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A comprehensive nonlinear model for GaAs MESFET transistor

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Abstract

An analytical two-dimensional (2D) model to accurately predict the channel potential and electric field distribution in sub-micron GaAs MESFET based on (2D) analytical solution of Poisson's equation using superposition principle is presented. The results so obtained for current voltage characteristics, Transconductance and drain conductance, are presented and validated against both experimental I-V curves and various Models of the submicron MESFET GaAs. The model is then extended to predict the effects of parasitic resistances Rs and Rd, carriers mobility according to the electric fields and the edges effects on the performance. This model will allow more significant simulation of the component characteristics, with a precision improved for various conditions of Schottky barrier.

Key words: *MESFET- GaAs ; Submicrom nonlinear model ; comparative study*
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1. Introduction

The field-effect transistor to Schottky gate on gallium arsenide says GaAs MESFET is a basic component in the telecommunication systems such as cellphones, computers and in the majority of microwave apparatuses which needs components being able to operate at more high frequencies, in order to obey the desires for the new generations. In this context, a simple and an accurate analytical two-dimensional (2D) model for GaAs MESFET is presented. In modelling the short channel effects in a short gate length MESFET, the 2D Poisson's equation satisfying different surface boundary conditions has been solved to get 2D electrostatic potential and electric field distribution.

The solution of Poisson's equation is accomplished by a technique proposed by Ratnakumar and Meindl [1]. The closed form analytical expressions for channel potential and electric field are derived and the results so obtained are approved by a comparative study drawn up with the experimental results, as well as with three different models (Materka, Mc Camant and Ahmed) [2]. The effect of reducing the gate length on the device output characteristics has also been studied. The important parameters for the modelling of drain current are calculated which provide the foundation for an accurate model. The resulting current-voltage (I-V) characteristics, Transconductance g_m and drain conductance g_d shows good agreement with the experimental curves.

2. MESFET models

To describe the operation and the characteristics of the field-effect transistors, various models were developed by different authors [3] rest on analytical equations for the simulation of the current Ids=f(Vgs,Vds). And as comparison us, we have selected three models, Materka, McCamant and Ahmed; who rest on the expressions appearing afterwards for each model.

2.1. Materka Model (1983) [11]

The current source I_{ds} controlled by the voltages (Vgs,Vds) is described by the formula (1) [11].

$$I_{ds} = I_{dss}\left[1-\frac{V_{gs}}{V_T+\gamma V_{ds}}\right]^2 \times tanh\left(\frac{\propto V_{ds}}{V_{gs}-V_T-\gamma V_{ds}}\right) \qquad (1\text{-}1)$$

Where: I_{dss} , V_T , $\propto$ and γ are the model parameters.
($\propto$), describe the transition from the linear region to the saturation region due to velocity overshoot.
(γ), is used to simulate effective threshold voltage displacement as a function of V_{ds}.
By derivation the drain current with respect to drain-source voltage and gate-source voltage individually, transconductance and output conductance are obtained and they are formulated below:

$$g_m = 2I_{ds}\left[\frac{\sinh\left(\frac{2\propto V_{ds}}{V_{gs}-V_T-\gamma V_{ds}}\right)-1}{(V_{gs}-V_T-\gamma V_{ds})\sinh\left(\frac{2\propto V_{ds}}{V_{gs}-V_T-\gamma V_{ds}}\right)}\right] \qquad (1\text{-}2)$$

$$g_d = 2I_{ds}\left[\left(1+\frac{1}{V_{gs}-V_T-\gamma V_{ds}}\right)+\frac{\gamma V_{gs}}{(V_T+\gamma V_{ds})(V_{gs}-V_T-\gamma V_{ds})}\right] \qquad (1\text{-}3)$$

2.2. McCamant Model (1990) [5]

In 1990, McCamant et al. [5] proposed an improved FET model for the device simulator [McCamant-1990] in which the variation of I_{ds} is given by (2)
Where: I_{ds0} , V_T , $\propto, \delta$ and γ are the model parameters

$$I_{ds} = \frac{I_{ds0}}{1+\delta V_{ds} I_{ds0}} \tag{2-1}$$

With:

$$I_{ds0} = \begin{cases} \beta\left(V_{gs} - V_T - V_{ds}\right)^n \left[1 - \left(\frac{\alpha V_{ds}}{3}\right)^3\right] for\ 0 < V_{ds} < \left(\frac{3}{\propto}\right) \\ \beta\left(V_{gs} - V_T - V_{ds}\right)^n \qquad for\ V_{ds} \geq \left(\frac{3}{\propto}\right) \end{cases} \tag{2-2}$$

