Influence of polarization, geometrical and structural parameters on GaAs MESFET output conductance under dark and illuminated conditions

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In this work, we investigate the effects of photonic intensity on several electrical and structural parameters of GaAs MESETs. First, a simulation software, describing the physical phenomena, is developed to calculate, display and plot the results.This program correctly explains all the behavior of the output conductance under illumination, as a function of polarization, geometrical and structural properties of these devices. Interesting results were obtained: (i) Increasing the photonic intensity and the channel thickness, the gate width and the doping lead to an increase in the output conductance. (ii) Reducing the gate length and the density of surface traps lead to an increase in the output conductance. (iii) Any increase in the illumination intensity optic lead to a progressive decrease in the apparent value of pinch-off voltage under illumination for which a universal equation is deduced in order to predict the apparent blocking voltage of an illuminated MESFET.

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1. Introduction

Modern electronic and optoelectronic technologies require the understanding and the investigations of photonic effects in several devices, such as MOSFETs, MESFETs, MISFETs, photoreceptors, etc. Thus, a great interest is shown due to the importance of optical performances of large band semiconductors among which gallium arsenide remains the most widely used material in device fabrication, such as solar cells, photodetectors, lasers, Electro-Absorption Modulators (EAM) GaAs, Metal-Semiconductors-Metal Photo Detector (MSM-PD), and the Photoconductive Semiconductor Switch (PCSS) [1-3]. Recently [4], the effect of GaAs step layer thickness in the Multiple-Stepped Quantum-Well (MSQW) solar cells was studied; it was reported that a decrease of the losses is induced by radiative recombination in the multiple quantum well MQW. It should be recalled that over recent decades, the field effect transistors based on Schottky barrier gallium arsenide, GaAs MESFET's, optically controlled (GaAs OPFET), attracted considerable attention in the design of various monolithic circuits. These circuits are optically controlled, particularly the Monolithic Microwave Integrated Circuits (MMICs) adopted to high signal generation [5] such as power amplifiers, oscillators, optoelectronic integrated circuits (OEICs) and mobile telecommunications circuits. However, microwave optical characteristics of the MESFETs are highly dependent on the device output conductance and the blocking voltage. Thereby, a specific theoretical model for the photo-dependence of the GaAs MESFET output conductance can solve this problem for MMICs and OEICs. For example, the output conductance trends are used in the linear circuits to improve the maximum frequency disposable [6-7].

In this context, we investigate the phenomenon of illumination in GaAs MESFETs, in order to contribute to the understanding of the physical laws that govern this phenomenon. It is worth noting that several experimental and theoretical models related to the study the effect of illumination on some MESFET parameters have been reported in the literature [8-11]. The starting point in the present study consists of considering some reported data [11] to investigate the influence of polarization, geometrical and structural parameters on GaAs MESFET output conductance, G_D, taking into account the effect of illumination. We then apply the results of this analysis to the determination of what might be the optimal illumination in order to improve the optical efficiency. Finally, we quantify the influence of the optical density on the channel blocking voltage.

2. Methodology

2.1 Device structure

The schematic structure of a conventional MESFET is shown in Fig.1.It is shown that on the semi-insulating GaAs substrate is deposited an n-type GaAs layer, of a thickness *a*, which forms the conducting channel. The drain, D, and source, S, contacts are Ohmic whereas the gate, G, contact is a Schottky contact. Various processes can be combined to create excess carriers in the semiconductor. Among these processes, we mention the photo excitation that leads to the generation of excess carriers with respect to equilibrium conditions, due the presence of illumination.

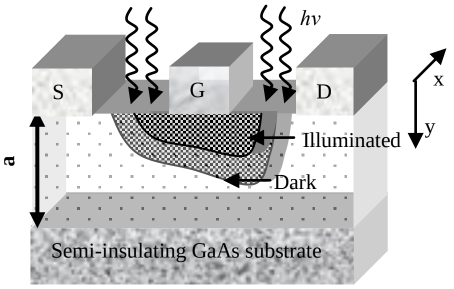


Fig.1. Structure of MESFET under dark and illuminated conditions.

The device, operated in the ohmic region, is illuminated by vertical optical radiation, hν, along the y axis. It should be noted that during their propagation photons are absorbed by the GaAs material. This phenomenon is characterized by an absorption coefficient, representing relative variation of the photon intensity per unit of length $\alpha_{GaAs} = 10^6$ m^{-1}, at a wavelength $\lambda_{GaAs} = 0.87$ µm.

