Journal of Electron Devices, Vol. 22, 2015, pp. 1880-1887

Journal of Electron Devices
www.jeldev.org

© JED [ISSN: 1682 -3427]
[ISSN: 2412 -1150](Online)

EFFECT OF THE ELECTRIC FIELD ON THE CARRIER MOBILITY FOR GaAs MESFET'S WITH SUBMICRON GATE.

***Mounir Azizi, Cherifa Azizi, Mourad Zaabat**
Faculty of exact sciences and natural and life sciences, Active Devices and Materials Laboratory
Larbi Ben M'Hidi university, Oum El Bouaghi, Algéria.
*mounir.perso@gmail.com

ABSTRACT:

GaAs MESFET's are considered as materials of choice by worldwide researchers for their High Electron Mobility Transistor (HEMT). In this paper the change of mobility due to different scattering mechanisms is studied. Also we present a comparison of four main analytical expressions of mobility-field dependence in the GaAs MESFET's devices. A numerical simulation of mobility and velocity versus electric-field was performed.

These expressions were implemented into two mathematical models describing the static characteristics of the GaAs MESFET's. We use a submicron gate device (L_g=0.28μm). Afterwards, we propose a simple expression describing the field-dependent mobility. We show that the results calculated using this model, agree well with experimental data. The proposed approach can be used in the case of logic or analog circuits based on submicron GaAs MESFET's.

keywords*:* Carrier Mobility, Drift Velocity, scattering effects, MESFET's GaAs, I-V characteristics.

I. INTRODUCTION

The active devices such as transistors make up the largest share of modern microelectronics activity. In this context a special attention is given to unipolar devices and more particularly to gallium arsenide field effect transistors with Schottky gate, due to their many interesting properties such as high electron viability, low effective mass, thermal conductivity and high saturation velocity [01].

For low electric field, the carrier mobility remains constant. However, when the applied electric field becomes important, the interaction of carriers with lattice vibrations cause a decrease in the carrier mobility. This decrease results in a non-linear variation of the drift velocity of the carriers. Consequently, a few mathematical expressions have been proposed but no one was taken as the reference law. Thus, each analytical model for static properties I_{ds}-V_{ds} was proposed with a special mobility expression that fits better its results.

In the present work we have carried out a simulation of different carrier mobilities and drift velocities expressions as a function of the electric field. Also the effect of the variable mobility on the I-V characteristics was demonstrated.

II. SCATTERING EFFECTS AND MOBILITY EXPRESSIONS

Usually, the electron drift velocity in a material is directly proportional to the electric field, which means that the electron mobility is a constant (independent of electric field). The carrier velocity is defined by the equation:

$$v(E) = \mu_n E \qquad (01)$$

When the electric field increases, the carrier velocity increases towards a maximum possible value, called the saturation velocity V_{sat}. This velocity is a characteristic of the material and a strong function of doping or impurity levels and temperature.

Carrier mobility is dependent on the drift velocity and the main factor determining it, except effective mass, is how long the carrier is ballistically accelerated by the electric field until it collides with something that changes its direction and/or its energy, that is scattering time. These scatterings have two main origins; interactions with the lattice and interactions with impurities [2].

When the temperature is greater than 0 K, the carriers can then collide with the crystal lattice [3]. Electron scattering by lattice vibrations depends on the nature of these vibrations: the concept of phonons (elementary quantum of vibrational energy), which are quantized modes of vibration propagation is then introduced.

When two atoms of the neighboring lattice vibrate in phase [3,4], this is called acoustic phonons. These vibrations generate a deformation potential called deformation potential scattering. If the atoms of the crystal are partially ionized, the movement of atoms generates a piezoelectric potential: it therefore generates a piezoelectric scattering.

When the atoms vibrate in opposition phase, this is called optical phonon, which can be easily excited by light waves. In the same way of the acoustic phonons, they could be transverse or longitudinal. These phonons create a proportional potential to the optical strain deformation: we speak of non-polar optical phonons. On the other hand, the polarization produced by the optical vibration of the ionic charges creates a dipole moment; this is called polar optical phonon.