Here n is an integer

$$g_m = \left\{ \frac{n I_{ds0}}{(1+\delta V_{ds} I_{ds0})(V_{gs}-V_T-V_{ds})} \qquad for\ 0 < V_{ds} \right. \tag{2-3}$$

$$g_d = \left\{ \frac{I_{ds0}\left[\propto\left(1-\frac{\propto V_{ds}}{3}\right)^2\right]}{(1+\delta V_{ds} I_{ds0})^2\left[1-\left(1-\frac{\propto V_{ds}}{3}\right)^3\right]} - \frac{\gamma n I_{ds0}}{(1+\delta V_{ds} I_{ds0})^2(V_{gs}-V_T-V_{ds})} - \right.$$
$$\delta {I_{ds}}^2 \qquad for\ \ 0 < V_{ds} < \left(\frac{3}{\propto}\right) \tag{2-4}$$

$$g_d = \left\{ - \frac{\gamma n I_{ds0}}{(1+\delta V_{ds} I_{ds0})^2(V_{gs}-V_T-V_{ds})} - \delta {I_{ds}}^2 \quad for\ \ V_{ds} \geq \left(\frac{3}{\propto}\right) \right. \tag{2-5}$$

2.3. Ahmed Model (1997) [2,3]

The Kacprzak-Materka model, which simulates the I-V characteristics of large signal devices, has been modified by Ahmed to predict the behaviour of submicron devices. In this modification the concept of a shift in threshold voltage has been introduced. It has been shown in the formula (3) that without taking into account the shift which is caused by the submicron geometry it is not possible to predict the device characteristics.

$$I_{ds} = I_{dss}\left[1 - \frac{V_{gs}}{V_T+\Delta V_T+\gamma V_{ds}}\right] \times \tanh(1 + \lambda V_{ds}) \tag{3-1}$$

With: $\Delta V_T = \frac{4a}{3L_g}$ (3-2)

$$g_m = \frac{2(A-1)I_{ds}}{AV_{gs}} \quad \text{with: } A = 1 - \frac{V_{gs}}{V_T+\Delta V_T+\gamma V_{ds}} \tag{3-3}$$

$$g_d = \frac{\lambda I_{ds}}{1+\lambda V_{ds}} + 2I_{ds}\left[\frac{\gamma(A-1)^2}{AV_{gs}}\right] + \frac{\alpha}{\sinh(2\alpha V_{ds})} \tag{3-4}$$

3. Proposed model formulation

One of the drawbacks of the previous models is their relative failure to capture the effects of a modulation of the drain-source voltage $\boldsymbol{V_{ds}}$. It is with this consideration in mind that we pose the following model of MESFET with a short gate length.

The channel potential cannot be entirely controlled by the gate bias and will be shifted by the penetration of lateral electric field. Therefore there are two factors which play an important role for the short channel effects [6] in the submicron MESFET. One is the lateral field distribution at the sidewall of the gate edge and the other is the efficiency of the gate metal in terminating the lateral electric field.

Thus solution for 2D Poisson's equation satisfying suitable boundary conditions is required to model the short channel effect. A simplified self aligned GaAs MESFET is shown in Fig.1 [10, 12], over which Poisson's equation is solved for the potential distribution $\boldsymbol{Vc(x,y)}$, where '**L**' is the gate length. '**a**' is the thickness of the active layer.

In order to avoid the problems resulting from different surface boundary conditions, the n-GaAs layer is assumed to contact directly to the gate metal, and the absorption of electric field by the depletion charges near the source/drain is not taken into account.