The effect of illumination on electrical and structural characteristics is studied and analyzed through the development of a simulation program. This software takes into account the laws that describe the physical phenomena. It leads to the calculation of the derivative and the solution of a system of equations as well as displaying the results in the form of curves. The present investigation concerns the influence of (i) polarization, (ii) geometrical and (iii) structural parameters on the output conductance of a MESFET illuminated by different optical densities. Finally, an important part has been devoted to the quantification of the pinch-off voltage, V_{GSoffA}, appearing under variable and increasing illumination intensities.

2.2 Theoretical model

It is well established that the output conductance of a MESFET may be obtained using the following relationship:

$$G_D = \left(\frac{\partial I_{DS}}{\partial V_{DS}}\right)_{V_{GS}=cst} \tag{1}$$

where V_{DS} is drain-source voltage and I_{DS} is the drain-source current.

The fundamental physical mechanism that appears under optical illuminations of MESFETs is the generation of free carriers (electron-hole pairs) in the semiconductor. This mechanism appears when the absorbed photon energy is greater than or equal to the semiconductor band gap. The incident photon fluxes create a photocurrent arising from the layer of semiconductor, metal side, which develops a photonic voltage (photovoltage) through the Schottky junction [12].

The presently adopted model describes the expression of the current of a MESFET as a function of a photo-induced potential across the Schottky barrier, the life time of minority carriers, the rate of recombination and the rate of the photo-generation [11], as follows:

$$I_{DS} = \frac{qZ\mu_n N_D}{2L_G}\left[\left\{2a - \left(\frac{2\varepsilon}{qN_D}(V_{bi} - V_{GS} - V_{op}\right)^{1/2}\right\} V_{DS} - \frac{2}{3}\left\{\left(\frac{2\varepsilon}{qN_D}\right)^{\frac{1}{2}}\left(\left(V_{bi} - V_{GS} + V_{op} - V_{DS}\right)^{\frac{3}{2}} - \left(V_{bi} - V_{GS} - V_{op}\right)^{\frac{3}{2}}\right)\right\}\right] + \frac{qZ\mu_n P_{op}}{h\nu L_G}(1 - R_m)(1 - R_S)(1 - \exp(-\alpha a))\tau_l V_{DS} - \frac{qZR\mu_n\tau_l}{L_G} V_{DS} \tag{2}$$

where Z is the gate width, L_G the gate length, *a* the thickness of channel, P_{op} is the optical density; ε the permittivity ($\varepsilon = \varepsilon_0\varepsilon_r$); R_s and R_m are reflection coefficients of the semiconductor and the gate metal, respectively; μ_p and μ_n are hole and electrons motilities, respectively; N_D the doping concentration in the active layer; V_{bi} is the potential of the Schottky barrier junction; q the electron charge; h the Planck constant; α the coefficient of optical absorption; λ the wavelength of incident illumination, τ_L lifetime of minority carriers, R is the recombination rate, V_{op} the optical voltage, and υ is the frequency of the optical beam. Finally the photo-voltage, V_{op}, is simply given by the expression [11]:

$$V_{op} = \frac{nkT}{q}\ln\left[\frac{qG_{op}\sqrt{\frac{kT}{q}}\mu_p\tau_l - Rq}{J_s}\right] \tag{3}$$

Where *n*, *k*, *T* and J_s are the ideality factor of the Schottky junction, the Boltzmann constant, the temperature in Kelvin, the inverse saturation current density of the Schottky junction, respectively; G_{op} is the rate generation, per unit volume, of excess carriers at the gate metal-semiconductor interface. From Eq.3, it is easy to note that: if the density of the incident light varies the rate of optical generation varies and consequently the photo-voltage developed through the junction gate is also changed.

Eq.1 and Eq.2 are used to derive the expression of the output conductance G_D as a function of geometrical parameters of the device and the characteristics of the channel parameters namely doping, N_D, and the surface density of traps N_T.

$$G_D = \frac{qZ\mu_n N_D}{2L_g}\left[\left\{2a - \left(\frac{2\varepsilon}{qN_{dD}}(V_{bi} - V_{GS} - V_{OP})\right)^{\frac{1}{2}}\right\} - \left\{\left(\frac{2\varepsilon}{qN_D}\right)^{\frac{1}{2}}(V_{bi} - V_{GS} - V_{OP} + V_{DS})^{\frac{1}{2}}\right\}\right] + \frac{qZ\mu_n P_{OP}}{L_g}(1 - R_m)(1 - R_s)(1 - \exp(-\alpha a)\,\tau_L) - \frac{qZR\mu_n\tau_l}{L_G} \quad (4)$$

This expression takes into account not only the photovoltaic effect through the optical voltage developed at the Schottky junction, but also the polarization of the device and the lifetime of minority carriers.