When the temperature increases, the lattice vibrations increases too, thusly the mobility drops at high temperature. However, in purely covalent crystals such as GaAs, the free carriers interact mainly with longitudinal acoustic vibration modes [5]. The dependence of mobility with temperature according to this mode of vibration is given by:

$$\mu \propto m^{*-\frac{5}{2}} T^{-\alpha} \quad (02)$$

m* is the effective mass, T the temperature and α ~ 3/2 for acoustic longitudinal vibration methods.

When we take into account the longitudinal modes of the optical vibration, as in the III-V ionic materials (GaAs, InP, GaN), the mobility temperature dependence is given by

$$\mu \propto T^{-\alpha} \quad (03)$$

With α ~ 2 for optical longitudinal modes

When the temperature increases, the ionization of impurities also increases, and the process of collision is limited by the collision with the ionized impurities. This diffusion process is predominant. For this type of interaction, the mobility temperature dependence is given by [5]:

$$\mu \propto T^{3/2} \quad (04)$$

The phonons and the lattice scattering cover the deformation mechanisms of piezoelectric and acoustic scattering, where the lattice scattering is a process at low temperature, in this case the mobility is related to temperature by [5,6]

$$\mu \propto T^{-3/2} \quad (05)$$

The mobility due to the lattice scattering increases with temperature decreasing.

There is a scattering mechanism called neutral impurities scattering. This mechanism occurs when an electron approaches a neutral atom, this is the result of non-ionized donors or neutral defects. This diffusion plays an important role in the mobility degradation [7]. Mobility due to the neutral scattering is given by

$$\mu_{neutral} = \frac{q^3 m^*}{80\pi\varepsilon h^3 N_{NI}} \quad (06)$$

N_{NI} is the concentration of neutral impurities.

Nevertheless, there are many other types of interaction but remain less influential. According to the Matthiessen rule, total mobility is given by [8, 9]:

$$\frac{1}{\mu} = \frac{1}{\mu_{lattice}} + \frac{1}{\mu_{impurity}} + \frac{1}{\mu_{faults}} + \frac{1}{\mu_{neutral}} \quad (07)$$

The following equation gives the classic law of the carrier mobility versus temperature at low electric fields in the case of gallium arsenide [10, 11].

$$\mu_T = \mu_{T_0} . \left(\frac{T_0}{T}\right)^{1/2} \quad (08)$$

The saturation velocity varies with temperature as [12]:

$$v_s = \frac{2.410^5}{1+\exp(\frac{T}{600})} \frac{m}{s} \quad (09)$$

The dependence of threshold voltage may be approximately given by [12]:

$$V_{th} = V_{th}(300°K) - \alpha_{vT} T \quad (10)$$

α_{vT} = 1.2mV/°C

However, when the electric field becomes important, there is no standard analytical expression that really reflects mobility-field dependence and this could only be defined and fixed by a complex Monte Carlo methods. From that, several analytical expressions have been proposed for this purpose.

We performed a comparative study between the different expressions in order to determine the best one for gallium arsenide. For low fields (the field is typically about 500V/cm or less) where $E<E_0$ which corresponds to the critical field, we have:

$$\mu(E) = \mu_0 \quad (11)$$

And for high fields where $E \geq E_0$, we have tested the following equations:

First expression [13]:

$$\mu_1(E) = \frac{\mu_0}{1+\left(\frac{E}{E_C}\right)} \quad (12)$$

Second expression [14, 15, 16]:

$$\mu_2(E) = \frac{\mu_0+v_S\left(\frac{E^3}{E_C{}^4}\right)}{1+\left(\frac{E}{E_C}\right)^4} \quad (13)$$

Third expression [17]:

$$\mu_3(E) = \frac{v_S}{E}\tanh\left(\frac{\mu_0 E}{v_S}\right) \quad (14)$$

Fourth expression [18,19]:

$$\mu_4(E) = \frac{\mu_0\left(1+A\left(\frac{\mu_0 E}{v_S}\right)^{t-1}\right)}{1+\left(\frac{\mu_0 E}{v_S}\right)^t} \quad (15)$$

with

$$A = 0.6\left[e^{10(\mu-0.2)} + e^{-35(\mu-0.2)}\right]^{-1} + 0.01 \quad (16)$$

and

$$t = 4[1 + \frac{320}{\sinh(40\mu)}] \quad (17)$$

$$E_c = {}^{v_s}/_{\mu_0} \quad (18)$$

$$\mu_0 = \frac{\tau q}{m^*} \quad (19)$$

$$E_0 = \frac{1}{2}\left[E_S + (E_S{}^2 - 4E_C{}^2)^{1/2}\right] \quad (20)$$

τ is the relaxation time, m^* the effective mass of the electron and v_s is the saturation velocity of GaAs.