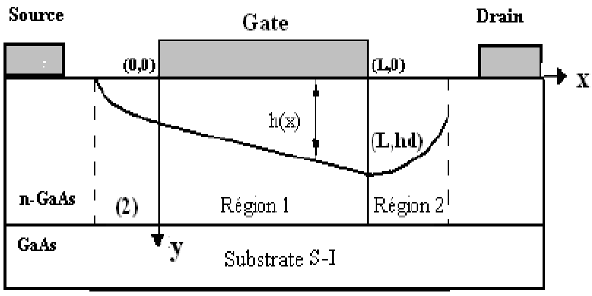


Figure 1. Schematic diagram of a self-aligned GaAs MESFET

3.1. 2D analytical model

The 2D Poisson equation for the depletion region, assuming complete depletion, is

$$\nabla^2 V_c(x,y) = \frac{d^2V_c}{dx^2} + \frac{d^2V_c}{dy^2} = -\frac{q}{\varepsilon_s} N_d(y) \tag{4}$$

$Vc(x,y)$ is the electrostatic potential, q is electron charge, εs is the dielectric permittivity of GaAs semiconductor, Nd (y) is the doping concentration, The doping is considered to be uniform, with the doping concentration Nd .

According to the superposition technique [1], (4) can be resolved as

$$V_c(x,y) = V(y) + V_l(x,y) \tag{5}$$

Where V(y) is the solution of Poisson's equation (6) for the MESFET structure in one dimension along y-axis near the mid of the channel (region 1). It is this potential profile that would result if the device were completely unaffected by lateral electric fields from the source and the drain; Vl(x, y) is the solution of 2D Laplace (7), it represents the voltage brought by the overflow of the depletion region side source and side drain (region2):

$$\frac{d^2V}{dy^2} = -\frac{q}{\varepsilon_s}N_d \quad (6)$$

$$\frac{d^2V_l}{dx^2} + \frac{d^2V_l}{dy^2} = 0 \quad (7)$$

To solve for $V(y)$ following boundary conditions are used

$$V(y)|_{y=0} = V_{bi} - V_g \quad (8)$$

$$\left.\frac{dV(y)}{dy}\right|_{y=a} = 0 \quad (9)$$

Where V_{bi} is the schottky-barrier built-in potential, V_g is the applied gate-source voltage. Using (8) and (9) in (6), the solution of 1D Poisson's equation is :

$$V(y) = \frac{-qN_dy^2}{2\varepsilon_s} + \frac{qN_day}{\varepsilon_s} + V_{bi} - V_g \quad (10)$$

Boundary conditions for $V_l(x,y)$ are derived from the boundary conditions for $V_c(x,y)$, through (5) and (10) as [4].

$$V_c(L,y) = V_{bi} + V_{ds} \;, V_l(L,y) = V_{bi} + V_{ds} - V(y)$$

$$\frac{dV_c(x,a)}{dy} = 0 \;,\; \frac{dV_l(x,a)}{dy} = 0 \;, \frac{dV_c(L,a)}{dx} = E_s$$

Where, V_{ds} is the applied drain-source voltage and Es is the saturation electric field.

Applying the standard technique of separation of variables produces a Fourier series solution, only the first Fourier series terms (with coefficient A_1^s and A_1^d) are sufficient to represent the potential near the source and drain. Thus the resulting expression for $V_l(x,y)$ is [4]

$$V_l(x,y) = \alpha\left[sinh\left(k(L-x)\right) + sinh(kx)\right]\sin(ky) \quad (11)$$

Where: $k = \frac{\pi}{2a}$

And: $\alpha = \frac{2aE_s}{\pi(\cosh(kl)-1)}$

Following (5), (10) and (11) the expression for the total voltage becomes:

$$V_c(x,y) = \frac{-qN_dy^2}{2\varepsilon_s} + \frac{qN_day}{\varepsilon_s} + V_l(x,y) + V_{bi} - V_g \quad (12)$$

The lateral electric field E_x and vertical electric field E_y distribution in the channel can be determined by differentiating (12) with respect to x and y, respectively

$$E_x = \alpha k\left[-cosh\left(k(L-x)\right) + cosh(kx)\right]\sin(ky) \quad (13)$$

$$E_y = \frac{-qN_d}{\varepsilon_s}y + \frac{qN_da}{\varepsilon_s} + \alpha k\left[sinh\left(k(L-x)\right) + sinhkx\cos ky. \quad (14)\right.$$

3.2. Effect of the mobility law

The current-voltage characteristics depend on the variations of the electrons mobility (μ) according to the electric field (E). The choice of a mobility law is important for a correct description of physical phenomena in the submicron gate MESFET's.