Furthermore, the rate of recombination at the surface, R, which is an important parameter in the modelling of photo-active devices [13], is given by:

$$R = \frac{N_t K_n K_p (n_s p_s - n_t p_t)}{K_n(n_s + n_t) + K_p(p_s + p_t)} \quad (5)$$

Where K_n and K_p are the capture factors of electrons and holes, respectively; n_s and p_s are the surface concentration of the carriers which take the values n_t and p_t when the Fermi level coincides with that of the traps [13].

2.3 Calculation procedure

The present simulation is based on relations (1) to (5) and the use of MATLAB version R2014b (8. 4. 0. 150421).The first step consists of using the commands of MATLAB to derive I_{DS} (Eq.2) with respect to V_{DS} in order to determine the conductance of the channel. Then, we study the influence of some structural parameters (L_G, a and Z) or GaAs characteristics (N_D and N_T) or the bias voltages (V_{GS} and V_{DS}) on changes in G_D. Finally, the results are plotted, interpreted and compared to literature. Details of the calculations and the sequence of steps are better represented by the flow chart given in appendix 1. The physical and geometrical characteristics of device parameters [11, 14] chosen in this simulation are summarised in Table 1.

The calculation are organized into five steps that consist of:

i. Introducing the device characteristic parameters: V_{bi}, R_s, R_m, α, λ, K_n, K_p, n_s, p_n, η, μ_n and μ_p.

ii. Deriving the output current, I_{DS},with respect to V_{DS}.

iii. Initializing the parameters (Table.1), calculation and curves'plotting.

iv. Extracting V_{GSoff} values from $I_{DS} = f(V_{GS})$ curve, then plotting them as a functionof P_{OP}.

v. Using an optimization technique to deduce the universal equations of V_{GSoff} as a function of illumination.

Table 1. Physical and geometrical parameters of the OPFET.

Parameters	Value	Ref
L_G (μm)	1	[11]
Z (μm)	10	[11]
a (μm)	0.2	[11]
R_s (%)	0.1	[14]
R_m (%)	0.1	[14]
N_D (/m3)	$0.5x10^{23}$	[11]
N_T (/m^2)	$4x10^{17}$	[11]
V_{bi}(V)	0.8	[11]
α (m^{-1})	10^6	[11]
λ (μm)	0.83	[11]

3. Results and discussions

3.1 Effect of polarization on output conductance

Fig.2.a and Fig.2.b represent the change of output conductanceas a function of the optical density for different negative polarizations V_{GS} (from 0 to -300 mV) and different positive polarizations of V_{DS} (100 to 400 mV). It should be noted that this study was carried out in static and ohmic regime. It is clear that regardless of the polarization, the channel conductance increases for small values of the optical density (P_{op}<30 mW/m^2) and then undergoes a saturation. Furthermore, for P_{op}< 10 mW/m^2, this increase is linear. Moreover, we notice that the maximum value of the output conductance (G_D=5.8 mΩ^{-1} at P_{op} = 100 mW/m^2) is obtained for V_{GS}= 0.0 V. However, when V_{GS} increases, in absolute value, the output conductance decreases (G_D = 3.7 mΩ^{-1}at V_{GS} = - 300 mV and P_{op} = 100 mW/m^2). On the other hand, for a given optical power (e.g., P_{op}= 100 mW/m^2), G_D decreases when the applied voltage V_{DS} increases; at V_{DS} = 100 mV, G_D=5.8 mΩ^{-1} and at V_{DS} = 300 mV, G_D = 4.8 mΩ^{-1}.

It is important to note that the current flowing between the drain and the source can only cross the activeregion, known as the conducting channel. The application of an optical density reduces the depth of the depletion region and therefore increases the drain-source current; thus modulating the drain currentI_{DS}, by the optical power. This could be origin of $G_D$variations as a function of applied voltages V_{DS} and V_{GS}which depend on optical density. Moreover, the holes and the electrons generated in the channel contribute to the photoconductive current in the active region. We observe the appearance of an optical current and an optical voltage developed across the Schottky junction. The photonic voltage developed across the space charge region increases with increasing illumination density, in agreement with experimentally reported results [12].

This photonic voltage reduces the width of the space charge zone and accordingly increases the current I_{DS}. Thus, under illumination, both photovoltaic and photoconductive effects increase while the output resistance decreases.