E_c: the critical field at which the velocity in the linear regime is equal to the saturation value.

E_s: the threshold field, corresponding to the maximum value of the electrons velocity, which can be calculated from the following relationship:

$$\left.\frac{dV}{dE}\right|_{E=E_S} = 0 \quad (21)$$

III. I-V CHARACTERISTICS WITH VARIABLE MOBILITY

In order to determine the influence of mobility on the static characteristics of GaAs MESFET, we used two recent non-linear models, Islam's [20] and Memon's [21] models which are based on Rodriguiz [22] and Materka [23] approaches.

The current intensity is calculated using Islam model by:

$$I_{ds} = I_{dss}\left(1 - \frac{V_{gs}}{V_T+\Delta V_T+\gamma V_{ds}}\right)^2 \times tanh(\alpha V_{ds})(1 + \lambda V_{ds} + \mu V_{gs}) \quad (22)$$

V_{gs}: gate-source voltage.
I_{dss}: saturation current.
α: saturation current parameter, used to simulate the linear region on V_{ds}.
λ: I_{ds}-V_{ds} dependence simulation parameter in the saturation region.
γ: simulation parameter of the threshold voltage on V_{ds}.

In this model threshold voltage and shift in threshold due to submicron geometry of the device are defined, respectively, as

$$V_T = q\frac{N_d a^2}{2\varepsilon_s} - \phi_b \quad (23)$$

and :

$$\Delta V_T = \frac{4a}{4L_g}V_T \quad (24)$$

$$I_{dss} = \frac{\beta}{1+\mu(V_{gs}-V_T-V_{ds}-\Delta V_T)} \quad (25)$$

q: electron charge.
N_d: carrier density in the channel.
a: channel thickness.
ϕ_b: Schottky barrier height.
ε_s: semiconductor permittivity.

L_g: intrinsic channel length (controlled by the gate).
β: trans-conductance parameter.
μ: variable mobility simulation effect.

In Memon's model (2006) it's noted the principle of the presence of an interface effect in the metal-semiconductor junction, which makes the imperfection of the Schottky barrier. This effect is the main cause of the decrease in V_{gs} through the channel. The I_{ds} expression calculated using Memon's model is given:

$$I_{ds} = I_{dss}\left(1 - \frac{V_{eff}}{V_T+\Delta V_T+\gamma V_{ds}}\right)^2 \times tanh(\alpha V_{ds})(1+\lambda V_{ds}) \quad (26)$$

$$V_{eff} = \frac{V_{gs}}{1+\eta e^{V_{gs}}}$$

IV. RESULTS.

In this paper, we describe the introduction of a new empirical apparent velocity field relationship suitable for GaAs MESFET's with submicron gate length. We propose a new model which is a very simple expression and easy to use in the different current-voltage analytical models.

The new expression is a variation with two segments approach of the velocity versus electric field. A linear variation of the carrier velocity with the increasing of the applied electric field, then a saturation at a large drain voltage.

The proposed expression of the velocity is given by:

$$v_n(E) = \mu_n(E)E = \frac{\mu_0 E}{\left(1+(\frac{E}{E_C})^{n+1}\right)^{1/n}} \quad (27)$$

So, the expression of the mobility is as follows:

$$\mu_n = \frac{\mu_0}{\left(1+(\frac{E}{E_C})^{n+1}\right)^{1/n}} \quad (28)$$

n may be taken equal to 1 or 2 for a best fitting of the Current -Voltage characteristics and to be as close as possible to the two segments approach.

The physical and geometrical parameters of our device are:

$N = 5 \times 10^{17}$ cm^{-3};
a = 90 nm;
L_G = 0.28 μm;
W = 100 μm;
Φ_b = 0.60 V;
V_T = -3.49V;
ΔV_T = -1.32 V.

