Electrical Characteristics of GaAs Nano- HEMT

Moumita Bhoumik

Abstract— In today's world, there is a demand for high frequency devices & circuits. And Nano technology can enhance the speed of devices & circuits due to reduction of its carrier transit time. Previously research work has been done regarding electrical characteristics of high frequency devices made up of semiconductor materials such as – MESFETs & HEMTs which included current-voltage characteristics and also Noise Power Spectral Density Analysis using various substrate materials like SiC, GaAs etc. [1] with gate length Lg in µm range. Now emphasis is given on electrical characteristics analysis on GaAs Nano-HEMT by reducing the gate length Lg in nm range.

Index Terms— Gallium Arsenide, Nano-HEMT, Noise PSD, 1/f Noise.

I. INTRODUCTION

Before the invention of the HEMT, the most widely used transistor for both microwave and high-speed digital applications was the GaAs metal semiconductor field effect transistor (MESFET) [1]. However, since electrons must transit through the doped channel in a MESFET, it does not take full advantage of the high mobilities in GaAs. The result is more than a 50-percent reduction in electron mobility, since ionized dopants scatter electrons. Hence, separation of the dopants channel from the electron transit channel is the key to the superior noise, gain and frequency performance of the HEMT.

One of the most mature transistors of this new generation is the High Electron Mobility Transistor (HEMT) [1] .The term 'High Electron Mobility Transistor' is applied to the device because this structure, as shown in figure 1, takes advantage of the superior transport properties i, e. high mobility and the velocity of electrons in a potential well of lightly doped semiconductor material.

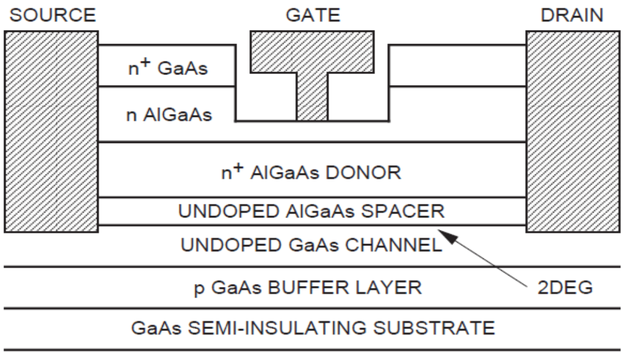

Figure.1. AlGaAs/GaAs HEMT Structure [2]

Recently, HEMTs have made rapid progress through its characteristics as high power & frequency devices and hence implemented in satellite, mobile and military applications. Many articles are present that clearly shows the merits of HEMTs, but the dimension used for gate length was in µm range. This thesis hence present the research being done by considering the gate length dimension in nanometer range (say 100 nm).

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Hence, in this paper, the parameters of HEMT device is considered in nm range and electrical characteristics including current-voltage characteristic and Noise Power Spectral Density analysis is obtained so as to investigate about the superiority of Nano-HEMT over other devices that were in µm range.

From Figure. 1. The HEMT structure can be formed of two distinct semiconductor layers [3]. The bandgap difference results in the formation of conduction and valence band discontinuities at the layer interface or heterojunction creating a quantum well in the conduction band. The wider band gap semiconductor is doped with donors while the smaller band gap material is left undoped. The conduction band electrons move from the donor layer to the undoped layer forming a two-dimensional electron gas (2-DEG) along the heterojunction. The band gap discontinuities are energy barriers spatially confining the electrons.