The analytical expression of this law that we use is a simplified relation [7] given as follows:

- For the low electric fields: E < Eo

$$\mu = 0 \quad (15\text{-}1)$$

- For the electric fields higher than **Eo** : (Eo < E < Em)

$$\mu = \frac{\mu_0}{\left[1+\left(\frac{E-E_0}{E_s}\right)^2\right]^{1/2}} \quad (15\text{-}2)$$

With:

$$E_0 = \frac{1}{2}\left[E_m + (E_m{}^2 - 4E_s{}^2)^{1/2}\right] \quad (15\text{-}3)$$

Eo : is a phenomenological parameter having the dimensions of an electric field

E_m: The threshold field, corresponding to the maximum of the overspeed regime.

E_s: The critical field for which the speed in linear regime is corresponding to the saturation speed.

3.3. Current-voltage characteristics I -V

To calculate the expression of the drain current in function the drain voltage for various values of the gate voltage, we use the following assumptions:

The current in the direction y is neglected; this approximation is valid for short gate devices.

The channel is divided in two regions according to the value of the electric field.

The basic equation used to derive the I-V relationship [8] is given by:

- Linear regime

This regime exists as the electric field in the channel is low and the electron mobility is equal to $\mu 0$. Expression of the drain current in this regime can be written as:

$$I_d\left(V_d, V_g\right) = \frac{I_p}{V_p}\left\{1 - \sqrt{\frac{V_{bi}-V_g}{V_p}}\right\}V_d \quad (16)$$

Where:

$I_p = \frac{(qN_d)^2 Z\mu_0 a^3}{2\varepsilon L}$ and: $V_p = \frac{qN_d}{2\varepsilon}a^2$

- Saturation regime

When the drain voltage increases, the electric field in the channel increases beyond E_0 . The electron mobility is given by (15-2).

The saturation current is:

$$I_{dsat} = I_p\left[\frac{1}{3} - \left(\frac{V_{bi}-V_g}{V_p}\right) + \frac{2}{3}\left(\frac{V_{bi}-V_g}{V_p}\right)^{3/2}\right] \quad (17)$$

With: $I_p = \frac{(qN_d)^2 Z\mu a^3}{2\varepsilon L}$

3.4. Transconductance and drain conductance

The expression of I_d is used to calculate the two basic parameters of the transistor, which are the transconductance g_m and the channel conductance g_d more commonly known as drain conductance.

The transconductance is the expression of the control mechanism of a transistor: it represents the variation of the current in the channel modulated by the gate voltage at constant drain-source voltage [9].

In the Linear regime

$$g_m = \frac{Z\mu_0}{L}(2\varepsilon qN_d)^{\frac{1}{2}}\left[\left(V_{bi} - V_g + V_d\right)^{\frac{1}{2}} - \left(V_{bi} - V_g\right)^{\frac{1}{2}}\right] \quad (18)$$

In the saturation regime

$$g_{m_s} = \frac{Z\mu_0}{L}(2\varepsilon qN_d)^{\frac{1}{2}}\left[\left(V_p\right)^{\frac{1}{2}} - \left(V_{bi} - V_g\right)^{\frac{1}{2}}\right] \quad (19)$$

The conductance reflects the resistance of the channel: it is the variation of the drain current according to the V_d voltage variation, with constant polarization of the gate.

In the Linear regime

$$g_d = \frac{Z\mu_0}{L}(2\varepsilon qN_d)^{\frac{1}{2}}\left[\left(V_p\right)^{\frac{1}{2}} - \left(V_{bi} - V_g + V_d\right)^{\frac{1}{2}}\right] \quad (20)$$

In the saturation regime

The conductance is perfectly zero, $g_{ds} = 0$ (21)

3.5. Influence of parasitic elements

The characteristics that we have presented are those of the internal or intrinsic sizes (I_d, V_d, V_g) to obtain the external or extrinsic characteristics of the component (I_{ds}, V_{ds}, V_{gs}), it is enough to take into account the effect of parasitic resistances to access of source R_s and drain R_d, and also the effect of R_p parallel resistance to the canal on values of the bias voltages [10].