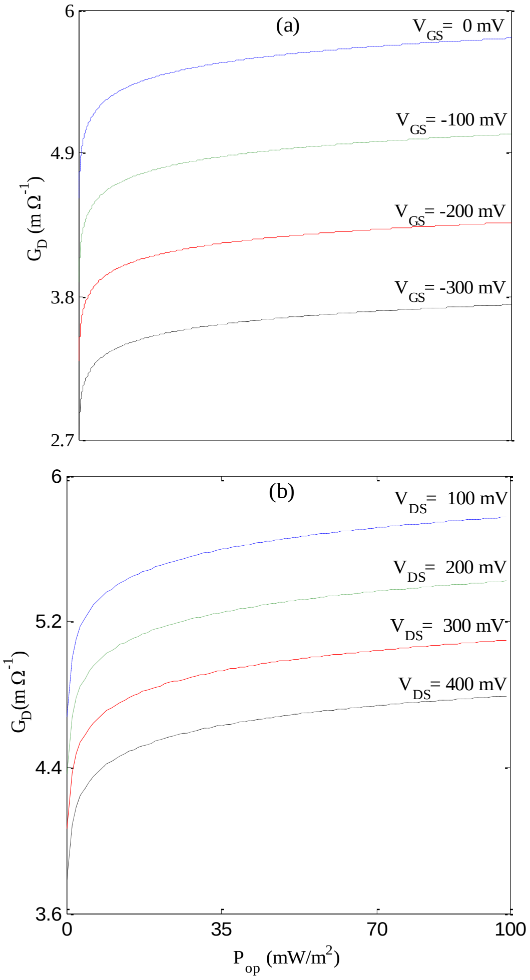


Fig.2. Output conductance versus optical densities: a) at different V_{GS} and V_{DS} = 100 mV, b) at different V_{DS} and V_{GS} = 0V.

Consequently, increasing illumination leads to an increase in not only the current flowing through the conducting channel but also inG_D. So we identified two opposite behaviourwith respect to the channel width: the effect of polarization (reduction) and illumination (widening) which lead to the saturation at high optical density. To put into evidence the validity of the present results we compare them (Table2) to those reported in literature [15] for an optical density, P_{op}= 234 mW/m^2 for L_G =1µm, Z=100 µm and a=0.25µm; it is clear that the agreement is quite good.

Table2. Model validation and comparison with literature.

P_{op} = 234 mW /m^2			
V_{GS} [V]	V_{DS} [V]	G_D [mho] [Present Work]	G_D [Ref. 15]
-01	0.1	79.95	81.10
	0.2	77.41	78.00
	0.3	74.93	75.10
0	0. 1	85.33	84.80
	0.2	82.79	83.50
	0.3	80.31	78.20

3.2 Structure effects

In this section, we focused our investigations on the influence of geometrical parameters namely, the gate length, L_G,and width, Z, and the thickness of the active layer, a, on the output conductance. Then we studied the influence of the conducting channel characteristics: the density of doping and density of surface traps. All the investigations were carried out, inohmic regime,at different optical intensities.

3.2.1 Geometrical properties

Figs. 3.a. and 3.b. represent the evolution of the output conductance as function of the gate width, Z, and the channel thickness, *a*, respectively, at different optical densities. A linear increase is noticed with the slope increasing when the optical density increases. This can be attributed to an increase of electrons mobility induced by a large active layer which facilitates the carriers flow.