A. Low-Noise AlGaAs/GaAs HEMT Structure

The conventional AlGaAs/GaAs HEMT structure [2] is grown on a GaAs semi-insulating substrate with the following epitaxial layers: an undoped buffer and GaAs channel layer, an undoped AlGaAs spacer layer, a heavily doped (n+) AlGaAs donor or gate-barrier layer, and an n+ GaAs capping or ohmic contact layer. These layers are essential for fabricating and understanding the operation of a HEMT device. Depending on the application (for example, low noise, power, or digital), modifications and refinements to the basic structure are necessary to obtain optimum device performance. Under normal bias conditions the drain-to-source electric field can inject electrons beyond the 2-DEG channel into the GaAs buffer layer, contributing excess drain current, resulting in gain reduction and degradation of the device noise performance. Introduction of a high band-gap AlGaAs buffer layer before the GaAs buffer suppresses the buffer layer drain-to-source leakage current by creating an energy barrier in the conduction band to reduce electron injection into the buffer, while reducing the velocity of injected electrons [4]. The use of an AlGaAs buffer, however, results in buffer-channel interface roughness that reduces the mobility in the device channel [5]. The interface roughness can be improved by incorporating a thin GaAs smoothing or AlGaAs/GaAs superlattice buffer [6] layer between the buffer and the channel. A superlattice buffer, thin alternating layers of differing materials sharing the same crystalline lattice, is very effective at confining carriers to the 2-DEG channel without sacrificing the material quality. The thin spacer layer separating electrons from their donors is to reduce the scattering of electrons by the positively charged donors. This is done by placing a thin spacer layer of undoped AlGaAs with a thickness ranging from 20 to 50 Å (2–5 nm) between the AlGaAs donor and the GaAs channel layer to separate the negatively charged 2-DEG from the ionized dopant atoms. At room temperature, a thin spacer layer of approximately 20 Å (2 nm) is preferred for low-noise and power devices due to the reduced parasitic source resistance and the increased transconductance and current density. A thicker spacer, conversely, provides higher electron mobility with a smaller charge density in the channel. At cryogenic temperatures the noise performance of a HEMT is strongly dependent on the spacer thickness, and a thickness of 40 Å (4 nm) has been determined to be optimum due to the large increase in electron mobility and velocity [7].

In order to eliminate parallel conduction in the AlGaAs donor layer, this layer must be completely depleted by both the AlGaAs/GaAs heterojunction and the Schottky gate. The donor layer is typically uniformly doped with Si at a doping level of approximately 10^{18} atoms/cm^3. The high doping level makes possible the small spacing between the gate and the carrier channel. A higher doping level results in a higher sheet charge density in the channel, increasing transconductance (g_m), unity current gain frequency (f_T), and current density, at the expense of a lower breakdown voltage. Fortunately, high sheet charge density and breakdown voltage can be achieved with planar-doping, sometimes also referred to as ℵ-doping or pulse-doping [8, 9]. The planar-doping layer is a monolayer of Si approximately 5 Å (0.5 nm) thick with a doping level of approximately 5 x 10^{12}/cm^2 located just above the spacer. The use of planar doping also allows a lower doping level in the AlGaAs layer for the gate barrier, increasing the breakdown voltage without sacrificing the channel sheet charge density.

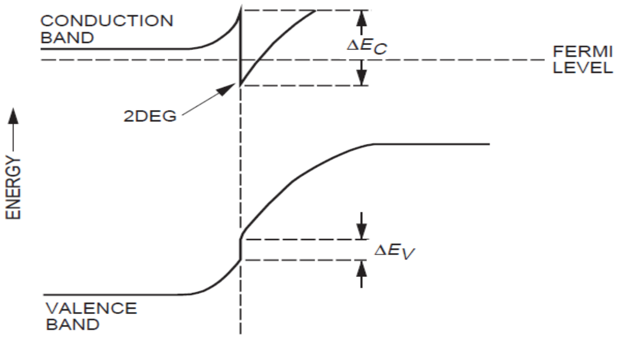

Figure.2. Energy band diagram of a generic AlGaAs–GaAs HEMT showing the 2D Electron Gas quantum well channel [2].

B. *Why Gallium Arsenide?*

Table 1. shows the fundamental material properties of GaAs, SiC, diamond, Si, GaN, and InP that are most important to electronic device performance [10, 11, 12].

Table 1. Material properties semiconductors at 300 K [10, 11, 12, 13].

Property	GaN AlGaN/GaN	SiC	Diamond	Si	GaAs AlGaAs/ InGaAs	InP InAlAs/ InGaAs
Bandgap energy, E_g (eV)	3.44	3.26	5.45	1.12	1.43	1.35
Electric breakdown field, E_c (MV/cm)	3	3	10	0.3	0.4	0.5
Saturated (peak) velocity electrons, v_{sat} (v_{peak}) ($\times 10^7$ cm/s)	2.5 (2.7)	2.0 (2.0)	2.7	1.0 (1.0)	1.0 (2.1)	1.0 (2.3)
Electron mobility, μ_n (cm^2/V·s)	900 2000^{α}	700	4800	1500	8500 $10{,}000^{\beta}$	5400 $10{,}000^{\chi}$
2DEG density, n_s ($\times 10^{13}$ cm^{-2})	1.0	N.A.	N.A.	N.A.	< 0.2	< 0.2
Thermal conductivity, κ (W/cm·K)	1.3 – 2.1	3.7 – 4.5	22	1.5	0.5	0.7
Relative permittivity, ε_r	9.0	10.1	5.5	11.8	12.8	12.5

Generally, to achieve high currents and high frequency operation, high charge carrier mobility (μ) and high saturation velocity (v_{sat}) are desirable. The high value for electron mobility of GaAs (8500 cm^2/Vs) is the main reason that field-effect transistors (FETs) fabricated from this material have such excellent high-frequency performance.