On figures (1 and 2) we show the result of numerical simulations of the carrier mobility models μ_1, μ_2 μ_3 and μ_4 using MATLAB software. The results were obtained for room temperature conditions (300 K).

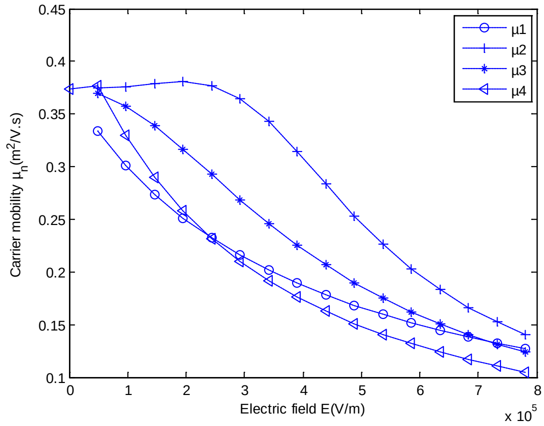

Figure 1: Carrier mobility versus electric field calculated using the four expressions at 300 K.

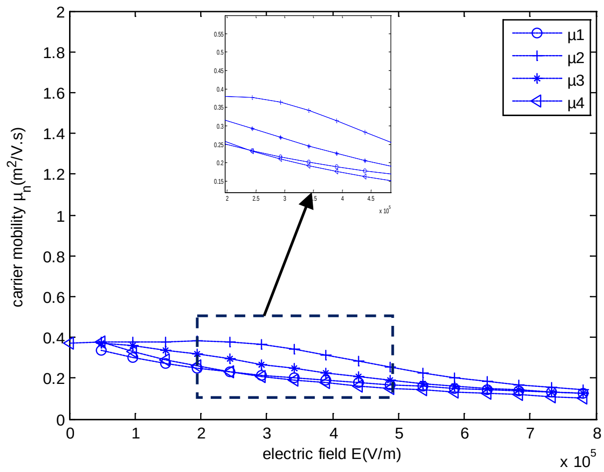

Figure 2: zooming on Carrier mobility versus electric field calculated using the four expressions at 300 K.

We observed clearly in figure 1 that the profiles of mobility calculated using the previous expressions are very similar and all begin with a decrease of the mobility, except for μ_2 in which a slight increase in electron mobility with increasing electric field is noticed, then the mobility decreases with the electric field until the value 0.140m^2/V.s at E=8×10^5V/m. The results of numerical simulations of models 3 and 4 of the carrier mobility for GaAs MESFET are shown in the same figure and clearly expose the similarity of the carrier mobility shapes versus electric field. The values of the mobility decreases when electric field increases. The maximum values calculated using the different models are very close to each other (μ_{3max}=0.369m^2/V.s, μ_{4max}=0.377m^2/V.s). While minimum values are slightly different (μ_{3min}=0.123m^2/V.s, μ_{4min}=0.104m^2/V.s at E=8×10^5V/m).

On figure 2 we have gathered the four carrier mobility expressions by zooming on the area where there is a large shift between the results.

Drift velocities versus electric field for the different models are shown on Figure 3. We note that the shape of V_2 is quite different from other models.

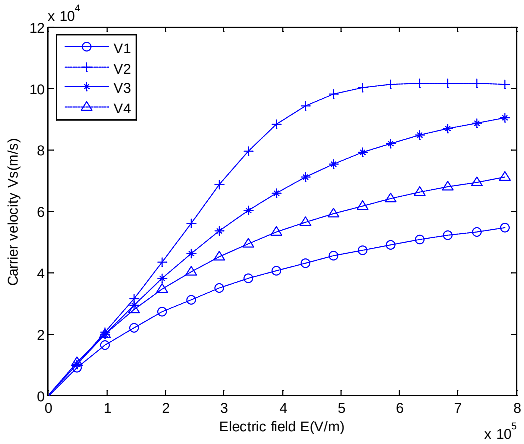

Figure 3: Drift velocity versus electric field calculated using the four expressions at 300 K.