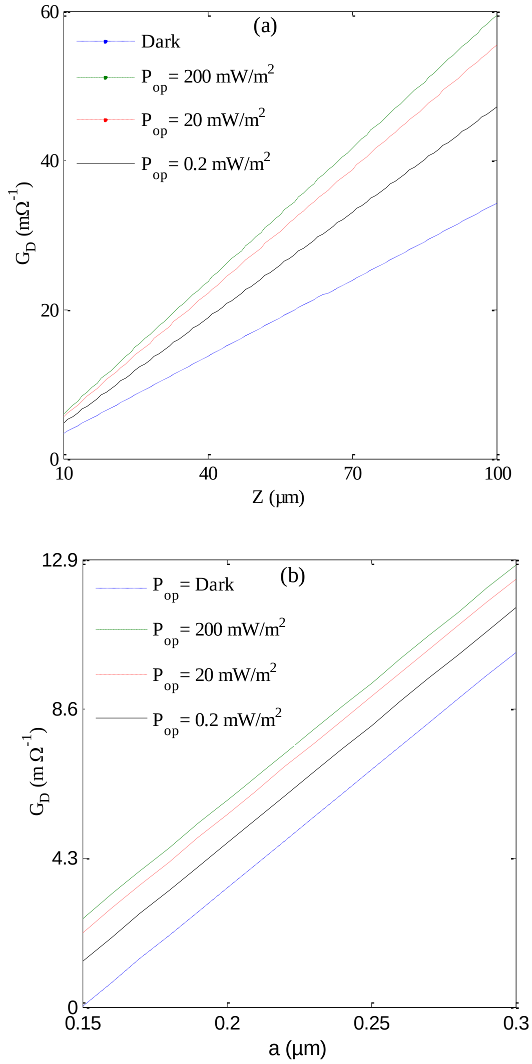


Fig.3. Output conductance,at V_{DS}=0.1 V, V_{GS}=0V, as a function of gate width (a),channel thickness (b).

The variations of G_D as a function of the gate length, $L_{G,}$ for different optical densities are shown in Fig.4, from which we can deduce that a reduction of L_G leads to an increase in G_D. This result, which is in good agreement with literature [16], canbe explained by the reduction of the channel resistance. This behaviour, well known in the MESFETs of short length gates, is attributed to the substantial extension of the space charge zone at the drain side. Moreover, it should be noted that the maximum value of G_D obtained at L_G = 0.3 µm becomes more important for higher optical densities. This is in agreement with previous results mentioning a reduction of the channel resistance when the optical density increases [14].

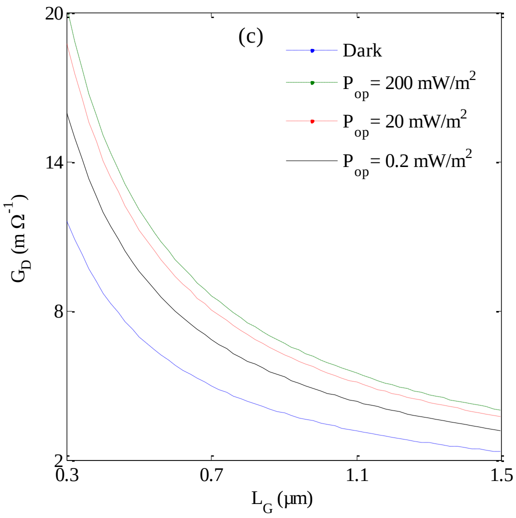


Fig.4. Output conductance, at V_{DS}=0.1 V, V_{GS}=0V, as a function of gate length (c).

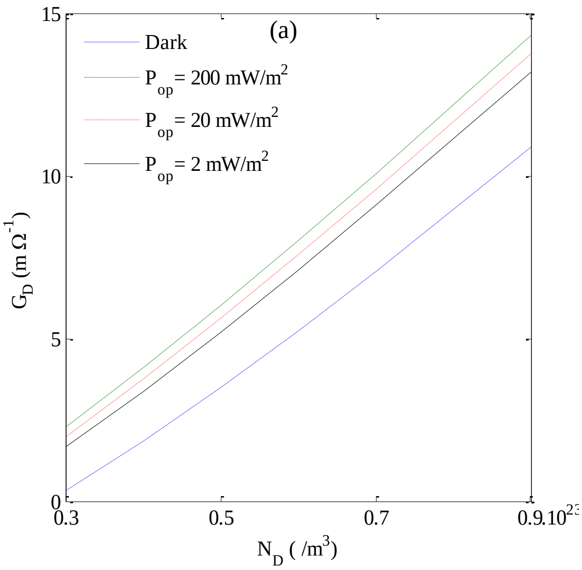
3.2.2 Characteristic parameters of conducting channel

The active layer doping of a MESFET is of great importance in the control of the value of the channel resistance. It is well established that a high doping not only keeps a large ratio between the length and height of the channel, but it also reduces the values of access resistances [17]. Moreover, the high doping reduces the width of depopulated areas and leads to a more important conducting region.

To evaluate the influence of the doping of the active region, N_D, on the output conductance of the illuminated device, we illustrate in Fig. 5.a, the obtained results of G_D versus N_D at different optical densities.It is clear that all the curves show a linear increase with maximum values for the highest doping levels and optical densities.

Furthermore, for a given doping, the conductance increases with the increase of the optical density. This result is due to the fact that any increase of the doping reduces the resistance of the channel and consequently leads to an increase in the output conductance.