A primary disadvantage of fabricating transistors from bulk GaN and SiC is the relatively low values for the electron mobilities, which are 900 cm2/Vs for GaN and depending on the polytype approximately 700 cm^2/Vs for SiC.

C. *Noise Power Spectral Density of Nano-HEMT*

Noise is a universal phenomenon, but the noise considered in this thesis is the noise in electronic circuits caused by the small current fluctuations that are generated within the semiconductor devices themselves. It is one of the most important characteristics of any semiconductor material or device. It has significant impact on circuit performance. These noises are usually associated with material failures or with imperfection of a fabrication process and are generated due to interaction with impurities or dislocations which create energy levels inside the forbidden gap of semiconductor materials. Thus leads to enhanced scattering of charge carriers and modifies the number of charge carriers through trapping and release [1, 15].

The study of noise is important because it provides information on the lower limits of the signal being processed by a circuit without significant deterioration in the signal quality. With decreasing device dimensions in modern electronic circuits, the signal levels being processed are also very low, decreasing the Signal-to-Noise ratio (SNR) [15].

There are various sources of noise in semiconductor devices which are as follows [15]:

Shot Noise:

Shot noise is the noise associated with the direct-current flow and is present in diodes and bipolar transistors. Shot noise refers to the random fluctuations of the electric current, which are caused by the fact that the current is carried by discrete charges (electrons). The shot noise spectral density is independent of the frequency. Noise sources which are independent of the frequency are categorized as white noise.

Thermal Noise:

This noise is associated with the thermal random motion of the charge carriers. Thermal noise is unaffected by the presence or absence of direct current, since the electron drift velocity is much less than the electron thermal velocity. Thermal noise 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.

Flicker or 1/ *f* Noise:

Flicker noise is found in all active devices as well as passive elements. Flicker noise is always associated with the flow of direct current flowing through the device. Flicker noise is the low frequency noise which affects the performance of device and can be neglected at very high frequencies, but it cannot be neglected in case of mixers, oscillators or frequency dividers which up convert low frequency noise to high frequency, thus giving inferior phase noise or SNR. 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, this noise may dominate the device noise at high frequencies well into the megahertz range [1].

Flicker noise is often called 'pink noise' because of the frequency dependence of the power spectral density. (Any noise source which shows frequency dependence is called 'colored noise'). The adjective 'ubiquitous' is often used in terms of 1/ *f* noise as it is used widely in different systems apart from electronic devices, such as radioactive decay, chemical systems, biology, fluid dynamics, astronomy, optical systems, network traffic and economics.

Generation Recombination Noise (GR Noise):

In a semiconductor, free carriers are necessary for the drift and diffusion conduction mechanisms. The generation process involves the creation of free carriers, and the recombination process involves the trapping of these free carriers in defects. If carriers are trapped at some critical spots, the trapped charge can also induce fluctuations in the mobility, diffusion coefficient, electric field, barrier height, space charge region width etc. Electronic states within the forbidden bandgap are referred to as traps, and exist due to the presence of various defects or impurities in the semiconductor or at its surfaces. The trapped carrier will be freed again after only a short time because of the thermal energy of the crystal lattice. This process is a series of independent discrete events. Each event causes fluctuation in the number of free carriers leading to a fluctuation in the material conductance. This fluctuation in the conductance leads to the generation-recombination noise when there is a current flow. The generation-recombination noise is a low frequency noise.

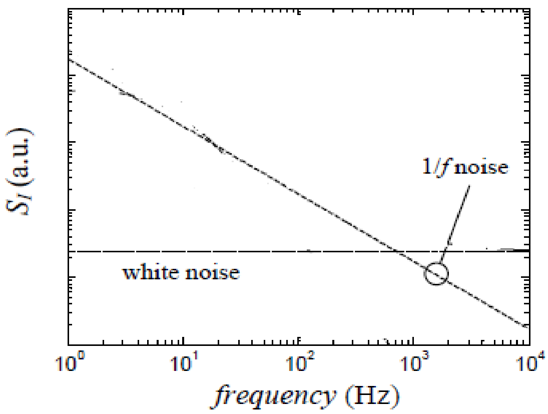

Figure.3. Nature of typical characteristics of 1/f noise involved with the semiconductor devices over a range of frequency [17].