On figures (4) and (5) we show the result of the carrier mobility and velocity versus electric field respectively, calculated using all the expressions at different temperature

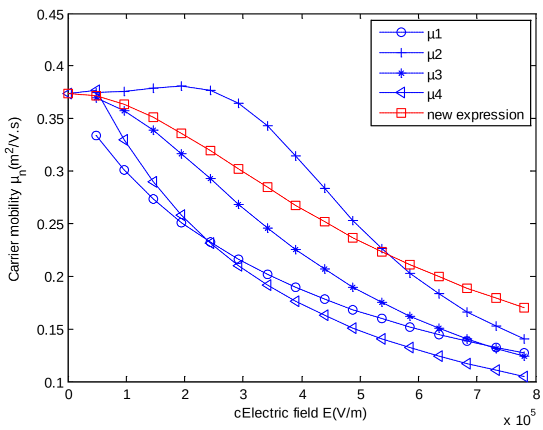

Figure 4: Carrier mobility versus electric field calculated using all the expressions and the proposed one at different temperature.

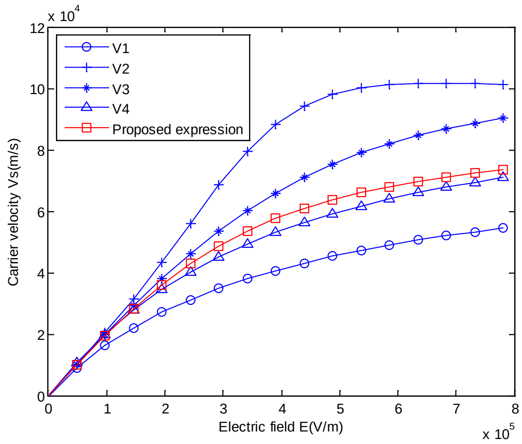

Figure 5: velocity-field dependence calculated using all the expressions and the proposed formula at different temperatures.

Figure 6 shows the comparison of the characteristics $I_{ds}(V_{ds})$ observed and calculated using Islam's model with new variable mobility expression for a GaAs MESFET's (*0.28x100 μm²*). We can clearly see that there is a broad agreement between the model and the experimental data at 0V and -1.1V in both linear and saturation region.

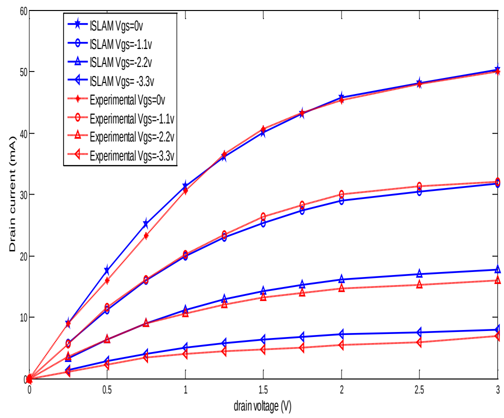

Figure 6: comparison of the characteristics $I_{ds}(V_{ds})$ observed and calculated using Islam's model with new variable mobility expression for a GaAs MESFET's (0.28 x 100 μm^2).

We show on figure 7 the simulation of I_{ds}-V_{ds} by the Memon's model using our proposed expression for mobility variation. We observe a good match between the model and experimental data both in the linear and the saturation regions for all the values of V_{gs}.

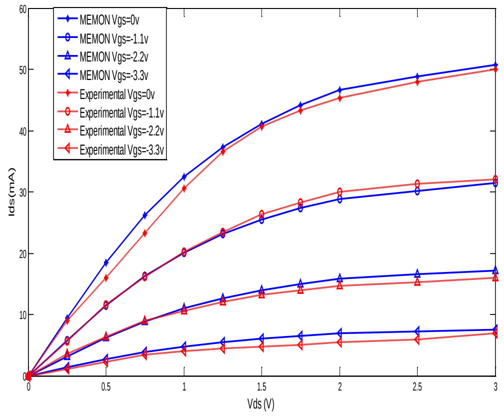

Figure 7: comparison of the characteristics Ids(Vds) observed and calculated using Memon's model with new variable mobility expression for a GaAs MESFET's (0.28 x 100 µm2).

RMS errors values were calculated at different V_{gs} and V_{ds} voltages, for the models under consideration, and presented in Tables 1 and 2 respectively.

Table 1: Comparison of RMS errors of I_{ds}-V_{ds} as a function of V_{gs} calculated by Islam's model using variable field-mobility dependence models (in mA).

