Simulation of Device Behavior for InAlAs/InGaAs HEMT under Optical Illumination

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Abstract—**This paper presents simulation of optical effects on the DC parameters of 100 nm single gate InAlAs/InGaAs High Electron Mobility Transistor (HEMT). The advantage of this model is that it provides us the flexibility to study the effects of optical illumination on the device parameters by specifying a user defined photo-generation rate as a constant or as a function of position in the device. The current–voltage characteristics of the device under dark and illuminated conditions have been simulated using luminous module (Silvaco Device Simulator) and recalling C-Interpreter function F.RADIATE to specify a constant photo generation rate. Significant increase in the drain to source current has been observed, suggesting future possible applications as optoelectronic device.**

Keywords- Heterostructure; HEMT; Optical-illumination; Photo-generation; Simulation.

I. INTRODUCTION

The concept of Internet of things (IOT) promises to connect anything with everything. The vision of IOT emphasizes on connecting physical things with the real world. This certainly requires a new revolution in the field of wireless and optical communication technology which further imposes the need for modern devices with ability to operate at higher frequencies and with reduced noise. With the advancements in the fabrication techniques, Compound semiconductor based heterostructure devices are replacing the conventional devices to operate at higher frequencies and low noise. Among various such devices, HEMT has emerged as a potential device to be able to operate effectively at higher frequencies and low noise.

HEMT, demonstrated in 1980 [1], exploits the superior carrier transport properties of modulation doped heterojunction. HEMT is now a well established technology and we can find its wide application in micro and millimeter wave frequency range [2]-[4]. HEMT technology has already reached a level where we have reduced the device dimensions to improve its performance in terms of noise and speed. Further reduction in gate length is limited by the short channel effects. HEMTs with a current–gain cut-off frequency of 562 GHz and with maximum frequency of oscillation of 330 GHz have been reported for 25 nm gate length [5]. In order to improve the further performance of the device, optical illumination seems to be a potential technique.

The material used for the fabrication of HEMT has evolved from the first generation lattice matched AlGaAs/GaAs HEMTs to AlGaAs/InGaAs/GaAs psuedomorphic HEMTs (pHEMTs). AlGaAs/InGaAs/GaAs pHEMTs suffer from dislocations due to high lattice constant mismatch between InGaAs and GaAs substrate. InAlAs and InGaAs lattice matched to InP substrate have emerged as suitable high band gap and low band gap materials respectively for HEMT structures. Compared to GaAs the InGaAs channel has higher mobility. Further, InAlAs does not suffer from the problem of Deep Levels (DX centers) as AlGaAs does [6]. Also the higher conduction band offset in InAlAs/InGaAs HEMT results in higher 2-DEG density as compared to AlGaAs/GaAs HEMT.

The study of the performance of high speed microwave semiconductor devices under optical illumination is an area of growing interest due to their potential application in fiber-optical communication and optical integration [7]. In context of optical applications, HEMT is emerging as an important optoelectronic device for high speed photo-detection, amplifier gain control, frequency tuning oscillators, and in phase shifters [8]-[15].

In the recent past, several authors carried out the simulation of optically illuminated MOSFETs and MODFETS [16][17]. Fallahnejad et.al [18] simulated the noise characteristics of AlGaN/GaN HEMT on SIC substrate for low noise applications using silvaco device simulator. None of these authors have used C –Interpreter function to specify the photo-generation rate. This paper simulates the effect of optical illumination on the performance of 100 nm InAlAs/InGaAs single gate HEMT using Atlas device simulator where C-Interpreter function F.RADIATE has been used.

The device structure and the simulation model for optical illumination are described in Section II. The simulation results thus obtained are reported and discussed in Section III. Finally the conclusion is presented in Section IV.

II. DEVICE STRUCTURE AND MODEL

The schematic of the 100 nm InAlAs/InGaAs SG HEMT is presented in Fig. 1, with dimensions tabulated in Table I. The structure is fabricated and reported by Wichmann [19].

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The gate is illuminated by a laser source in a perpendicular direction. ATLAS device simulator has been used to simulate the device behavior. ATLAS simulator uses luminous module, a general purpose light propagation and absorption program integrated into the atlas framework for optical illumination. This module includes various physical models for light propagation. Ray tracing model has been used here, which is a general method for light propagation in 2D and 3D non-planar geometries and completely ignores coherence and diffraction effects.

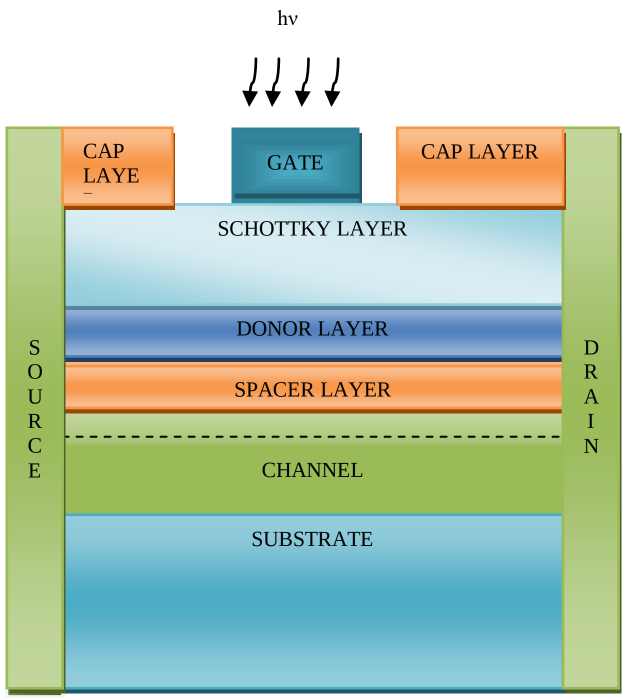

Figure 1. Simulated structure of InAlAs/InGaAs HEMT under illumination.

