EFFECT OF MODULATION LIGHT ON THE CHARACTERISTICS OF QUANTUM DOT TRANSISTOR UNDER ILLUMINATION

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Abstract

This paper depicts the theoretical investigation of the performance of the Quantum Dot Transistor (QD Transistor) under signal modulated optical illumination .A device structure consist of Quantum Dots (QD) in the GaAs layer of nAlGaAs/GaAs MODFET known as QD Transistor is considered for illumination. The photoconductive effect in the GaAs and QD layer which increases the 2DEG Channel electron concentration is considered. The excess carriers due to photo generation are obtained by solving the a.c continuity equation. The energy levels are modified due to generation of carriers. The offset voltage, sheet concentration , I-V characteristics, transfer characteristics as a function of frequency have been evaluated and discussed. The I-V characteristics shows a better sensitivity , amplifying and switching capability of the device with respect to incident optical power density.

Keywords: Two dimensional electron gas, QD Transistor, photovoltage, modulated signal.

1 INTRODUCTION

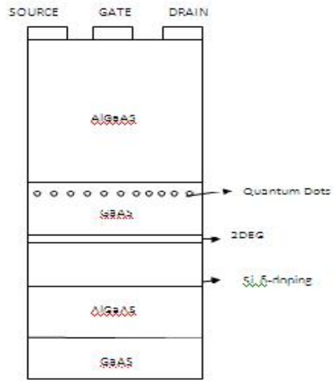
An enormous interest has been created in the study of optical effect in high speed devices due to their application in fiber optical communication and optical integration.In general Metal Semiconductor Field Effect Transistors (MESFET) can be used as a radio frequency switch, gain control for amplifiers, for locking and frequency modulation, oscillator tuning , mixing,phase shifting etc [1]. Although some investigators have carried out both experimental and analytical studies on the effect of illumination and signal modulated illumination in GaAs Metal Semiconductor Field Transistor (MESFET) and A1GaAs/GaAs MODFET and Quantum Dot Transistors [1]-[11], which show that there is significant effect of induced light on the electrical parameters of the device. Still thereis lack of theoretical and experimental work describing the effect of illumination on QD Transistor with signal modulated illumination. Hence it is desired to investigate the effect of signal modulated optical illumination on the characteristics of a QD Transistor. When the optical radiation is modulated at the signal frequency, the charge carriers generated in the depletion, neutral regions and the active layer with QDs of the device are also modulated by the signal.

A detailed analysis considering all effects resulting from optical illumination on QD Transistor is a very complex task. However, by making some assumptions, a simplified analysis considering the relevant photo-effects can be made [12].

In this paper, we have assumed that the signal modulated radiation falls on the QD Transistor. This allows the signal modulated radiation to create free electron-hole pairs in the GaAs layer with Quantum Dots, heterojunction regions and the neutral & depletion regions of AlGaAs which are also modulated at the signal frequency. The excess carriers are solved using the ac continuity equations for electrons and holes. The Poisson’s equation is used for solving the electric field and voltage. The effect of signal modulated radiation on I-V characteristics, offset voltage, transfer characteristic and sheet concentration have been presented.

2 THEORY

The structure of Quantum Dot Transistor considered for illumination is shown in Fig(1). It consists of a GaAs/AlGaAs modulation doped FET containing a layer of InAs quantum dots separated from the two dimensional electron gas (2DEG) in the GaAs channel. The doped AlGaAs barrier layers provide excess carriers to the GaAs quantum well and the quantum dot layer. The impurities in the doped AlGaAs layer provide electrons to the undoped GaAs layer, and the space charges. Therefore, a quantum well is formed at the boundary of the undoped AlGaAs and the undoped GaAs. The thickness of the GaAs quantum well is about or less than the exciton Bohr radius. The electron and holes in the GaAs quantum well are confined by the AlGaAs energy barrier, respectively.



Fig(1). Schematic Diagram of Quantum Dot Transistor

We consider only partial depletion of the device. The excess carriers (electrons and holes) due to signal modulated radiation are generated in the depletion and neutral regions of the AlGaAs layer[10] and also in the GaAs layer with QDs. The excess electrons are accumulated in the potential well (2-DEG) and the holes move towards the surface and it is also attracted to the negatively charged quantum dots. These excess carriers generated are calculated by solving the ac continuity equations for electrons and holes.

The ac continuity equations for excess electrons and holes generated in the neutral and depletion regions of the device are

$$\frac{\partial n(x,t)}{\partial t} = \frac{1}{q}\frac{\partial J_n(x,t)}{\partial x} + G_n(x,t) - U_n(x,t) \qquad (1)$$

for electrons and

$$\frac{\partial p(x,t)}{\partial t} = -\frac{1}{q}\frac{\partial J_p(x)}{\partial x} + G_p - \left[U_p(x,t) + \frac{R_s(x,t)}{a}\right] \qquad (2)$$

for holes

where $J_n(x,t)$ and $J_p(x,t)$ are the electron and hole current densities and are represented by

$$J_n(x,t) = qv_x n(x,t) + qD_n\frac{\partial n(x,t)}{\partial x} \qquad (3)$$

and

$$J_p(x,t) = qv_x p(x,t) - qD_p\frac{\partial p(x,t)}{\partial x} \qquad (4)$$

In the above equation, G_n and G_p are the volume generation rates and $U_n(x,t) = \frac{n(x,t)}{2_n}$ and $U_p(x,t) = \frac{p(x,t)}{2_p}$ are the recombination rates, D_n and D_p are the diffusion coefficients and n(x,t) and p(x,t) are the electron and hole concentrations, v_x is the carrier saturated velocity along vertical x-direction, assumed the same for both electrons and holes.