	V_{gs} = 0V	V_{gs} = -1.1V	V_{gs} = -2.2V	V_{gs} = -3.3V	*Average errors*
ΔI_{ds1}	0.985	1.681	0.290	0.285	0.810
ΔI_{ds2}	0.985	1.681	0.290	0.285	0.810
ΔI_{ds3}	0.985	1.681	0.290	0.285	0.810
ΔI_{ds4}	0.985	1.681	0.290	0.285	0.81
$\Delta I_{ds\ new}$	0.977	1.658	0.337	0.196	0.792

Table 2: Comparison of RMS errors of I_{ds}-V_{ds} as a function of V_{gs} calculated by Memon's model using variable field-mobility dependence models (in mA).

	V_{gs} = 0V	V_{gs} = -1.1V	V_{gs} = -2.2V	V_{gs} = -3.3V	*Average errors*
ΔI_{ds1}	0.621	1.188	0.580	0.775	0.791
ΔI_{ds2}	0.621	1.189	0.580	0.775	0.791
ΔI_{ds3}	0.621	1.189	0.580	0.775	0.791
ΔI_{ds4}	0.621	1.189	0.580	0.775	0.791
$\Delta I_{ds\ new}$	0.614	1.169	0.627	0.679	0.772

V. DISCUSSION.

By closely examining the mathematical relations of carrier mobility we notice that they are rational functions with E as a variable, except for the fourth model where the variation of µ has a tangential form. We have seen that the carrier mobility is limited by several different scattering mechanisms depending on temperature. We already know that the carrier mobility depends on the timing of different collisions happening during their displacement, due to the presence of impurities, phonons, other carriers and any other defects in the lattice. However, the lattice vibration increases with the amplification of the applied electric field. These vibrations increase the probability of collisions, so it may explain the decrease in mobility versus electric field.

A good fitting of mobility has substantially enhanced the non-linear modelling of the static characteristics of the GaAs MESFET's.

VI. CONCLUSION.

The GaAs MESFET transistors are attractive devices for the use in microwave applications because of their relatively simple processing and their high-speed and low noise performances [26]. The development and the improvement of new dies of components require new results from modelling, new realisations and new characterisations [25]. The carrier mobility acquires major importance in determining the output characteristics of a GaAs MESFET's. A good fitting of mobility has a great influence on the accuracy of the electrical conductivity and many other physical parameters.

In this paper first we have tried to give a broad review of different types of scattering mechanisms in GaAs materials and their contributions towards total mobility. We have also shown the degradation of mobility with temperature and its subsequent effect on drain current. We then make a synthesis of some mobility-field expressions for GaAs MESFET's.

Therefore, we propose a new expression for the mobility-field dependence in GaAs.We show that the results calculated using this model agree well with experimental data. This expression can explain very well the carrier behavior at a wide range of electric field. It can also be implemented easily into computer models describing GaAs devices; in particular, GaAs ion implanted FET's with non-uniform mobility profiles. They also may be used in analytical calculations of the device performance (for example, when an analytical expression for the differential mobility as a function of the field is needed).

Analytical approximations for the drain I- V relationship including variable mobility profile and field distribution in the channel from the drain to the source of GaAs MESFET's are discussed.

References

[1]. LIU BO ET AL, J. Semicond.34, 044006, (2012).

[2]. JAN KUZMIK and ALEXANDROX GEORGAKILAS, IEEE Trans on Electron Devices, 58, 720, (2011).

[3]. PETER Y. YU; MANUEL CARDONA. Fundamentals of Semiconductors: "Physics and Materials Properties". Springer. pp. 205–.ISBN 978-3-642-00709-5. (2011).

[4]. SEEGER, K., Electrical conductivity and its temperature dependence, in Semiconductor Physics, Springer, Editor. p. 48. (2004).

[5]. DONALD A NEAMEN, MCGRAW HILL, 4th Edn.,New York (2012)

[6]. D. PANDEY, A. BHATTACHARJEE and T. R. LENKA "Study on Temperature Dependence Scattering Mechanisms and Mobility Effects in GaN and GaAs HEMTs" physics of semiconductor devices, 17th international workshop on physics of semiconductor devices, (2013).

[7]. CLEMENS OSTERMAIER ET AL, IEEE Electron Device Letters, 30, 1030, (2009).

