE Transactions on Electron Devices*, **63**, 565-572.
http://dx.doi.org/10.1109/TED.2015.2504726

[10] Levinshtein, M.E. (2000) Investigation of Low Frequency Noise Properties of Wide Gap Semiconductors, SiC and GaAs, And the Main Properties of the SiC Based Power Devices, Diodes and Thyristors. Technical Report, European Research Office of the US Army, London.

[11] Von Haartman, M. (2006) Low-Frequency Noise Characterization, Evaluation and Modeling of Advanced Si- and SiGe-Based CMOS Transistors. PhD Thesis, University in Stockholm, Sweden.

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