TABLE I. DEVICE DIMENSIONS

Layer	Dimension	Doping Concentration
Schottky(InAlAs)	12 nm	nid
Donor (InAlAs)	5 nm	10^{25} per m^3
Spacer(InAlAs)	5 nm	nid
Channel(InGaAs)	20 nm	nid
Buffer (InAlAs)	200 nm	nid

The device is physically modeled by using Shockley-Read-Hall (SRH), Concentration dependent mobility (CONMOB) and parallel electric field dependence mobility (FLDMOB) models. The SRH is a recombination mode that uses fixed minority carrier lifetimes. CONMOB uses simple power law temperature dependent mobility and FLDMOB is required to model any type of velocity saturation effect. Gummel Newton Iteration scheme has been used to obtain the numerical solution. Drift diffusion model is employed to evaluate potential, electron and hole concentration with appropriate assumptions and hence, calculate the drain to source current [20].

Ray tracing uses the real part of the refractive index to calculate the optical intensity at each grid point and imaginary part to calculate the carrier concentration due to photo generation at each grid point. Ray tracing models the source current due to photo generation as [20]:

$$I_s = \frac{qB_n \lambda W_t}{hc} \qquad (1)$$

q is the electronic charge. B_n is the intensity of the beam number n defined in the SOLVE statement. λ is the source wavelength specified by the wavelength parameter in the BEAM statement which is used to model the effect of optical illumination on the device behavior. h is the Planck 's constant. c is the speed of light in vacuum. W_t is the width of the incident beam.

The source current available to the device including the losses due to reflection and transmission is modeled as available photo-current:

$$I_A = \frac{qB_n \lambda}{hc} \sum_{i=1}^{N_r} W_R \int_0^{y_i} P_i \alpha_i e^{-\alpha y} dy \qquad (2)$$

q is the electronic charge, B_n is the intensity of the beam number n, λ is the wavelength of the incident radiation specified in the BEAM statement, h is the Planck's constant and c is the speed of light, W_R is the width associated with the ray. P_i accounts for the attenuation the incident ray suffers due to non unity transmission coefficients and absorption. y is the distance traced by the ray in the device. The limits of integration extend from the origin of the ray to the depth that the ray traces in the device. α_i is the absorption coefficient in the material that the ray is traversing which depends on the imaginary part of the optical index of refraction of the material and is given as:

$$\alpha_i = \frac{4\pi k}{\lambda} \qquad (3)$$

k is the imaginary part of the optical refractive index.

Photo-generation rate accounts for the number of electron hole pairs generated in the channel due to illumination. C-interpreter function F.RADIATE is used to specify a constant photo-generation rate. BEAM statement is used to specify the C-interpreter function using F.RADIATE [20] parameter in the input deck. It calls the radiate function that defines a constant photo-generation rate of 10^{25} carriers per cubic centimeter. Optical Source and available currents thus produced are calculated using equations (1) and (2). The photo-generated carrier increases the overall drain to source current of the device.

Maximum optical efficiency of the device is obtained by assuming the gate metal and the subsequent layers of the device to be transparent. In such case the optical source current is equal to the available photo-current.

III. RESULTS AND DISCUSSION

Device behavior of 100 nm InAlAs/InGaAs SG HEMT has been investigated under optical exposure and dark condition. Optical Source current and available photo current in the channel are evaluated for a constant photo-generation rate specified using F.RADIATE C-interpreter function in the luminous module of Atlas 2-D device simulator.

Fig. 2 presents the simulated drain to source current (I_D-V_{DS}) characteristics under dark and illuminated conditions at a constant photo generation rate of 10^{25}per cubic centimeters. For low values of drain to source bias, current proportional to drain to source bias flows from drain to source along the electron gas channel. As the drain to source bias is increased, the electron velocity and the channel current saturate.

As the device is exposed to optical illumination, the drain to source current increases. This is because the photo-generated carriers produce a source photo-current. Under the assumptions made, the source current is equal to the available photo-current. This available photo-generated current is added to the dark drain to source current and hence, increases the overall drain to source current of the device under optical illumination.