[8]. MATTHIESSEN, A. and C. VOGT, "The influence of temperature on the electric conductive-power of alloys". Philosophical Transactions of the Royal Society of London, 154: p. 167-200. (1864).

[9]. MATTHIESSEN, A. and C. VOGT, "On the influence of temperature on the electric conductive-power of thallium and iron". Philosophical Transactions of the Royal Society of London, 153: p. 369-383. (1863).

[10].CHAO ZHANG, GUICUI FU, HANTIAN GU, DONG ZHANG "Simulation of Temperature Effects on GaAs MESFET Based on Physical Model". IEEE Prognostics & System Health Management Conference (PHM-20l2 Beijing). (2012)

[11]. J. S. BLAKEMORE, "Semiconducting and other major properties of gallium arsenide," Journal of Applied physics, vol. 53, pp. 123-181, (1982).

[12]. T.A. FJEDLY. T. YTERDAL, M.S.SHUR "Introduction to Device Modeling and circuit simulation" New York (1998).

[13]. S. MORARKA, S. MISHRA "2-D model for the potential distribution and threshold voltage off fully depleted short-Chanel ion-implanted silicon MESFET'S", newspaper off semiconductor technology and science, Vol 5, N°3, p 173-181, Marsh (2005).

[14]. S. BOSE, M. GUPTA, R.S. GUPTA "Id–Vd characteristics of optically biased short channel GaAs MESFET" ELSEVIER. Microelectronics Journal 241–247. 32 (2001)

[15]. MAYUMI HIROSE, JIRO YOSHIDA, MEMBER, IEEE, and NOBUYUKI TOYODA "An Improved Two-Dimensional Simulation Model (MEGA) for GaAs MESFET applicable to LSI design. Computer-Aided Design of Integrated Circuits and Systems, IEEE Transactions on (Volume:7 , Issue: 2)225 – 230 (2002)

[16]. MESFET Applicable to LSI Design" IEEE transactions on computer-aided design. vol. 7. N°. 2, February (1988).

[17]. KIYOYUKI, HIROYUKI "Importance of Low-Field Drift Velocity Characteristics for HEMT Modeling", IEEE ELECTRON DEVICE LETTERS, VOL. EDL-8, NO. 2, FEBRUARY (1987).

[18]. S.BOUZINA "L'influence des paramètres physiques et géométriques sur les propriétés statiques du transistor MESFET GaAs", Thèse de magister, Université De Constantine, (2003).

[19]. J. CHAPMAN "Heat Transfer (4th ed.)", Macmillan, New York, p. 358, (1984).

[20]. JINGMING XU and MICHAEL SHUR "Velocity-Field Dependence in GaAs". IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. ED-34, NO. 8, AUGUST (1981).

[21]. MANSOOR M. AHMED, HAROON AHMED, AND PETER H. LADBROOKE," An Improved DC Model for Circuit Analysis Programs for Submicron GaAs MESFET's", IEEE Transactions On Electron Devices, Vol. 44, No. 3, (March 1997).

[22]. N. M. MEMON, M. M .AHMED AND F. REHMAN "A Comprehensive Four Parameters I-V Model for GaAs MESFET Output Characteristics" Journal of Solid State

Electronics, Vol. 51, pp 511-516 (2007).
[23]. RODRIGUEZ T. J AND ENGLAND, "A five-parameter dc GaAs MESFET model for nonlinear circuit design," Proc. IEEE , pt. G, Vol. 139, No. 3, pp. 325-332, (1992).
[24]. TOMASZ KACPRZAK AND ANDRZEJ MATERKA, "Compact dc Model of GaAs FET's for Large-Signal Computer Calculation" IEEE Journal Of Solid-State Circuits, Vol. Sc-18, No. 2, (April 1983).
[25]. S.MELLAL, C.AZIZI, M.ZAABAT AND All, "influence of the two-dimensional analysis on the MESFET transistor characteristics", Journal of Electron Devices, Vol. 20, pp. 1724-1728 (2014).
[26]. Y. SAIDI, W. ALLIOUAT, I.HAMMA, M. ZAABAT, C.AZIZI, "Effect of mobility on (IV) characteristics of GaAs MESFET", Journal of Electron Devices, Vol.11, pp.602-608 (2011).