Modeling and Simulation of 2-D GaAs MESFET under Illumination

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Abstract - A two dimensional numerical model of an optically gated GaAs MESFET with non uniform doping has been developed for the characterization of the device as a photo detector. First the photo induced voltage (V_{op}) at the Schottky gate contact is calculated for estimating the channel profile. The Continuity Equation in the gate depletion region and the neutral region are then solved numerically under dark and illumination conditions. Results reveal that the depletion widths are strongly influenced by illumination and hence characteristics changes with illumination.

Index Terms - OPFET, Schottky, Photovoltage.

I. INTRODUCTION

Direct Optical control of microwave devices and monolithic microwave integrated circuits can results in better switching, amplitude, phase control, and frequency control. It can reduce weight, enhance efficiency, and increase the speed of operation of microwave systems [1]. With such numerous advantages many application like optically controlled amplifiers, oscillators, Light Amplifying Optical Switch (LAOS) and phase shifters etc. become feasible.

Several researchers experimentally showed that gain, drain current and small signal parameters of GaAs MESFET can be controlled by varying incident light on the device in the same manner as varying the gate bias voltage [2]. The optical radiation is absorbed in the gate depletion region, neutral channel region. The excess carriers cause a change in the built-in potential at the Schottky contact due to a photovoltaic effect and modulate the conductivity of the channel and enhance the substrate leakage current due to the photoconductive effect. It is seen that the width of the gate depletion region at any point in the channel decreases in the presence of illumination.

When the gate length becomes shorter than about 2 µm, two dimensional effects dominate the device’s operation. Therefore to shed further light on the mechanisms governing the photoeffects, both the device structure and the appropriate physical two dimension equations should be taken into consideration. This paper represents the full solution of Poisson’s and Continuity equations using a two-dimensional numerical simulation [2, 3]. In the present work the internal photovoltage effect which takes place at active layer-substrate junction and surface recombination at surface are assumed to be negligible.

II. THEORY

The structure under consideration is a conventional GaAs MESFET with semitransparent gate. The schematic structure of the MESFET under consideration is shown in Fig. 1. The MESFET that is simulated has a channel length (L) of 0.25µm and active region thickness (a) of 0.15µm.

Fig 1: Structure of GaAs MESFET

\[ N_d(y) = \frac{Q}{\sigma \sqrt{2\pi}} \exp\left(\frac{-(y-R_p)^2}{\sigma^2}\right) \]  

(1)

where

- \( Q \) Ion implanted dose,
- \( \sigma \) Straggle parameter
- \( R_p \) Projected range.

A. Calculation of Photovoltage

The optical radiation has been assumed incident in the vertical direction y-direction [5]. For the optical power density P_{opt}, the total photogeneration, G_{op} in the gate depletion region can be obtained as

\[ G_{op} = z P_{opt} \frac{\alpha(1-R_m)(1-R)}{h\nu} \int_0^L \int_0^{y_A(x)} \exp(-\alpha y) dy \, dx \]  

(2)

The upper limit \( y_A \) depends on the channel voltage and, thus, also on channel length, x.
\[ y_{dg} = \sqrt{\frac{2\varepsilon[V(x) - \Delta - V_g + \phi_d]}{qN_{Dr}}} \]  

Where \( N_{Dr} \) is the equivalent constant of ion-implanted profile.

In the presence of a large gate bias resistance, the photovoltage developed at the Schottky contact can be approximated by the open-circuit voltage, given by

\[ V_{op} = \frac{KT}{q} \ln \left( \frac{qG_{op}}{ZLJ_{sc}} \right) \]  

Where
- \( \varepsilon \) - Permittivity of the GaAs,
- \( R_m \) - Reflection coefficient at the entrance and
- \( R_s \) - Reflection coefficient at the metal semiconductor contact
- \( P_{opt} \) - Incident optical power density,
- \( h \) - Planck’s constant,
- \( \nu \) - Frequency of the incident radiation,
- \( \alpha \) - Optical absorption coefficient of the semiconductor at the operating wavelength,
- \( \tau_L \) - Mean lifetime of the minority carriers under illumination
- \( q \) - Electron charge,
- \( V_{ds} \) - Drain to source voltage
- \( \Phi_{bi} \) - Built in voltage of the Schottky barrier gate,
- \( V_{bi} \) - Built in voltage between the channel to source junction
- \( V_{op} \) - Photo induced voltage.
- \( K \) - Boltzmann’s constant
- \( J_{sc} \) - Minority carrier current density of the Schottky junction.

