HFET's Channel Noise Modelling with Mole Fraction (x) and Doping Concentration (N_d) Based on Monte-Carlo Mobility Formulation

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Abstract

A simple analytical expression for the standard deviation of channel noise for Au-$Al_xGa_{1-x}As$/GaAs heterostructure field-effect transistors (HFETs) is developed based on Monte-Carlo formulation of field-dependent mobility and a linear charge control model. In addition of this expression is explicit function of HFETs geometry parameters and biasing conditions, it estimates the noise performance with respect to the composition mole fraction (x) and doping concentration (N_d) and hence is very useful for HFET-based devices design and optimization purposes. A simulation of channel noise with respect to biasing conditions, composition mole fraction and doping concentration is performed. The simulation shows the decreasing of noise at high doping concentration and that the noise increases slightly with and seems to be independent of composition mole fraction at certain biasing conditions.

Keywords: Heterojunctions, FET, Noise, Modelling, Monti-Carlo.

I. INTRODUCTION

Structures such as heterojunction field-effect transistors (HFETs) have an increasing importance for low-noise amplifiers applications remarkably at (1-10) GHz frequency range [1].

Despite its importance, little data is available on the dependent of HFETs channel noise, and hence its noise parameters, on some important device parameters such as mole fraction (x) and doping concentration (N_d). This data can be applied in design and optimization purposes for HFETs-based devices.

Wu and Van der Ziel [2] and Brookes [3] proposed analytical noise models that take into account only the thermal noise in the channel. Cappy et al. [4] proposed a numerical noise model that takes into account non-stationary electron-dynamic effects and explains the results of noise figure measurement. Anwar et al. [5] have reported a noise model for $Al_xGa_{1-x}As/GaAs$ HFETs which is based on the self-consistent solution of Schrödinger and Poisson's equations. Asgaran et al. [6] have been developed and experimentally verified simple analytical expressions for MOSFETs noise parameters. The expressions which are based on analytical modeling of MOSFETs channel noise are explicit functions of MOSFETs geometry and biasing conditions only.

Unfortunately, none of these models takes into account the channel noise dependent on x and N_d. The study of channel noise is important in predicting the noise performance of heterostructure devices which characterized by four noise parameters, i.e., the minimum noise figure, equivalent noise resistance, optimum source resistance, and optimum source reactance.

Because the charge control of MOSFETs and HFETs are very much alike [8], we present a general model as an endeavor to relate the channel noise for Au-$Al_xGa_{1-x}As/GaAs$ HFETs to x and N_d based on the analytical expressions developed by [6] for the charge control and the Monte-Carlo formulation of the field-dependent mobility for $Al_xGa_{1-x}As/GaAs$ in [9] and [7].

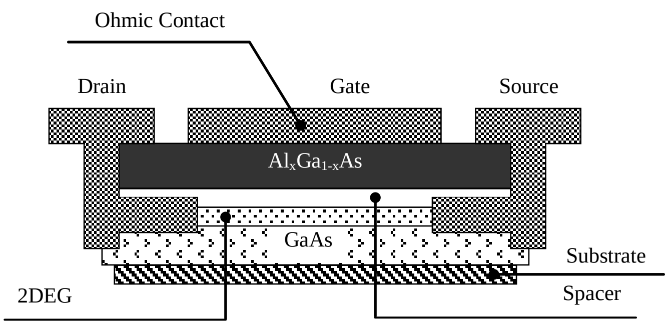

Fig.(1) Simple construction of heterostructure field-effect transistor (HFET). Thicknesses of the doped and undoped (spacer) $Al_xGa_{1-x}As$ layers are d_d and d_i, respectively.

II. 2DEG CHARACTERISTICS

The simple construction of HFETs is shown in Fig.(1). Two characteristics control the behaviour of the two-dimensional electron gas (2DEG) inside the channel which represents the channel charge in heterojunction they are the charge control and the carrier velocity.