The type of noise which is mainly observed in semiconductor devices such as MESFETs and HEMTs is Flicker noise, also known as 1/f noise. It is known as 1/f noise since the noise power spectral density is inversely proportional to frequency that can be determined by using two major models of 1/f noise:

a) Surface Model -developed by McWhorter in 1975, which deals with Generation- Recombination Noise.

b) Bulk Model-developed by Hooge in 1969, which deals with 1/f noise or flicker noise [16].

Power Spectral Density of 1/f Noise (Flicker Noise) [1]:

The 1/ *f* noise is a fluctuation in the conductivity of metals and semiconductors. The power spectral density (PSD) is proportional to 1/ *f* over a wide range of frequencies. The mechanism that gives 1/*f* noise is number fluctuation, described by Hooge with the following empirical formula for the drain current fluctuations in the device.

This flicker noise is a major source of noise at low frequencies and is found in almost all electronic materials and semiconductor devices like metal films, Ionic Solutions, MOSFETs, BJTs, JFETs, MESFETs and HEMTs.

Hence, in this thesis, the noise power spectral density versus frequency characteristics for GaAs Nano-HEMT will be observed to determine its reliability.

II. THEORETICAL MODEL OF I-V CHARACTERISTICS OF GALLIUM ARSENIDE NANO-HEMT

If assumed a constant mobility, then for low values of Vds (i, e. drain to source voltage), the drain current Id in the linear region is given by [14]

$$Id = \varepsilon_N \mu \frac{W}{2L(d+\Delta d)}[2(Vgs - Voff)Vds - Vds^2] \qquad (1)$$

For Vds≤Vgs-Voff

If Vds is further increased, then the carrier reaches the saturation voltage and the saturated drain current becomes [14]

$$Id = \varepsilon_N \mu \frac{W}{2L(d+\Delta d)}(Vgs - Voff)^2 \qquad (2)$$

For Vds> Vgs-Voff

Where,

ϵ_N - permittivity of the substrate material in HEMT

Vgs- the gate to source voltage

Voff - the offset voltage

The offset voltage Voff can be calculated by the formula [14]

$$Voff = \Phi_b - \frac{\Delta Ec}{q} - Vp_2 \qquad (3)$$

The Schottky barrier height for the HEMT device can be calculated by [14]

$$\Phi_b = \frac{kT}{q}\ln\left(\frac{N_d}{n_i}\right) \qquad (4)$$

Vp_2 can be calculated by using [14]

$$Vp_2 = qN_d d_d^2/2\epsilon_N \qquad (5)$$

III. THEORETICAL MODEL OF NOISE PSD ANALISIS OF GALLIUM ARSENIDE NANO-HEMT WITH FREQUENCY

The typical expressions for noise power spectral density using Hooge's Model is given by [16]:

$$S_{id} = \frac{{I_d}^2 \alpha_H}{fN} \qquad (6)$$

Where,

Sid is the noise power spectral density

Id is the current flowing through the Nano-HEMT device αH is the Hooge's parameter for the substrate material f is the frequency of operation N is the total number of conduction electrons

This flicker noise is intrinsic to the Nano-HEMT which is associated with the locally occurring random fluctuations of carrier density or velocity that cause voltage or current fluctuations at the device terminals.

Hooge's Parameter Details

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 [20]

$$\alpha_H = a_l/\lambda_{ph}$$

Where 'a_l' is the lattice constant and 'λ_{ph}' *is* the mean free path of the electrons in the case of phonon scattering.

The dimensionless parameter αH, referred to as the Hooge parameter, was first suggested to be constant and equal to 2×10-3. Later, it was found that αH depends on the crystal quality, and hence its value varies with the different substrate material that is chosen. It was also proposed that only phonon scattering contributes to the number fluctuations (N) that result into drain current fluctuation too. The factor 1/*N* results from independent mobility fluctuations by each of the *N* conducting carriers.