\[ K1 = \frac{P_{opt}(1 - R_m)(1 - R_s)\alpha \tau_L}{hv} \]  

Where
- \( \psi \) - is the two dimension potential distribution across the channel.

The boundary conditions are taken from [2] to solve equation (7). The electric fields \( E_x \) and \( E_y \) along x and y directions, respectively have been obtained by solving equation (7) using Leibmann’s Iterative method [2]

\[ E_x = \psi'(i + 1, j) - \psi'(i - 1, j) \]

\[ E_y = \psi'(i, j + 1) - \psi'(i, j - 1) \]

These equations have been utilized for estimating the field dependent mobility and the drain current characteristics equation. The field dependent mobility is given [6]

\[ \mu(E_x) = \mu_0 + 2(2\mu_0 E_x^2 + 3\nu_{sat}) \frac{E_x}{E_c^2} \]  

Where
- \( \mu_0 \) - Low field electron mobility
- \( \nu_{sat} \) - Saturation velocity
- \( E_c \) - Critical field

IV. CURRENT MODELING

The dc component of the total drain-source current is contributed by the carriers due to ion-implantation, \( I_{ion} \) and optical generation in the depletion, \( I_{dep} \) and channel regions, \( I_c \) [3]. It can be represented as

\[ I_{ds(\text{total})} = I_{ion} + I_{dep} + I_c \]  

A. DC drain-source current due to ion-implantation

The channel current due to ion –implantation is obtained using the relation

\[ I_{ion} = \frac{\mu Z V}{L} \int_{V_{op}}^{V} dV \]  

\[ Q_{ion} \] is obtained as

\[ Q_{ion} = \frac{Q}{2} \sigma f \left[ \frac{y_{dg} - R_b}{\sigma^2} \right] \left[ \frac{a - R_b}{\sigma^2} \right] \]  

Where \( y_{dg} \) is the distance from the surface to the modified gate edge of the gate depletion region due to photo voltage developed across the Schottky barrier and is given as

\[ y_{dg} = \sqrt{\frac{2\varepsilon[V(x) - V_g - \Delta + \phi_d] - V_{op}}{qN_{Dr}}} \]  

On substitution of \( Q_{ion} \) into \( I_{ion} \), we have

\[ I_{ion} = \frac{Q}{2} I_i + \frac{Q}{2} \sigma f \left[ \frac{a - R_b}{\sigma^2} \right] V_{dj} \]
\[ I_1 = \int_0^{y_{ds}} \frac{y_{ds} - R_p}{\sigma \sqrt{2}} \text{d}V \]

\[ = \frac{2\sigma^2 qN_{In}}{e} \left[ \frac{a_2}{2} \left\{ -a_2 e^{-y_{ds}} - \frac{1}{\sqrt{1!}} \left( e^{-a_2} - 1 \right) \right\} + \frac{a_{21}}{2} \left\{ a_2 e^{-y_{ds}} - \frac{1}{\sqrt{1!}} \left( e^{-a_2} - 1 \right) \right\} + \frac{1}{4} \left\{ e^{-y_{ds}} - e^{-y_{ds}} \right\} + \frac{1}{2\sqrt{2}} \left( a_{1} - a_{1} \right) \right] \]

\[ \text{Where} \]

\[ a_2 = \frac{\left[ y_{ds} \right]_{y=0} - R_p}{\sigma \sqrt{2}} \]

\[ a_{21} = \frac{\left[ y_{ds} \right]_{y=y_{ds}} - R_p}{\sigma \sqrt{2}} \]

**B. DC current due to carriers generated in the neutral region:**

In neutral region, carrier transport is done due to diffusion and recombination. So the continuity equation takes the form,

\[ \frac{\partial^2 n}{\partial y^2} = \frac{n_2}{\tau D_n D_n} - \frac{\alpha \phi e^{-\alpha y}}{D_n} \]

Where \( D_n \) is the diffusion coefficient.