A. Charge Control

According to the charge control model in [10], the channel charge per unit area can be expressed as a function of the position (z) along the channel as

$$Q(z) = C_{ox}(V_{GT} - \alpha V(z)) \qquad \ldots (1)$$

where C_{ox} is gate capacitance per unit area, α is the bulk-charge effect coefficient (for most $Al_xGa_{1-x}As/GaAs$ α=1.2 [10]), V(z) is the source referenced quasi-Fermi potential that varies along the channel from 0 at the source side to V_D at the drain side, V_D is the drain-to-source bias voltage. V_{GT} (=V_G-V_{th}) is the turn-on voltage where V_G is the gate-to-source bias voltage, and V_{th} is the threshold voltage. A commonly used equation for V_{th} is

$$V_{th} = \varphi_B - \frac{\Delta E_c}{q} + E_{Fo} - \frac{qN_d}{2\varepsilon}(d_d)^2 \qquad \ldots (2)$$
$$d = d_d + d_i$$

where ε and d are the permittivity and thickness of the electron supply layer with a wider band-gap energy, respectively, q is the electron charge, φ_B is the barrier height of the of the Schotky-gate, ΔE_c is the conduction band discontinuity at heterojunction, E_{Fo} is the equilibrium Fermi-potential, N_d is the doping concentration in the electron supply layer, d_d is the thickness of doped wider band-gap layer, and d_i is the spacer layer thickness.

ε, ΔE_c, and φ_B are all functions of x with approximations in [11]. According to these approximations the threshold voltage in (2) is a dependent of x as well as N_d. Fig.(2) shows the variation of V_{th} in wide range of N_d with x as parameter.

The gate capacitance per unit area (C_{ox}) defined in [12] as

$$C_{ox} = \frac{\varepsilon}{(d + \Delta d)} \qquad \ldots (3)$$

where Δd is the corresponding offset distance of the 2DEG from the heterointerface. Ignoring the non-linear dependence of the average position of the 2DEG channel (Δd) from heterointerface on the gate bias, Δd is assumed to be constant value (≈ 80 Å) depending on the lattice (a) [12]. C_{ox} is a function of x because of the variation of ε with the last.

by substituting (2) and (3) the charge control model in (1) can be expressed as a function of x and N_d as

$$Q(z,N_d,x)=C_{ox}(x)(V_{GT}(N_d,x)-\alpha V(z,N_d,x)) \qquad \ldots (4)$$

B. Carrier Velocity

The carrier velocity is given by a piecewise model [13] as

$$v(z,N_d,x)=\begin{cases} \dfrac{\mu_{\text{eff}}(N_d,x)E(z,N_d,x)}{1+\dfrac{E(z,N_d,x)}{E_c(N_d,x)}} & ,E(z,N_d,x)<E_c(N_d,x) \\ v_{sat}(N_d,x) & ,E(z,N_d,x)\geq E_c(N_d,x) \end{cases} \qquad \ldots (5)$$

where E is the longitudinal electric field along the channel, E_c is the critical field ($=2v_{sat}/\mu_{eff}$), v_{sat} is the saturation velocity of carriers, and μ_{eff} is the effective mobility that is only a function of the gate voltage. The effective mobility (μ_{eff}), saturation velocity (v_{sat}), and the critical (E_c) are three independent parameters which determine v-E properties inside the heterojunction channel. These three parameters are considered to be functions of x and N_d of $Al_xGa_{1-x}As/GaAs$ heterojunction by X. Zhon and H. S. Tan [9] based on Monte-Carlo formulation technique. The effective (μ_{eff}) is

$$\mu_{\text{eff}}(N_d,x)=\mu_1(x)+\frac{\mu_2(x)}{1+(N_d/N_\mu(x))^{\alpha(x)}} \qquad \ldots (6)$$