To improve the MESFETs performances, it is of great importance to reduce the surface state densities that inevitably exists at the metal/semiconductors interface when preparing device contacts. The presence of traps in such surface states leads to the appearance of several anomalies during device operations. In this context, we illustrate in Fig. 5.b, the influence of the surface traps density, NT, on the output conductance at different optical densities. It can be seen that, for all optical densities, the output conductance decreases with increasing N_T. This behaviour confirms the presence of traps especially on the surface whichcreatea space charge zone in the channel; this leads to an increase in the resistances of the source-drain ohmic contacts, and consequently to a decrease in the drain current.



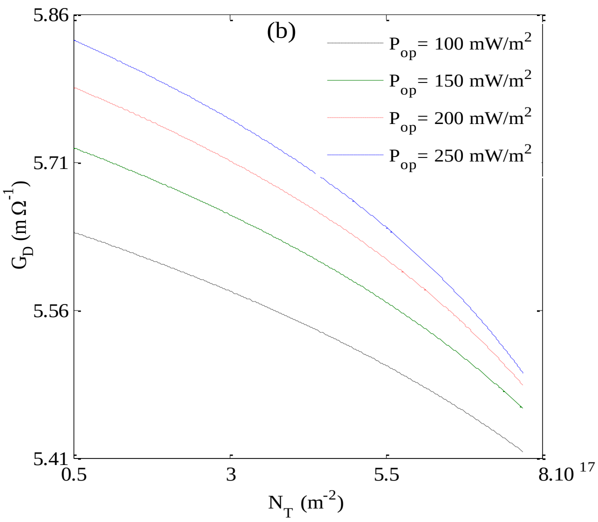


Fig.5.Variations of output conductance with doping concentrations (a) and density of traps (b).

3.3 Quantification of illumination effects on the blocking voltage

The most important phenomenon to consider in the design of a GaAs MESFET is the control of its blocking voltage, V_{GSoff}. Under normal operation, when the device is illuminated, the classic pinch off voltage is modified due the reduction of the width of the space charge zone (caused by the illumination) and the appearance a photonic tension through the depletion region.Hence, the pinch offvoltage is notonly one ofOPFET electrical parameters, but also an important variable forthe optimizationmanufacturing parameters such the channel depth [10]. Thus, to quantify the apparent value of this voltage of the illuminated device, defined as the V_{GS} voltage corresponding to a null output current, I_{DS}, and noted V_{GSoffA}, we carry out a simulation of transfer characteristics$I_{DS} = f(V_{GS})$ at different optical densities. The value of V_{GSoffA} was deduced from $I_{DS} = f(V_{GS})$ characteristics at different optical densities. The obtained results are shown in Fig.6. The curve can be divided into two distinct regions: (i) For low optical densities (P_{op}<10 mW/m^2), there is a rapid and linear increase which is better illustrated in the insert of Fig. 6 and (ii) for higher optical densitiesV_{GSoffA} varies very slowly with P_{op} leading to a saturation region.

Using an optimization technique, the linear region (insert of Fig. 6) may be approximated by the following equation:

$$| V_{GSoffA} | = 9.10^{-3} P_{op} + 0.73 \quad (6)$$

Let us recall that in the absence of illumination, for a constant doping N_D, the voltage V_{GSoff} is given by.

$$V_{GSoff} = V_{bi} - V_p \quad (7)$$

Where V_{bi} is the internal potential and V_p is the pinch-off voltage with:

$$V_p = \frac{qa^2 N_D}{2\varepsilon}$$

By considering the data in Table1, it is easy to determine:

$$V_p = \frac{qa^2 N_d}{2\varepsilon} = 1.53\ \mathrm{V}$$

and

$$V_{GSoff} = V_{bi} - V_p = 0.8 - 1.53 = -0.73\mathrm{V}$$

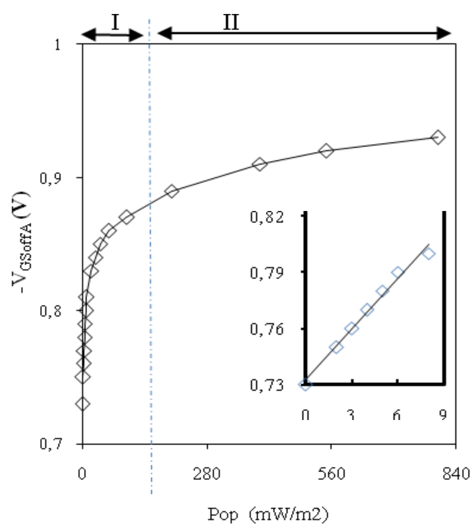


Fig.6. Apparent pinch voltage as a function of optical densities

Thus, relation (6) can be written as:

$$V_{GSoffA} = V_{GSoff} - 9.10^{-3} \mathrm{Pop} \Rightarrow$$

$$\frac{V_{GSoffA}}{V_{GSoff}} = 1 - \frac{9.10^{-3}}{V_{GSoff}} (P_{op}) \quad (8)$$