Boundary condition at \( y=0 \), \( n = \alpha \phi \tau_n \) and \( y=y_{ds} \), \( n = \alpha \phi \tau_n \exp(-\alpha y) \) is used to solve it. The photogenerated electron concentration in the neutral region is given by,

\[ n_2 = \alpha \phi \tau_n + \frac{1}{D_n} \left( \alpha^2 - 1 \right) e^{-\alpha y} \left( \frac{\phi e^{-\phi}}{\alpha \tau_n} \right) \]

\[ L_{nw} \] is the diffusion length of electrons and is given as,

\[ L_{nw} = \sqrt{D \tau_n} \]

The charge density developed due to electrons generated in the active channel is given by

\[ Q_{neutral} = q \int_{y_{ds}}^{y} n_2 \text{d}y \]

So the drain-source current contributed by photogenerated electrons in the channel neutral region is calculated as

\[ I_{neutral} = \frac{q \mu Z V_{ds}}{L} \int_0^{y_{ds}} Q_{neutral} \text{d}V \]

\[ = \frac{q \mu Z}{L} \left[ \alpha \phi \tau_n \left\{ \left( \frac{1}{A} \right) (I_5 - I_6) + \frac{\phi \tau_n}{A} (I_5 - I_6) \right\} \right] \]

Where \( A = D_n \left( \alpha^2 - \frac{1}{L_{nw}} \right) \) and the current components \( I_5, I_6, I_7 \) are as follows

\[ I_5 = \frac{qN_{In} L_{nw}}{\epsilon} \left\{ \exp B (B - 1) - \exp B (B - 1) \right\} \]

\[ I_6 = \exp(-\frac{a}{L_{nw}}) V_{ds} \]

\[ I_7 = \exp(\alpha a) V_{ds} \]

\[ I_8 = \frac{qN_{In}}{e\alpha} \left[ \exp (E) (E - 1) - \exp (E) (E - 1) \right] \]

\[ B = -\frac{\left[ y_{ds} \right]_{y=y_{ds}}}{L_{nw}} \]

\[ B_1 = -\frac{\left[ y_{ds} \right]_{y=y_{ds}}}{L_{nw}} \]

\[ E = -\alpha \left[ y_{ds} \right]_{y=y_{ds}} \]

\[ E_1 = -\alpha \left[ y_{ds} \right]_{y=0} \]

**C. DC current due to carriers generated in the depletion region:**

Since the transport mechanism is drift and recombination in depletion region, the continuity equation becomes

\[ \frac{\partial n}{\partial y} + \phi \alpha e^{-\alpha y} \frac{n}{\tau_n} = 0 \]

As the surface recombination is not considered, the photo generated electrons in the gate depletion region are given by

\[ n_{dep} = \frac{\alpha \phi \tau_n}{1 + \alpha \nu \phi \tau_n} e^{-\alpha y} \]

developed due to electrons contributed from the gate depletion region is

\[ Q_{dep} = q \int_{y_{ds}}^{y} n_{dep} \text{d}y \]

\[ = \frac{\phi \tau_n q}{1 + \alpha \nu \phi \tau_n} \left[ 1 - e^{-\alpha y_{ds}} \right] \]

The corresponding current

\[ I_{dep} = \frac{\mu Z V_{ds}}{L} \int_0^{y_{ds}} Q_{dep} \text{d}V \]

Which results into

\[ I_{dep} = \left( \frac{q \mu Z}{L} \right) \left( \frac{\phi \tau_n}{1 + \alpha \phi \tau_n} I_2 + \frac{\phi \tau_n}{1 + \alpha \phi \tau_n} V_{ds} \right) \]