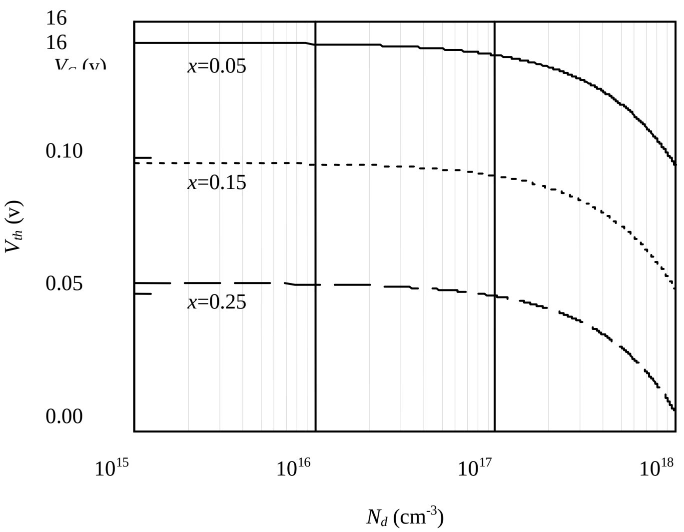

Fig.(2) Variation of threshold voltage (V_{th}) with doping concentration (N_d) for several values of mole fraction (x).

where μ_1, μ_2, N_μ, and α are fitting parameters and assumed to be composition dependent. In the same manner, the saturation velocity (v_{sat}) and the critical field for velocity saturation (E_c) are obtained as follows

$$v_{sat}(N_d, x) = v_o(x) + v_1(x)\left(N_d / N_v(x)\right) + v_2(x)\left(N_d / N_v(x)\right)^{1.04} \quad \dots (7)$$

$$E_c(N_d, x) = E_o(x) + E_1(x)\left(N_d / N_E(x)\right)^{\rho(x)} \quad \dots (8)$$

The best polynomials fit these parameters are illustrated briefly in [9]. By substituting equations (6), (7), and (8) into (5), the carrier velocity can be expressed as a dependent of x and N_d (Fig.(3)).

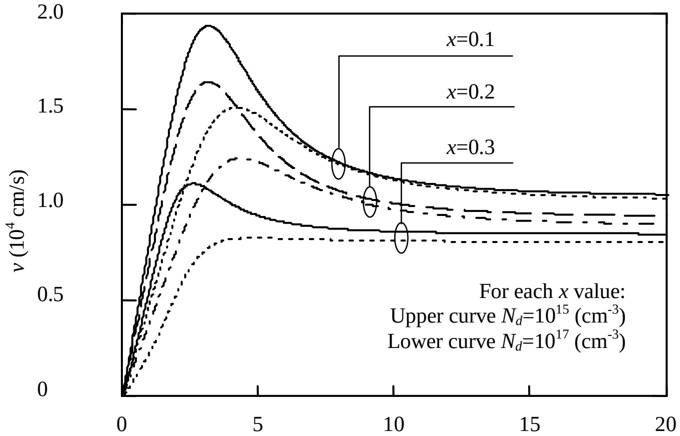

Fig.(3) Carriers velocity vs. longitudinal electric field with doping concentration (N_d) and mole fraction (x) calculated using (5).

III. MODELLING OF CHANNEL NOISE

We start modeling the channel noise of HFET by dividing its channel into two sections: the gradual and the velocity saturation regions (see Fig.(4)). It is assumed that most of the drain current noise of the HFET is generated in the gradual region, and the noise of the velocity saturation region is negligible. This is because of the fact that in this region, carriers travel at their saturation velocity and therefore they do not respond to the electric field caused by the voltage fluctuation in the channel [14].

The HFET drain current which dominated by the drift current can be expressed at any point (z) in the channel as [6]

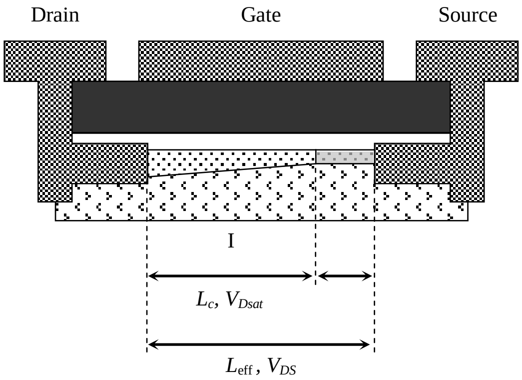

Fig.(4) Cross section of the channel of a HFET, divided into two regions: (I) gradual and (II) velocity saturation regions. L_c is the point in the channel where the channel field E is equal to the critical field E_c and the velocity of carriers is equal to their saturation velocity v_{sat}.