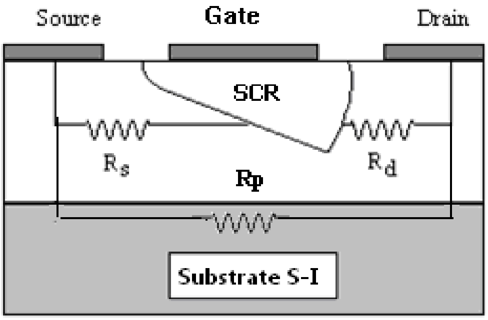


Figure 2. Parasitic resistances in the MESFET GaAs.

To obtain the real expressions of characteristics Ids(Vds, Vgs), it is enough to replace the intrinsic terms by the extrinsic terms in all the preceding relations:

$$\begin{cases} I_d = I_{ds} - \left(V_{ds}/R_p\right) \\ V_d = V_{ds} - (R_s + R_d)I_d \\ V_g = V_{gs} - R_s I_d \end{cases} \quad (22)$$

4. Results and discussions

In order to validate the characteristics of current I-V, transconductance and conductance of GaAs MESFET transistor witch describe the suggested model and the chosen models, a software of simulation based on the expressions established in the preceding paragraphs is realized in Matlab, as well as the obtained results are represented by curves and are discussed.

4.1. Characteristics courant-voltage I-V

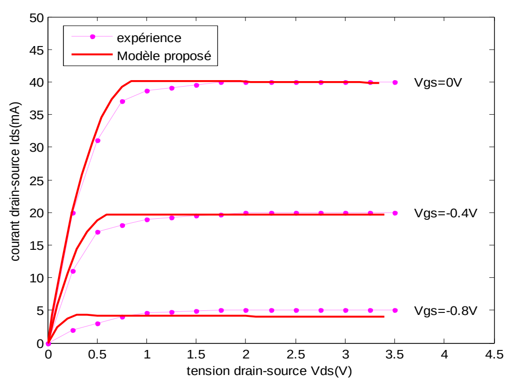
The numerical calculation of the drain current according to the polarization voltages calls upon the expressions (16), (17) and (22) for the model suggested thus that the expressions (1), (2) and (3) for the three selected models.

The study was made on a submicron GaAs MESFET transistor which parameters are gathered in table (1):

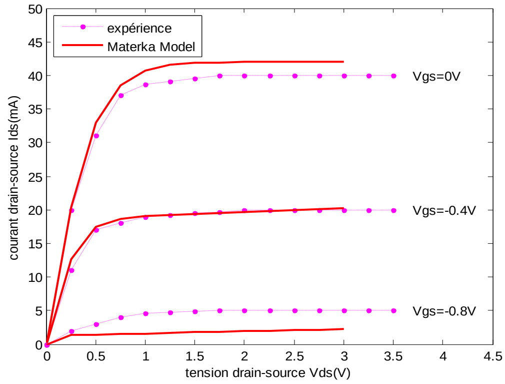
L (µm)	a(µm)	Z(µm)	µo(m²/Vcm)
1	0,153	300	0,4000
Nd(At/m³)	**Vs(m/s)**	**Vbi(V)**	**Vp(V)**
1,17 10²³	3.6 10⁵	0,85	1.93

Table 1. GaAs MESFET transistor parameters

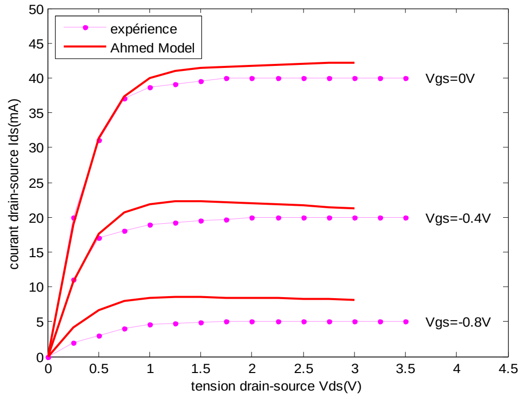
The figures (3a), (3b), (3c) and (3d) represent the comparison of characteristic *Ids (Vds, Vgs)* measured and calculated using simulation for the four models.