IV. UNITS

Table. 2. List of Parameters used in equations (1, 2 , 3, 4 ,5 ,6) and their values that are used to obtain results for this thesis.\

SYMBOL	DESCRIPTION	VALUE /UNIT
W	Gate width	1 µm
L	Gate Length	100 nm
N_d	Donor level concentration	$1x10^{18}$ cm^{-3}
k	Boltzmann's constant	$1.38x10^{-23}$ J/°K
T	Operating temperature	300 K
q	Electronic charge	$1.6x10^{-19}$ C
d_d	Thickness of doped layer in Nano-HEMT	52 nm
d_i	Thickness of undoped layer in Nano-HEMT	8 nm
$\Delta d= d_d+d_i$	Correction factor	60 nm
Φb	Schottky barrier height	0.697
µ	Mobility	8500 cm^2/Vs
E_g	Band gap energy of GaAs	1.43 eV
N_v	Density of state in valance band	$9x10^{18}$ cm^{-3}
N_c	Density of state in conduction band	$4.7x10^{17}cm^{-3}$
ϵ_s	Semiconductor permittivity	$12.9x8.85x10^{-14}$ F/cm
V_{p2}	Pinch-off voltage in doped layer	1.75 V
f	Operating frequency	1 MHz
N	No. of conduction electrons	10^{18}
α_H	Hooge's Parameter	0.0975

V. RESULTS AND DISCUSSIONS

V-I Characteristics Analysis on GaAs Nano-HEMT:

The semiconductor materials that is used to form heterojunction in this high frequency device HEMT is GaAs (Gallium Arsenide) due to its superior electron mobilities that is far higher than any other semiconductor materials.

The V-I Characteristics plotted for GaAs HEMT for Lg in micrometer range is shown as following Figure.4.

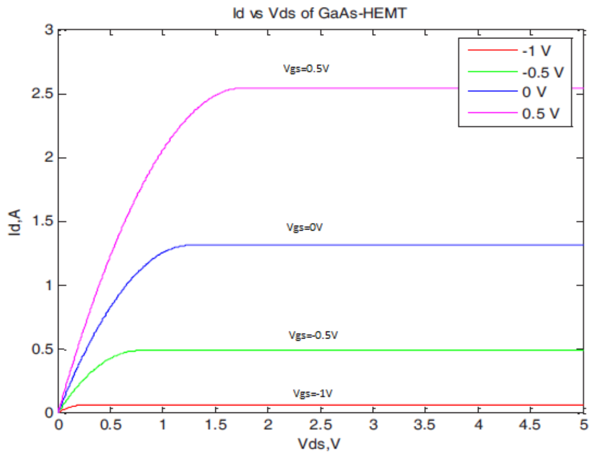

Figure.4. Plot for I-V characteristics of GaAs HEMT for Vgs=-1,-0.5, 0, 0.5 V, over the range of Vds=0 to 5 V (at step size of 0.5 V) [1].

But when the same GaAs HEMT device is changed in terms of its gate length parameter Lg which is made in nanometer range for giving rise to GaAs Nano-HEMT, the V-I characteristics obtained for it is shown in following Figure.5.

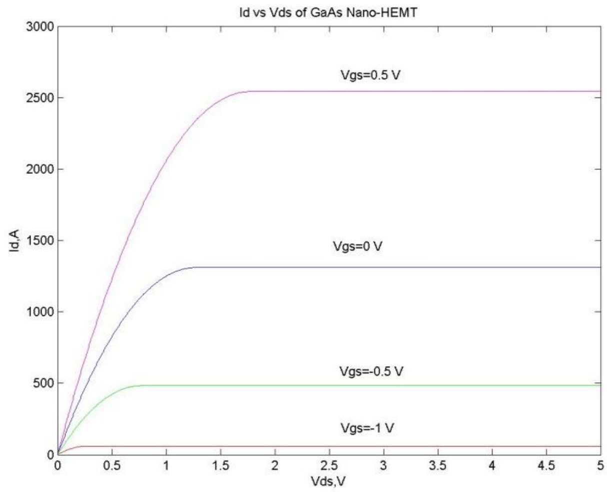

Figure.5. Plot for I-V characteristics of GaAs Nano-HEMT with Lg=1 nm, for Vgs=-1,-0.5, 0, 0.5 V, over the range of Vds=0 to 5 V (at step size of 0.5 V).

For Lg in range of µm, maximum drain current was obtained (for Vgs=0.5 V) as almost 3 A. But, when Lg is reduced to nm range, the drain current Id as almost 3000 A, which is very huge value.

Noise PSD Analysis on GaAs Nano-HEMT:

HEMT is a field-effect transistor where the drain current is controlled by the gate bias, which modulates the carrier concentration in the channel. The drain current (Id) fluctuation can be related to the fluctuation of the gate bias (Vgs) or equivalently the flat band voltage (VF_B). Since the gate current is negligible compared to the drain current, hence we can safely assume that there is no contribution from the gate current to the drain current noise [18].