$$I = WQ(z, N_d, x)v(z, N_d, x) \qquad \ldots (9)$$

where W is the width of the device, Q is the channel charge per unit area and v is the velocity of carriers in the channel. Substitute for Q and v from equations (4) and (5), respectively, in (9) yields

$$I = \mu_{\text{eff}}(N_d, x) \cdot C_{ox}(x)(V_{GT}(N_d, x) - \alpha V(z, N_d, x)) \cdot \frac{E(z, N_d, x)}{1 + \dfrac{E(z, N_d, x)}{E_c(N_d, x)}} \qquad \ldots (10)$$

As the drain-to-source voltage of the device is increased, the longitudinal field increases gradually along the channel until it reaches to the critical field somewhere near the drain. This situation is depicted in Fig.(4). The point in the channel where $E=E_c$ is denoted as L_c. Substituting $E=dV/dz$ in (10), integrating from 0 to z, and solving for V, one has

$$V(z, N_d, x) = \frac{1}{2\alpha}\{(2V_{GT}(Nd, x) - V_o(N_d, x)) - [(2V_{GT}(N_d, x) - V_o(N_d, x))^2 - 4\alpha E_c(N_d, x)V_o(N_d, x)z]^{\frac{1}{2}}\} \qquad \ldots (11)$$

where

$$V_o(N_d,x)=\frac{I}{WC_{ox}(x)v_{sat}(N_d,x)} \quad \dots (12)$$

Using (11), E in the gradual part of the channel is obtained as

$$E(z,N_d,x)=$$
$$\frac{E_c(N_d,x)V_o(N_d,x)}{[(2V_{GT}(N_d,x)-V_o(N_d,x))^2-4\alpha E_c(N_d,x)V_o(N_d,x)z]^{\frac{1}{2}}} \quad \dots (13)$$

Since the longitudinal electric field is continuous along the channel L_c can be obtained by equating E to E_c as

$$L_c(N_d,x)=\frac{V_{GT}(N_d,x)(V_{GT}(N_d,x)-V_o(N_d,x))}{\alpha E_c(N_d,x)V_o(N_d,x)} \quad \dots (14)$$

It is assumed that at any point in the channel beyond L_c, carriers travel at their saturation velocity.

To calculate the drain current noise, the gradual part of the channel is divided into small sections of length dz. Each section acts as a resistor of value dR, which can be obtained as

$$dR(z,N_d,x)=$$
$$\frac{dV(z,N_d,x)}{I}=\frac{-dz}{\mu_{\mathrm{eff}}(N_d,x)WQ(z,N_d,x)+\dfrac{I}{E_c(N_d,x)}} \quad \dots (15)$$

The current noise generated from a small section of the channel located at z is the product of the square of the local conductance g_{DS} and the voltage noise generated from each section [14]. Therefore

$$\begin{aligned}\overline{\Delta i^2(z,N_d,x)} &= g_{DS}^2(z,N_d,x)\cdot\overline{\Delta v^2(z,N_d,x)}\\ &= 4kT\cdot g_{DS}^2(z,N_d,x)dR(z,N_d,x)\Delta f\end{aligned} \quad \dots (16)$$

where Δf is the range of operation frequency. The local conductance can be expressed in terms of the device parameters as [15]

$$g_{DS}(z, N_d, x) = \frac{\mu_{\text{eff}}(N_d, x) W C_{ox}(x)(V_{GT}(N_d, x) - \alpha V(z, N_d, x))}{L_{\text{eff}}(N_d, x)} \cdot \frac{1}{1 + \frac{E(z, N_d, x)}{E_c(N_d, x)}} \quad \ldots (17)$$

where L_{eff} is the effective channel length.