The analysis of this relation shows that under dark conditions ($P_{op} = 0$) we get $V_{GSoffA} = V_{GSoff}$. Whereas, under illumination ($P_{op} \neq 0$), we obtain $V_{GSoffA} < V_{GSoff}$. Moreover, as the illumination gets higher the pinch-off voltage becomes lower. Thus, reducing the width of the space charge region and consequently the conducting channel gets larger, in agreement with literature [10].

4. Conclusions

We investigated the influence of optical densities on the output conductance dependence on polarization and structural properties of MESFETs via the development of a program based on physical phenomena governing such devices. The developed a model which treats the data numerically and graphically enabled us to correctly explains all the behaviour of the output conductance. Moreover, it not only led to the determination of the variation of G_D as a function L_G, W, n and N_T, but also to the evolution of the current as a function of V_{GS} at different optical densities thereby determining the apparent blocking voltage introduced by the optical effect. Thus, through this model, a universal formula was established that can be used to control the influence of the optical density on the blocking voltage of a MESFET. The comparison of our results with the literature showed good agreement. Finally, and in order to improve the performance of a MESFET, some results of this study are highlighted:

- The illumination that generates pairs electron - hole pairs (for hν >E_g) explains the reduction of the width of the space charge zone and thereby the increase of the channel output conductance.
- The reduction of the gate length and the density of surface traps increase the output conductance
- Increasing the channel thickness, the gate width and the dopinglead to an increase the output conductance.
- The relationship determining the variations of the blocking voltage of the MESFET as a function of the illumination is an important universal equation for the prediction of the apparent blocking voltage of an illuminated MESFET.

References

[1] R. G. Walker, J. Heaton, in 'Broad Band Optical Modulators-Science, Technology and Applications', A. Chen and E. J. Murphy, Eds. Boca Raton, FL, USA: CRC Press, 207 (2012).

[2] A. Karar, C. L. Tan, K. Alameh, Y. T. Lee, F. Karouta, J. Lightwave Technol.**31**, 1088 (2013).

[3] W. Shi, X. Wang and L.Hou IEEE Trans. Electron.Devices.**60,** 1361 (2013).
[4] Y. Wen, Y. Wang, K. Watanabe, M. Sugiyama and Y. Nakano, IEEE J. Photovoltaics, **3**, 289 (2013).
[5] P. C. Schindler, D. Korn, C. Stamatiadis, M. F. O'Keefe, L. Stampoulidis, R. Schmogrow, P. Zakynthinos, R. Palmer, N. Cameron, Y. Zhou, R. G. Walker, E. Kehayas, S. Ben-Ezra, I. Tomkos, L. Zimmermann, K. Petermann, W. Freude, C. Koos, and J. Leuthold, J. Lightwave Technol.**32**, 760 (2014).
[6] Z. Hadjoub, F. Z. Khelifati, D. Nebti, A. Gueraoui and A. Doghmane, J. Optoelectron. Adv. Mater.**15**, 1131 (2013).
[7] Z. Hadjoub, K. Cheikh and A. Doghmane, Optoelectron. Adv. Mater. -Rapid Commun.**3**, 360 (2009).
[8] C. Zhao, L. Bie, R. Zhang., and J. Kanicki, IEEE Electron Device Lett., **35**, 75 (2014).
[9] S.Tripathi and S.Jit, IET Circuits Devices Syst. **109**, 053102 (2013).
[10] S.N. Chattopadhyay, C. B. Overton, S. Vetter, M. Azadeh, B. H. Olson, and N. El Naga, J. Semicond. Technol. Sci.**10**, 213 (2010).
[11] P. Chakrabarti, S. K. Shrestha, A. Srivastava, and D. Saxena, IEEE Trans. Microwave Theory Tech.**42,** 365(1994).
[12] A. A. A. De Salles, IEEE Trans.Microwave Theory Tech., **MTT-31**, 812 (1983).
[13] G.J.Rees, Solid-State Electronics **28**, 517 (1985).
[14] B.K. Mishra, L. Jolly and S.Behra, IJRRAS **9,** 442 (2011).
[15] Shubha, B. B. Pal, and R. U. Khan, IEEE Trans. Electron Devices **45**, 78 (1998).
[16] M. Tomizawa, M. Uchida and T.Ugeta, IEEE Trans. Electron Devices**ED4-31**, 435 (1984).
[17] J. A. Adams, I. G. Thayne, C. D. W. Wilkinson, S . P. Beaumont, N. P. Johnson, A. H. Kean and C. R. Stanley, IEEE Trans. Electron Devices **40,** 1047 (1993).

