Comparative Study of Noise Power Spectral Density Analysis on Nano-HEMTs Using GaAs & GaN Substrates

Moumita Bhoumik
Mallabhum Institute of Technology, Assistant Professor, Department of Electronics & Communication Engineering, Bishnupur, West Bengal, India

Abstract

Nano technology has the capability to change the features of modern day semiconductor technology due to its fast response and high speed abilities. HEMTs on the other hand are known for its superiority over other semiconductor devices like MESFETs due to the utilization of high electron mobilities of substrate materials. Hence analysis on Nano-HEMTs is done in this thesis to investigate about its device characteristics by using various substrates such as GaN & GaAs. In terms of drain current parameter some materials are superior to others but it is necessary to do the analysis in terms of their noise generating abilities during high temperature operation. This study analysis depicts the noise PSD analysis on Nano-HEMTs using different substrates.

1. Introduction

Nano-HEMTs are considered in this thesis hence the research is done by considering the gate length dimension in nanometer range.

The two most used semiconductor materials for HEMT are Gallium Arsenide (GaAs) and Gallium Nitride (GaN).

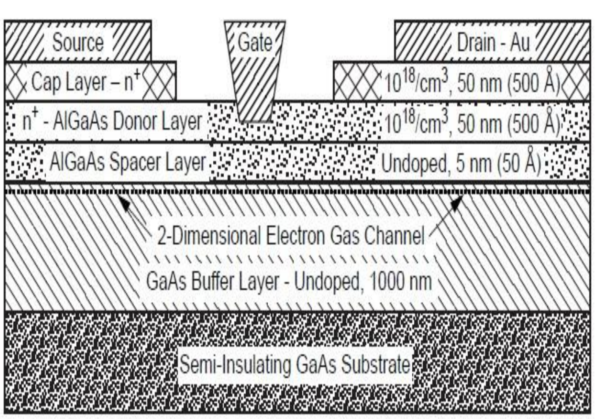

Figure.1. GaAs Nano-HEMT structure. [1]

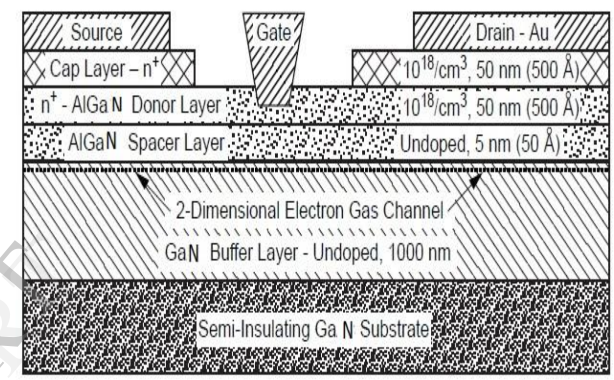

Figure.2. GaN Nano-HEMT structure. [1]

The conventional AlGaAs/GaAs and AlGaN/GaN Nano-HEMT structures [2] are grown on GaAs and GaN semi-insulating substrates respectively with the following epitaxial layers: an undoped buffer and GaAs/GaN channel layer, an undoped AlGaAs/AlGaN spacer layer, a heavily doped (n+) AlGaAs/AlGaN donor or gate-barrier layer, and an n+ GaAs/GaN capping or ohmic contact layer. These layers are essential for fabricating and understanding the operation of a HEMT device. And 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/GaN buffer layer, contributing excess drain current, resulting in gain reduction and degradation of the device noise performance. Introduction of a high band-gap AlGaAs/AlGaN buffer layer before the GaAs/GaN buffer respectively 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 [3]. The use of an AlGaAs/AlGaN buffer, however, results in buffer-channel interface roughness that reduces the mobility in the device channel [4]. The interface roughness can be improved by incorporating a thin GaAs/GaN smoothing or superlattice buffer [5] 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. This thin spacer layer separating the 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/AlGaN with a thickness ranging from 20 to 50 Å (2–5 nm) between the AlGaAs/AlGaN donor and the GaAs/GaN 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 [6].

In order to eliminate the parallel conduction in the AlGaAs/AlGaN donor layer, these layers must be completely depleted by both the AlGaAs-GaAs or AlGaN-GaN heterojunctions and the Schottky gates. 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 pulse-doping [7, 8]. 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.

In this thesis, the noise analysis is done in terms of noise PSD (Power Spectral Density) versus frequency analysis and Relative noise PSD versus temperature analysis on Nano-HEMT using various substrates such as Gallium Arsenide (GaAs) & Gallium Nitride (GaN). The noise analysis can be done by obtaining the drain current versus gate-source voltage characteristics of GaAs & GaN Nano-HEMTs and by obtaining further analysis with respect to frequency and temperature.