The spectral density of the drain current noise, S_{iD}, is the sum of the drain current noise generated from each section. Therefore, one can write

$$S_{iD}(N_d, x) = 4kT \int_0^{L_c} g_{DS}^2(z, N_d, x) dR(z, N_d, x) \quad \ldots (18)$$

Substituting for dR and g_{DS} from (15) and (17), respectively, and using (13), the drain current noise spectral density of the device is obtained as

$$S_{iD}(N_d, x) = 4kT \cdot \frac{4V_{GT}^2(N_d, x) + V_o^2(N_d, x) - 2V_o(N_d, x)V_{GT}(N_d, x)}{3V_{GT}^2(N_d, x)[V_{GT}(N_d, x) - V_o(N_d, x)]} \alpha I \quad \ldots (19)$$

It can be observed that the model presented in (19) is analytical and takes into account mobility degradation due to the channel electric field. Moreover, (19) is an explicit function of the device geometry and biasing conditions and for the first time to the Aluminum (Al) mole fraction (x) of $Al_xGa_{1-x}As/GaAs$ heterojunction and doping concentration (N_d).

From (10), it is seen that at the point along the channel where the carrier velocity is saturated, i.e., $v = v_{sat}$, the drain current, I , is equal to

$$I = W C_{ox}(V_{GT}(N_d, x) - \alpha V_{Dsat}(V_G, N_d, x)) v_{sat}(N_d, x) \quad \ldots (20)$$

where V_{Dsat} is the drain voltage required for saturation of currier velocity. Therefore

$$V_o(N_d, x) = V_{GT}(N_d, x) - \alpha V_{Dsat}(V_G, N_d, x) \quad \ldots (21)$$

where V_o is defined in (12). Consequently, (19) can be simplified as

$$S_{iD}(V_G, N_d, x) =$$
$$4kTI \cdot \left[\frac{1}{V_{Dsat}(V_G, N_d, x)} + \frac{\alpha^2 V_{Dsat}(V_G, N_d, x)}{3V_{GT}^2(N_d, x)} \right] \quad \ldots (22)$$

$$S_{iD}(N_d, x) = 4kTI\beta(N_d, x) \quad \ldots (23)$$

$$\beta(N_d, x) = \frac{1}{V_{Dsat}(V_G, N_d, x)} + \frac{\alpha^2 V_{Dsat}(V_G, N_d, x)}{3V_{GT}^3(N_d, x)} \quad \ldots (24)$$

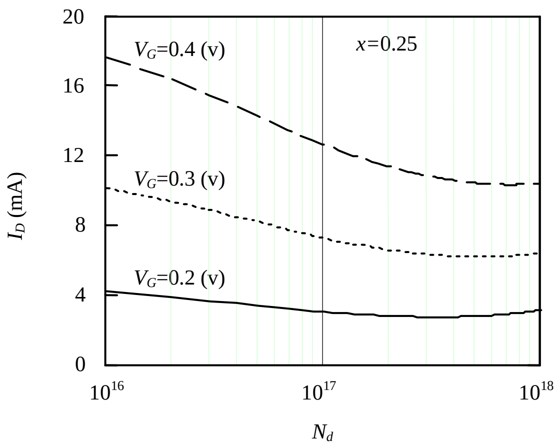

Fig.(7) Drain current (I_D) variation with doping concentration (N_d) and several biasing conditions for V_G at mole fraction x=0.25 and V_D=1.5V_{Dsat} (to insure being in the saturation region).

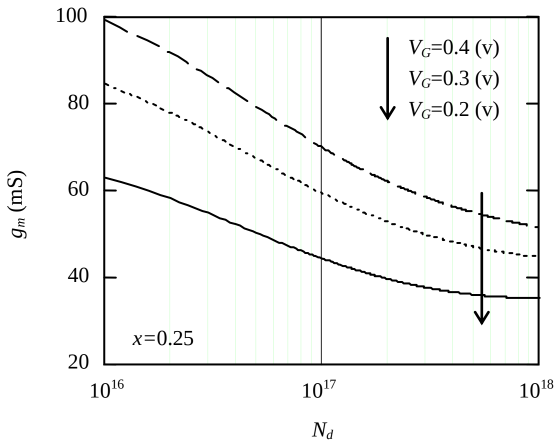

Fig.(8) Transconductance (g_m) variation with doping concentration (N_d) and several biasing conditions for V_G at mole fraction x=0.25 and V_D=1.5V_{Dsat} (to insure being in the saturation region).