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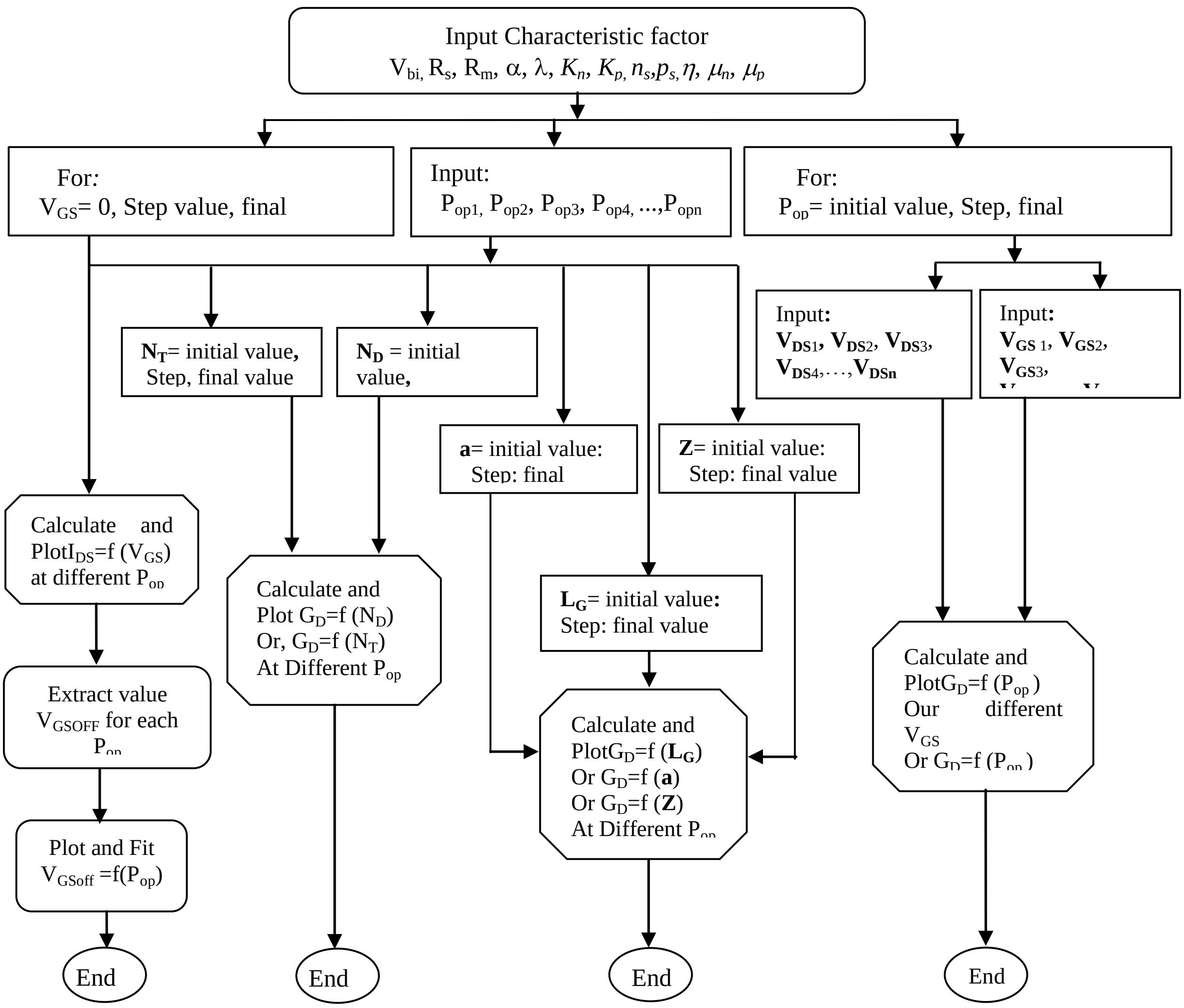
Appendix 1



Flow chart.