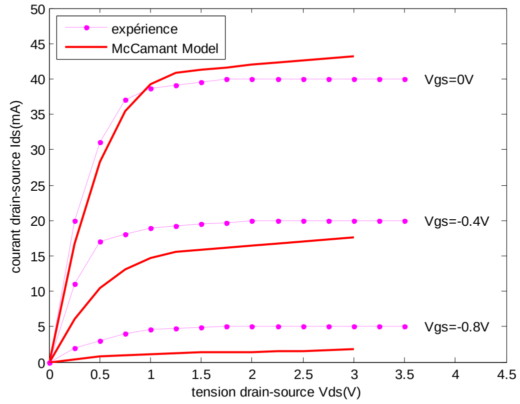
(a)



(b)



(c)



(d)

Figure 3. Variations I-V characteristics of the MESFET 1 transistor according to the model: (a) suggested model, (b) Materka model, (c) Mc Camant model, (d) Ahmed model

The figure (3-a) illustrates **I-V** characteristics of the suggested model and shows that theoretical results and those of the experiment **[8]** have the same behavior towards the tension of drain and coincide well, in particular with the high values of the **Vds** voltage. This shows the good founded of the method. The weak variation observed towards saturation is mainly due to the mobility law used.

The figures (3-b), (3-c) and (3-d) present respectively ***I-V*** characteristics of Materka model , Mc Camant model and Ahmed model, the curves reflect a light shift between the experimental values and the simulated characteristics, in particular to the high values of the $\boldsymbol{V_{ds}}$ voltage, this shows the inaccuracy of these models for the submicron devices. It is mainly about the incapacity of these models to simulate the finished $\boldsymbol{g_d}$ value in the saturation region which is usually observed in the MESFET with short channel.

4.2. Transconductance and drain conductance

The variation of g_m and g_d by using the equations of the transconductance and the drain conductance established previously for the four models, in comparison with the experimental data [2], are presented on the figures 4 and figures 5, respectively. The curves show once more the validity of the suggested model and the variation present for the other models in particular in the saturation region.

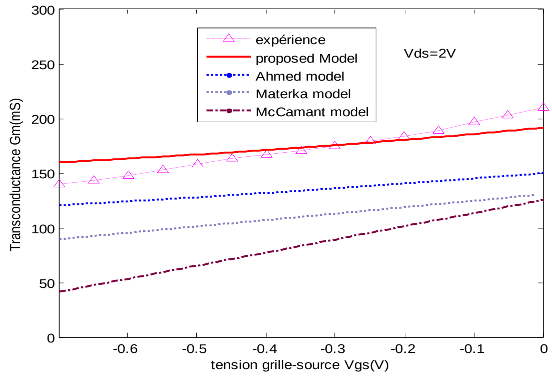


Figure 4. Variation of the transconductance according to the gate voltage for the MESFET

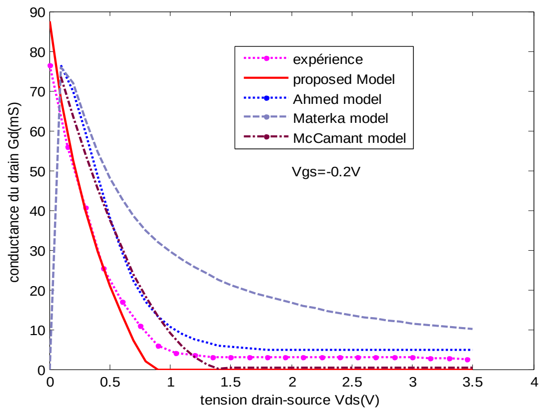


Figure 5. Variation of the conductance according to the drain voltage for the MESFET

5. Conclusion

In this paper we have proposed an analytical model of submicron GaAs MESFET based on (2D) solution of Poisson's equation using superposition principle; For developing of the extrinsic characteristics of the component we have introduced the parasitic resistances and edges effects. To check the validity of this model, the I-V characteristics, transconductance and drain conductance of the MESFET are simulated and compared with three different models of same MESFET. Thy gives similar results; However, there are some differences in the results when compared to the experimental measurements. It has been shown that the proposed model gives improved results at the saturation region, so it represents a good model capable to simulate the characteristics of the MESFET.

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