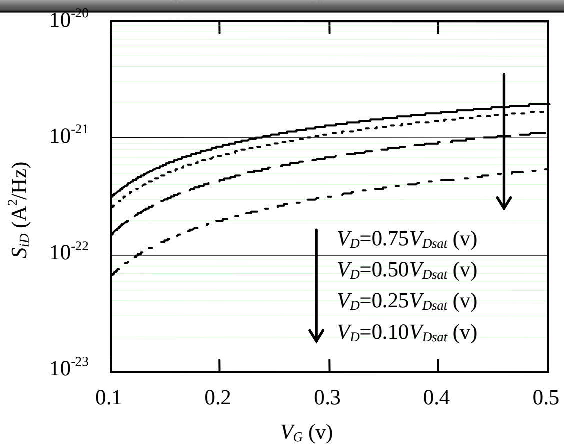

Fig.(5) Channel noise spectral density (S_{iD}) vs. gate voltage (V_G) for different fractions of V_{Dsat} (to insure being in the linear region) at N_d= 10^{16} (cm^{-3}) and x=0.25.

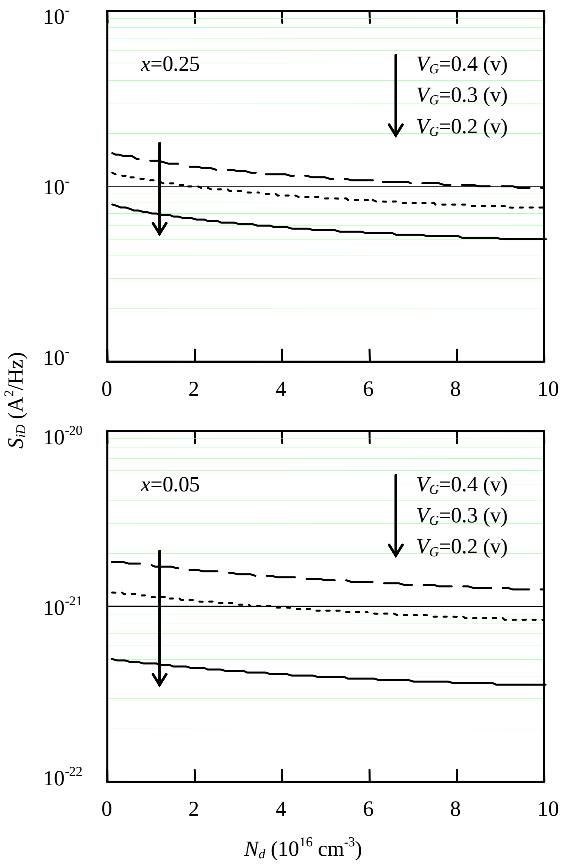

Fig.(6) Channel noise spectral density (S_{iD}) vs. doping concentration (N_d) for different values of gate voltage (V_G) at V_D=0.5V_{Dsat} (to insure being in the linear region).

Equation (23) is similar to the traditional channel noise expression, i.e., $S_{iD}=4kT\gamma g_{do}$, where g_{do} is the drain transconductance at $V_D=0$ and γ is called the channel noise coefficient. In long-channel devices $g_{do}=g_m$ and $\gamma=2/3$ [16]. However, in the case of short-channel devices, both g_{do} and γ are complicated functions of the device parameters [17]. Therefore, although (23) looks similar to the traditional channel noise expression, it is much simpler in the case of short-channel devices. The channel noise model developed can be used to express analytical expressions for HFETs noise parameters, i.e., the minimum noise figure, equivalent noise resistance, optimum source resistance, and optimum source reactance.

IV. RESULTS AND DISCUSSION

The developed model is able to plot the characteristics of the HFETs channel noise spectral density (S_{iD}) versus biasing conditions, mole fraction (x) of the wider band-gap energy material ($Al_xGa_{1-x}As$), and doping concentration (N_d), as well as other device geometric parameters. The channel thermal noise performance is shown through Figs.(5-7) for a HFET with parameters summarized in TABLE (I).