Important traps are those located near the metal semiconductor interface within kT at around Fermi level due to band bending, in thermal activation and tunnelling mechanisms. The power spectral density (PSD) of the gate current noise shows a quadratic dependence on the gate current intensity.

In HEMT, the gate current flows through two Schottky barriers, one at the gate metal and the other near the two-dimensional carrier channel. Based on different noise generation mechanisms for Schottky barrier structure, a comprehensive study for low frequency noise in the gate current of HEMT structure is developed.

Low frequency noise is very important for microwave device performance since it can be upconverted into the microwave range and dominates the phase noise of oscillators and mixers. Low frequency noise measurements also can provide a spectroscopy tool for defects involved with the device.

The noise generated inside this device is due to drain current fluctuation caused due to material or crystal defects in HEMTs. This noise power spectral density analysis stresses on the power spectral density of noise due to the drain currents we have obtained from the earlier analyzed figures (4, 5).

The noise PSD analysis on GaAs HEMT comprises of plotting of noise PSD for different values of Vgs from -1 to 0.5 V, over a range of Vds from 0 to 5 V in Figure.6. since this analysis involves the corresponding drain current as obtained by plotting V-I characteristics of HEMT using GaAs.

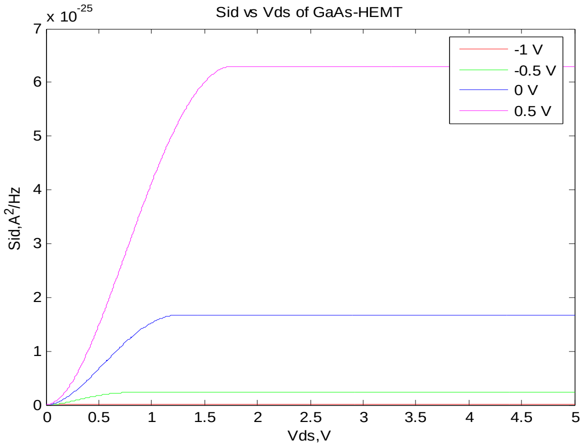

Figure.6. Plot for Sid vs. Vds of GaAs-HEMT for Vgs=-1,-0.5, 0, 0.5 V, over the range of Vds=0 to 5 V (at step size of 0.5 V) [1, 19].

Again when the same GaAs HEMT device is changed in terms of its gate length parameter Lg which is made in nanometer range for giving rise to GaAs Nano-HEMT, the Noise PSD vs V_{ds} obtained for it is shown in following Figure.7.

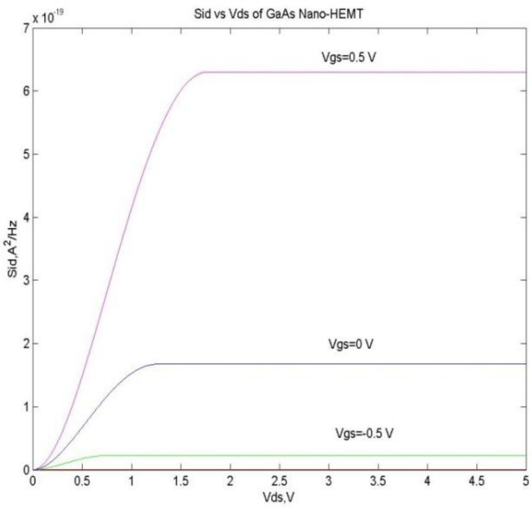

Figure.7. Plot for Sid vs. Vds of GaAs Nano-HEMT with Lg=1 nm for Vgs=-1,-0.5, 0, 0.5 V, over the range of Vds=0 to 5 V (at step size of 0.5 V)

Hence, from Figure (6, 7) it is clearly observed that Noise PSD is increasing from GaAs HEMT (10^{-25} A^2/Hz) to GaAs Nano-HEMT (10^{-19} A^2/Hz).

VI. CONCLUSION

Hence, in this thesis the electrical characteristics of Nano-HEMT using GaAs substrate was determined in terms of voltage-current (V-I) characteristics and 1/f Noise PSD analysis by considering reduced gate length in nanometer range. Also, it is observed that the amount of drain current generated by GaAs Nano-HEMT is nearly thousand times greater than normal GaAs HEMT, but the former lacking in maintaining low noise PSD with higher frequency range, which is very poor as compared to GaAs HEMT. With the help of this analysis, further research may be carried so as to obtain other characteristics of Nano-HEMT using various substrates and also to implement a suitable design so as to lower the noise PSD level with increase in frequency range.

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