Table. 1. Material properties of GaAs & GaN HEMTs at 300 K [9, 10, 11].

Property	GaAs	GaN
Bandgap Energy E_g (eV)	1.43	3.44
Electric Breakdown Field E_c (MV/cm)	0.4	3
Saturated velocity electrons V_{sat} ($x10^7$ cm/s)	1.0 (2.1)	2.5 (2.7)
Mobility of electrons μn (cm^2/Vs)	8500 $10{,}000^{\beta}$	900 2000^{α}
2DEG Density η_1 ($x10^{15}$ cm^{-3})	0.2	1.0
Thermal Conductivity K(W/cmK)	0.5	1.3-2.1
Relative Permittivity (ε_r)	12.8	9.0

2. Results and Discussion

2.1. Voltage-Current Characteristics of Nano-HEMTs using GaAs & GaN substrates

As the gate length L_g of HEMT is reduced from micrometer (µm) rage to nanometer (nm) range, say 100 nm, it gives rises to Nano-HEMTs. Now the current-voltage characteristics of such devices can be analysed to observe the superiority of Nano-HEMTs over HEMTs.

The drain current I_d in the linear region of a HEMT is given by [14]

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

For $V_{ds} \leq V_{gs}-V_{off}$

If drain-source voltage 'V_{ds}' is further increased, then the carrier reaches the saturation voltage and the saturated drain current becomes [14]

$$I_d = \varepsilon_N \mu \frac{W}{2L(d+\Delta d)}(V_{gs} - V_{off})^2 \qquad (2)$$

For $V_{ds} > V_{gs}-V_{off}$

Where,

ϵ_N - permittivity of the substrate material in HEMT

Vgs- the gate to source voltage

V_{off} - the offset voltage

Here, semiconductor materials such as GaAs & GaN are considered as the substrates of Nano-HEMT, to obtain the following drain current (Id) versus gate-source voltage (Vgs):

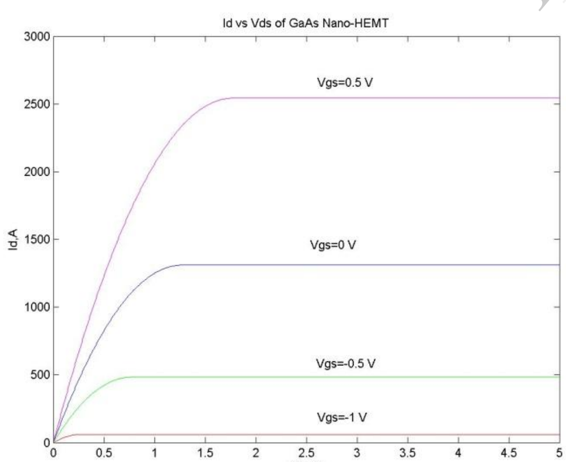

Figure.3.V_{ds}-I_d characteristics of GaAs Nano-HEMT with Lg=100 nm over V_{gs} = -1V to 0.5 V (0.5 step size) [12]

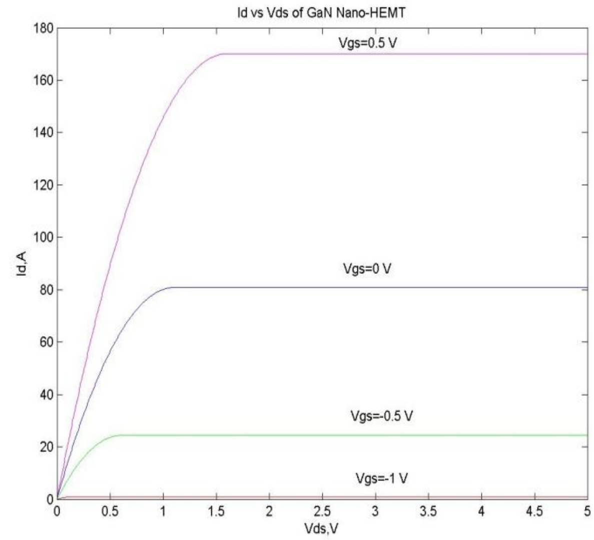

Figure.4.V_{ds}-I_d characteristics of GaN Nano-HEMT with Lg=100 nm over V_{gs} = -1V to 0.5 V (0.5 step size)

From figures (3, 4) it is clearly observed that the drain current value for GaAs Nano-HEMT is very larger than GaN Nano-HEMT for similar gate length and gate-source voltage values.