The radiation flux density is assumed to be modulated by the signal frequency, under small signal conditions

$$n(x,t) = n_0 + n_1 e^{j\mu_s t} \qquad (5)$$

$$G(x,t) = (¤_0 + ¤_1 e^{j\mu_s t})\sim e^{-\sim a(x+d)} \qquad (6)$$

where subscript zero(0) indicates dc values and subscript one(1) indicates ac value of the flux density of optical illumination per unit time, ω_s is the angular frequency of the modulated signal and α is the absorption coefficient per unit length.

Partial depletion of the device is considered, so that the analysis is valid even at low temperature. The transport of the excess carriers in the neutral region is due to the process of diffusion and recombination and that in the depletion regions is due to drift and recombination. The recombination takes place at both bulk and the surface. The ac continuity equations are solved for photogenerated electrons in the depletion region and in the neutral region.

The velocity field relation for electrons is assumed in the form [12]

$$v(x) = v_s(1 - e^{(-«E/v_s)}) \qquad (7)$$

where µ is the low field mobility, v_s is the saturated velocity and E is the field. The velocity tends to saturate at high electric field.

3 CURRENT VOLTAGE CHARACTERISTICS

To obtain the I_{DS}-V_G relation, we need to determine the relation between 2-DEG electron concentration n_s and the gate voltage v_G. Considering the partial depletion of the AlGaAs layer, the Poissons equation is represented as

$$\frac{\partial^2 \cdot}{dx^2} = -\frac{q}{£}(N_D^+ + N_A^+ - n_1(x,\mu_s)) \qquad (8)$$

where $n_{1t}(x,\mu_s)$ is the number of excess electrons due to photogeneration , N_D^+ is the impurity concentration , N_A^+ is the ionised acceptor density. The effect of holes is neglected ,since the mobility of holes is very less when compared to the mobility of electrons. Also, the degenerate statistics is applied for the concentration [13], because the doping concentration is high in a QD Transistor . Thus

$$N_D^+ = \frac{N_D}{1 + 2\exp\left\{\frac{E_F - E_D}{kT}\right\}} \qquad (9)$$

and

$$n = \frac{N_C \exp\left\{\frac{E_C - E_D}{kT}\right\}}{1 + 0.27\exp\left\{\frac{E_C - E_F}{kT}\right\}} \qquad (10)$$

where N_D is the doped layer concentration and N_c is the density of state function at the conduction band. Equation (12) is an approximation to Fermi-Dirac integral[13].E_F,E_C and E_D are the Fermi, minimum of conduction band and donor energy levels, respectively. Let us substitute $E_C = E_{C0} - q\cdot$ and $E_D = E_{D0} - q\cdot$ where subscript zero refers to the case when there is no heterojunction .When gate is in contact with the semiconductor, the Fermi energy is written as $E_{F1} = E_{F0} + qV_G$ where E_{F0} =0 is taken as the reference energy.

By using the transformation

$$\frac{\partial^2 \cdot}{dx^2} = \frac{\partial}{d\cdot}\left(\frac{\partial \cdot}{dx}\right)\frac{\partial \cdot}{dx} \qquad (11)$$

the electric field $E^2(-d)$ at the gate semiconductor interface is Calculated.

Then the total charge in 2-D gas is obtained as

$$Q_T = \pounds E(-d) \qquad (12)$$

The total charge includes charge due to surface ,bulk and the charge due to photo generation.The current voltage characteristics is obtained using the relation

$$I_D = Q_T Z v(y) \qquad (13)$$

where Z is the gate width and $v(y)$ is the velocity of electrons at any point y. By considering the realistic velocity field relation $v(y) = v_s(1 - e^{(-«E/v_s)})$,where $E = -\frac{dV}{dy}$,equation(19) covers both low field and high field region. Integrating from y=0 to y=L ,'L' being the gate length, yields

$$\int_{V(0)}^{V(L)} \frac{dV}{\ln\left(1 - \frac{I_D}{Q_T Z v_S}\right)} = -\frac{v_S}{«} L \qquad (14)$$

$V(0) = I_D R_S'$ and $V(L) = V_D - I_D R_D$, R_S' and R_D being the source and drain parasitic resistances.Thus

$$V_D = I_D\left(R_D + R_S'\right) - \frac{v_S L}{«}\ln\left(1 - \frac{I_D}{Q_T Z v_S}\right) \qquad (15)$$

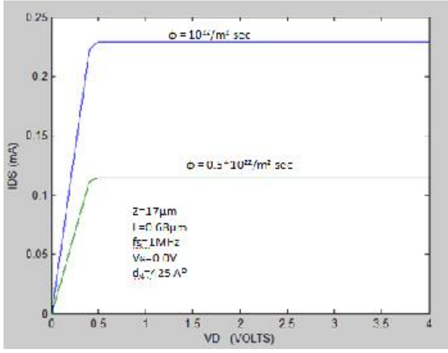
equation (23) represents the current–voltage (I-V) relation for the QD Transistor under optically illuminated condition.