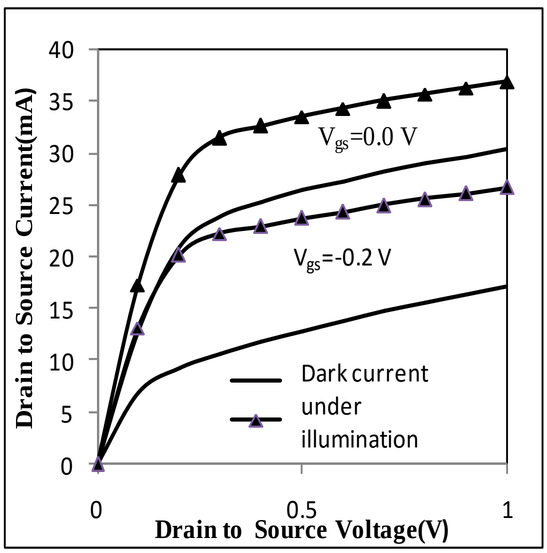

Figure 2. Variation of drain to source current with drain to source voltage under illumination and dark condition for a 100 nm InAlAs/InGaAs HEMT (λ=0.623 um and P_{op}=10 Watt/cm^2).

Fig. 3 shows the variation of drain to source current (I_{ds}) with gate to source voltage (V_{gs}) under dark and exposure conditions. Under exposure the threshold voltage of the InAlAs/InGaAs HEMT shifts turning the device on at a lower gate to source voltage. This suggests an increase in the transconductance of the device and hence the frequency of operation.

Fig. 4 depicts the drain (I_D-V_{DS}) characteristics of the device for varying optical power density. With increasing optical power density the available photo-current in the channel increases thus, increasing the drain to source current.

Table II represents the simulated source current (Eqn.1) generated at varying optical power density. It shows that as we increase the optical power density, the optical source current increases.

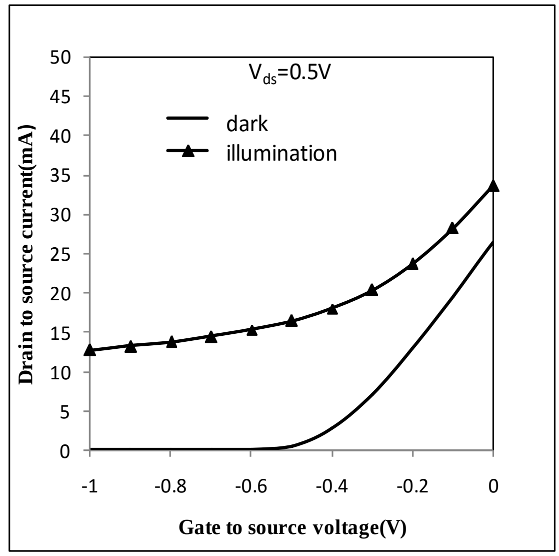

Figure 3. Variation of drain current with gate to source voltage under illumination and dark condition for a 100 nm InAlAs/InGaAs HEMT. (λ=0.623 um and P_{op}=10 Watt/cm^2).

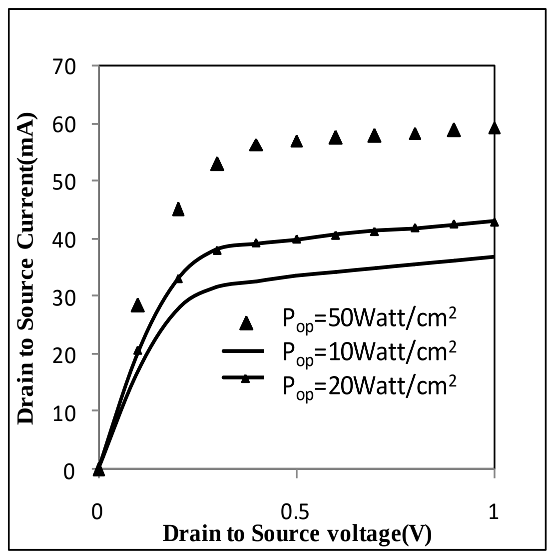

Figure 4. Variation of drain to source current with drain to source voltage for different optical power density for 100 nm InAlAs/InGaAs HEMT.

TABLE II. SOURCE CURRENT AT DIFFERENT OPTICAL POWER DENSITY

Optical Power Density (Watt/cm^2)	10	20	50
Optical Source current(mA)	0.415	0.830	2.075

IV. CONCLUSION

I-V characteristics of InAlAs/InGaAs HEMT under illumination has been studied using luminous module in

Atlas device simulator. Under exposure, the drain to source current is found to increase maximum by 7.6 mA for gate to source voltage ($V_{gs}=0$ V) and drain to source voltage ($V_{ds}=0.3$ V) at an optical power density of 10 Watt/cm^2. A significant shift in the threshold voltage is observed. At a voltage corresponding to the dark threshold voltage (-0.6 V) the device offers a higher drain current of 15.3 mA under illumination. Thus, optical illumination is seen to enhance the performance of the device. The simulation technique used gives us freedom to utilize any source. This would be helpful in studying both photovoltaic and photoconductive effects. This model provides us the flexibility to study the effects of optical illumination on the device parameters by specifying a user defined photo-generation rate. The accuracy of the model can be further improved by incorporating losses due to reflections at the interface. The photo-generation rate defined in the model is taken as a constant by the user. This work can be further extended by defining the photo-generation rate as a function of position in the device.

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