2.2. Noise Power Spectral Density (PSD) Analysis of Nano-HEMTs using GaAs & GaN substrates with drain to source voltage (V_{ds})

After obtaining the drain current of GaAs & GaN Nano-HEMTs [15], the noise PSD can be calculated by following the Hooge's expression [16]:

$$S_{id} = \frac{I_d{}^2 \alpha_H}{fN} \qquad (3)$$

Where,

S_{id} is the noise power spectral density

I_d is the current flowing through the Nano-HEMT device

α_H is the Hooge's parameter for the substrate material

f is the frequency of operation

N is the total number of conduction electrons

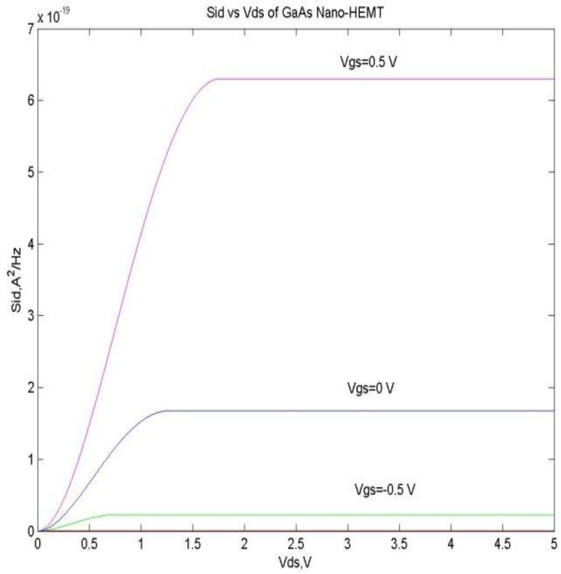

Figure.5. V_{ds}-S_{id} characteristics of GaAs Nano-HEMT with Lg=100 nm over V_{gs} = -0.5 V to 0.5 V (0.5 step size) [12].

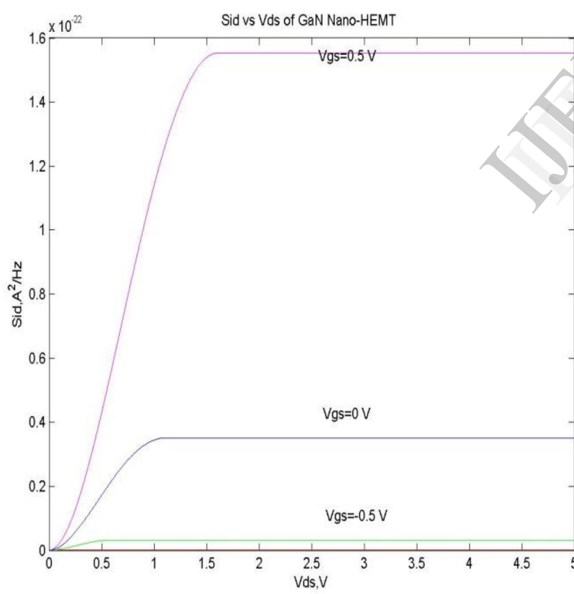

Figure.6. V_{ds}-S_{id} characteristics of GaN Nano-HEMT with Lg=100 nm over V_{gs} = -0.5 V to 0.5 V (0.5 step size)

From figures (5, 6) it is observed that noise PSD value for GaAs Nano-HEMT is higher (10^{-19} A^2/Hz) and that of GaN Nano-HEMT is lower (10^{-22} A^2/Hz). This is due to high drain current generation in GaAs Nano-HEMT as compared to GaN Nano-HEMT.

2.3. Relative Noise Power Spectral Density (S_{id}/I_d^2) analysis of Nano-HEMTs using GaAs & GaN substrates with Temperature

In case of HEMTs, the defect may exist in the semiconductor bulk or the gate dielectric which cause trapping or detrapping of inversion layer carriers and hence exhibits a predominant characteristic trapping time constant 'τ'. This gives rise to a noise which is called Generation-Combination noise [16]. The general expression for Generation-Recombination noise is given as [17]:

$$S = \frac{Sid}{Id^2} = \frac{AF(1-F)\zeta}{1+(\omega\zeta)^2} \qquad (4)$$

Where,
Sid/Id^2 is the relative noise power spectral density of current fluctuation
ζ is the trap time constant
ω is angular frequency (i,e. ω =2πf, f is the operating frequency of the HEMT)

The relative noise PSD analysis on GaAs & GaN Nano-HEMTs can be obtained by plotting of relative noise PSD due to drain current fluctuation in the device at frequency 'f' of 1 MHz [16], over a temperature range from 500 K to 1000 K. The corresponding S_{id}/I_d^2 versus temperature plot is as follows:

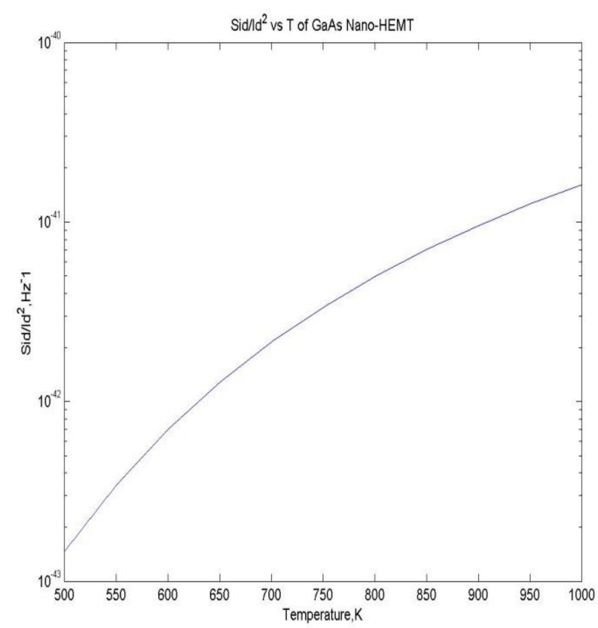

Figure.7. S_{id}/I_d^2-T characteristics of GaAs Nano-HEMT with L_g=100 nm for T= 500 K to 1000K (100 step size)

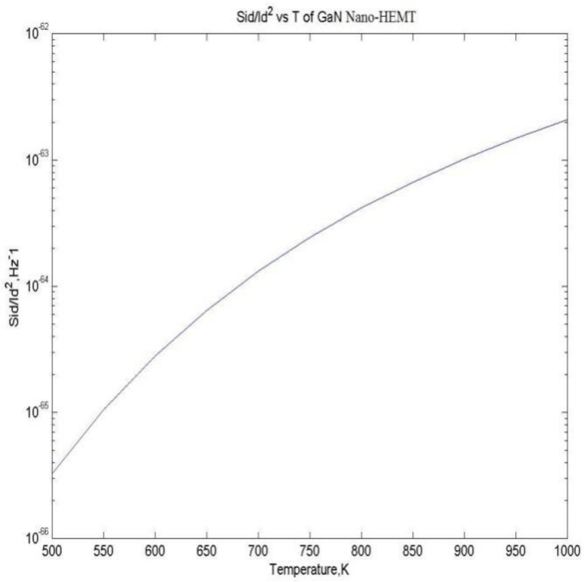

Figure.8. S_{id}/I_d^2-T characteristics of GaN Nano-HEMT with L_g=100 nm for T= 500 K to 1000K (100 step size)

The comparative plots of S_{id}/I_d^2 versus temperature for GaAs & GaN Nano-HEMTs can be shown as:

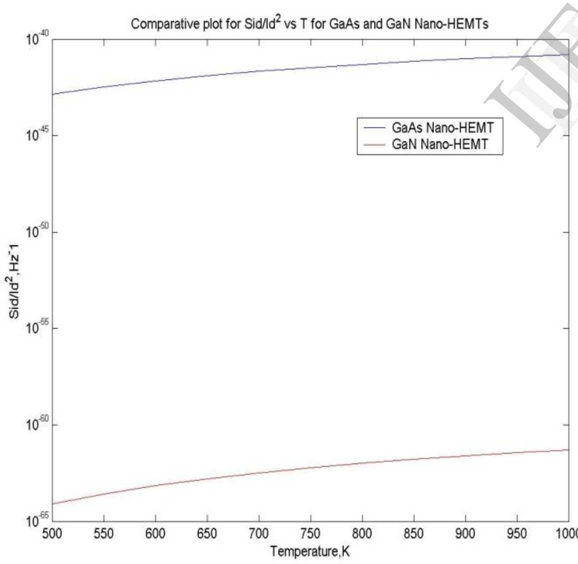

Figure.9. Comparative plots of S_{id}/I_d^2-T characteristics of GaAs & GaN Nano-HEMTs with L_g=100 nm for T= 500 K to 1000K (100 step size)

From figures (7, 8, 9) the variation of relative noise PSD over temperature range above 500 K can be observed. It is also observed that GaN Nano-HEMT exhibits better noise performance than GaAs Nano-HEMT at high temperature ranges (above 500 K).

3. Conclusion

The MATLAB 7 simulation for all the plots regarding GaAs & GaN HEMTs shows the comparative analysis including V_{ds}-I_d characteristics, V_{ds}-S_{id} characteristics & S_{id}/I_d^2-T characteristics of the devices. In this thesis, only two semiconductor materials i, e. GaAs & GaN is considered for the noise analysis, but there is a possibility of existence of far more superior materials that may be implemented to Nano-HEMTs to improve its features further.

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