5 RESULTS AND DISCUSSION

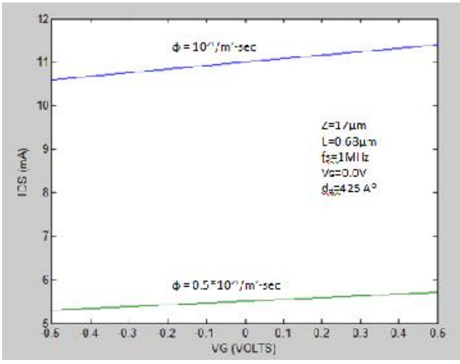
Numerical calculations have been carried out for a QD Transistor, considering the effect of signal modulated optical radiation. We have considered the gate width as Z=17μm. The dimensions and other basic parameters used in the calculation are given in Table-I. Fig(2) shows the I-V characteristics of QD Transistor calculated for both saturation and non saturation region at a particular signal modulated frequency and at different radiation flux density. We have significant increase in the current with a higher pinch off as radiation flux density increases.

TABLE 1.PARAMETERS USED FOR THE CALCULATION.

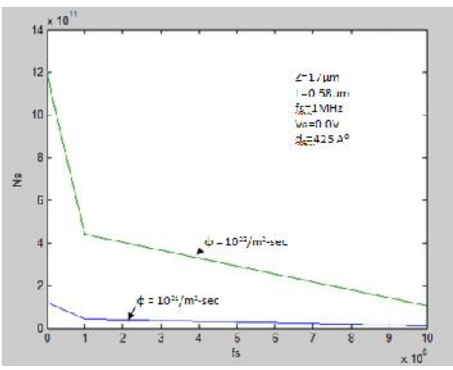
Symbol	Name	Value
Z		17μm
L	Gate Width	0.68μm
Vs	Gate Length	2×10^7cm/s
h	Saturation velocity	6.6×10^{-34}
q	Plancks Constant	1.6×10^{-19}
ϵ_1	Electron charge	13.2 ϵ_0
ϵ_2	Permittivity of GaAs	12.1ϵ_0
ϵ_0	Permittivity of AlGaAs	8.854×10^{-12}
μ	Permittivity of Vaccum	F/m
	Low field mobility	6800cm^2/vs



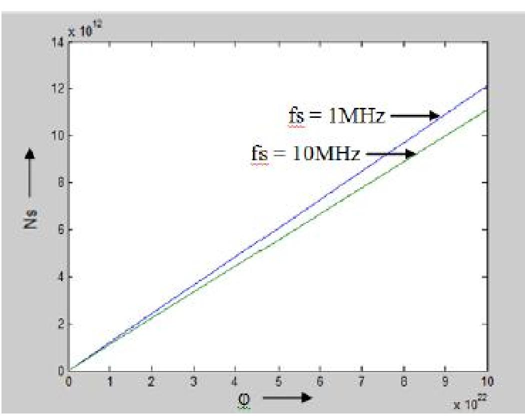
Fig(2). I-V characteristics at a particular signal frequency and at different radiation flux densities



Fig(3).Transfer characteristics at different radiation flux densities under illumination



Fig(4).Sheet concentration versus signal frequency at different radiation flux density and at a fixed gate voltage under illumination



Fig(5).Sheet concentration versus radiation flux density at different signal frequency

Fig(3) shows the transfer characteristics of the device under illumination. Fig(4) shows the plot of sheet concentration versus radiation frequency at constant radiation flux density..The sheet concentration decreases with signal frequency first slowly up to 10MHz and then rapidly up to 1GHz. Fig(5) shows the plot of sheet concentration versus radiation flux density at different signal frequency and at a gate voltage of V_G=0V. It shows that sheet concentration increases as we go on increasing the radiation intensity. These graphs show the sensitivity of the device to radiation and also the amplifying and switching capability of the device with respect to incident optical power density.

6 CONCLUSION

The effect of signal modulated optical illumination on the characteristics of QD Transistor with partial depletion of the active layer has been carried out. The sheet concentration of 2-DEG ,I-V characteristics and transfer characteristics have been calculated as a function of signal modulated frequency of incident radiation and plotted and discussed. The effect of illumination on the presence of QDs lead to improved absorption and increases in the drain current considerably. The I-V characteristics shows a better sensitivity , amplifying and switching capability of the device with respect to incident optical power density.

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