The channel noise spectral density (S_{iD}) variation with gate voltage (V_G)

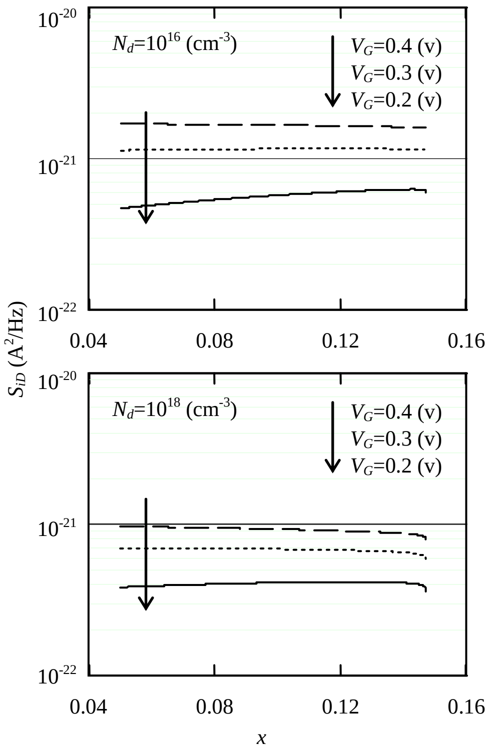

Fig.(9) Channel noise spectral density (S_{iD}) vs. mole fraction (x) for different values of gate voltage (V_G) at $V_D=0.5V_{Dsat}$ (to insure being in the linear region).

at $N_d = 10^{16}$ (cm^{-3}) and x=0.25 for different fractions of V_{Dsat} to insure being in the linear region of I-V characteristics is shown in Fig.(5). This figure clears that S_{iD} is forward proportional to both V_G and V_D. Such results are because of the increasing of the biasing conditions leads to raise the number of carriers that exposed to the random fluctuations in the electrical field of the channel. The increase in V_G provides a wider channel that ensures the channel to have more capacity for larger amount of carriers. In the other hand the increase of V_D leads to raise the electrical field across the channel then to faster movement and more numbers of free electrons pass through the noisy region inside the channel.

However, the proportional of noise performance forwardly with biasing conditions is illogical if related to the gradual region shortening with bias rising only. To be more accurate one must takes into account the increasing of both electrical field fluctuations and the total number of carrier passes through the gradual region with bias condition rising.

The dependence of S_{iD} on doping concentration (N_d) is plotted in Fig.(6) for different values of mole fraction (x) at several biasing conditions for V_G with V_D equal to the half of V_{Dsat}. These variations show the decreasing of S_{iD} at high doping concentration. However, the increasing of doping concentration is not a good choice to reduce the channel noise because its leads to decrease the drain current (I) and hence the transconductance (g_m) for the HFET as shown in Fig.(8) and Fig.(9), respectively.

The dependence of S_{iD} on mole fraction (x) is plotted in Fig.(7) for different values of doping concentration (N_d) at several biasing conditions for V_G, with V_D equals to the half of V_{Dsat}. S_{iD} increases slightly with mole fraction (x) and seems to be independent on it at certain biasing conditions. This independency is valid because the noise performance is a result of electrical fluctuations across the channel and the number of carriers to come under. The effect of x on noise performance is to be limited in one fact that is the slightly reduction of noise with increasing of x. This fact come as a result of slowing down the velocity of carriers across the gradual region with the increasing of x (Fig.(3)) and hence reduce he number of carriers to be subject

TABLE (I)
Device parameters used by the present model

Parameter	Value	Unit
L_g	1	μm
W	145	μm
d_i	20	Å
d_d	80	Å
Δd	80	Å

to the electrical field fluctuations.

V. CONCLUSION

We have developed an analytical expression for the channel noise spectral density (S_{iD}) of an Au-$Al_xGa_{1-x}As$/GaAs heterostructure field-effect transistors (HFETs) that takes into account the variation of S_{iD} with both Aluminium (Al) mole fraction (x) and doping concentration (N_d) based on linear charge-control formulation and Monte-Carlo formulation of field-dependent mobility. The S_{iD}-N_d and S_{iD}-x characteristics can be expressed in analytical forms suitable for the analysis, predict, design, and optimization of digital and analogue HFET circuits. It is also very useful in studying the noise behaviour of HFET devices.

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