The current \( I_8 \) is given by
\[
I_h = \frac{q N_{Dr}}{\alpha e} \left[ \left( \frac{y_{dg} | v_{\mu} - \frac{1}{\alpha}}{\mu} \right) \exp(-\alpha y_{dg} | v_{\mu}) \right] - \left( \frac{y_{dg} | v_{s\alpha} - \frac{1}{\alpha}}{\mu} \right) \exp(-\alpha y_{dg} | v_{s\alpha}) \right] \quad (31)
\]

Computations and simulations have been carried out for GaAs MESFET at 300 K under various illuminated conditions using 2D modeling. The gate metallization has been assumed to be thin enough to allow 90\% of the incident radiation to pass through. The parameters used in the calculations are shown in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel length, L</td>
<td>0.25 (\mu)m</td>
</tr>
<tr>
<td>Channel depth, d</td>
<td>0.15 (\mu)m</td>
</tr>
<tr>
<td>Device width, Z</td>
<td>100 (\mu)m</td>
</tr>
<tr>
<td>Absorption coefficient, (\alpha)</td>
<td>1.79 \times 10^3 /m^2</td>
</tr>
<tr>
<td>Intrinsic carrier concentration, (n_i)</td>
<td>0.85 V</td>
</tr>
<tr>
<td>Incident optical power, (P_{opt})</td>
<td>1m, 0.1 W/m^2</td>
</tr>
<tr>
<td>Reflection coefficient at entrance, (R_m)</td>
<td>10% of (P_{opt})</td>
</tr>
<tr>
<td>Reflection coefficient at metal contact, (R_s)</td>
<td>10% of (P_{opt})</td>
</tr>
<tr>
<td>Temperature, (T)</td>
<td>300 K</td>
</tr>
<tr>
<td>Position of Fermi level below the conduction band, (\Phi)</td>
<td>0.02 V</td>
</tr>
<tr>
<td>(N_{Dr})</td>
<td>0.658 \times 10^{17}$/m^3</td>
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<tr>
<td>(R_p)</td>
<td>0.861 \times 10^3 (\mu)m</td>
</tr>
<tr>
<td>(\mu_b)</td>
<td>3000 (cm^2/s/V)</td>
</tr>
<tr>
<td>(\mu_n)</td>
<td>3483 (cm^2/s/V)</td>
</tr>
</tbody>
</table>

**V. RESULTS AND DISCUSSIONS**

Fig. 2 shows the variation of the photo voltage developed at the Schottky contact with the optical power density. Surface recombination has not been taken into account. The photo voltage developed at the Schottky junction increases with the incident optical power density \(P_{opt}\) and finally saturates at higher values of optical power density. This saturation at higher values of optical density is due to reduction in the lifetime of the carriers in the presence of illumination, which limits the excess photo generation under the intense illumination.

**TABLE 1**

PARAMETERS USED IN THE MODELING

Fig. 3 shows the variation of gate depletion width in the channel with the distance \(x\) along the channel under dark and illumination conditions. Photovoltaic effect in the illuminated condition reduces the applied gate bias and causes the next reduction in the width of the gate depletion region in the illuminated condition.

The Figure 4 shows the variation of channel potential with \(L_x\) and \(L_y\) for different illumination (\(P_{opt1}=0W/m^2\), \(P_{opt2}=0.2W/m^2\)). It clearly shows that the channel potential increases towards the drain side. This is because the biasing is applied at the drain.
The variation of gate depletion width, variation of photo voltage Vop across the Shottky barrier and the I-V characteristics obtained by the numerical method has been found to be consistent with those of the model reported by P. Chakrabarti et al [7]

VI. CONCLUSION

A two-dimensional simulation program for non-uniformly doped GaAs MESFET has been developed. The program solves numerically the basic continuity equations. The model has been applied to simulate the characteristics under different illuminated conditions. The numerical model developed here computes the various d.c. characteristics, including photovolatge, variation of gate-depletion width in the channel and the current-voltage characteristics.

The model presented here can be used to characterize an ion-implanted GaAs MESFET for optically controlled applications. The results obtained from the simulation compares satisfactorily with reported results for similar structures.

REFERENCES