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Simulating Optical Behavior of Nano Dimensional InAlAs/InGaAs HEMT for IoT Applications

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Abstract — **Recent interest in the optical behavior of bulk semiconductor based alloy heterostructures [1-3] has led to this work that simulates the effect of optical illumination on the DC parameters of 100 nm InAlAs/InGaAs High Electron Mobility Transistor (HEMT). This paper uses a C-interpreter function in the Silvaco Device Simulator that gives the flexibility of defining the photogeneration rate as a position/time dependent function. The modeling of photogeneration rate as a function of position in the device helps us to analyze the effect of illumination in the different regions of the device and its impact on the device parameters. The simulation results suggest an improvement in the device performance under illumination predicting possible applications in high frequency optoelectronics.**

Keywords - Photogeneration, HEMT, interpreter, simulation, optical illumination.

I. Introduction

Internet of things which is emerging as the technology of future involves multiple technologies, including wireless communication, real-time analysis, detectors/sensors, robotics and embedded technology. These systems are hugely based on micro-electronic devices which are able to operate at very high frequency and high speed with minimum transmission noise. There has been a continuous progress in the field of micro-electronic devices to meet these requirements. Among these device systems, HEMT that offers very high carrier mobility has evolved as one such device [4].The data speed, latency requirements and always-on connectivity requirement of IOT can be met by InAlAs/InGaAs HEMT quite well.

The concept of HEMT was first proposed in the year 1980 by *Mimura et.al.* at Fujitsu labs[5]. The first HEMT device was commercialized in the year 1983 [6], Fujitsu demonstrated a four stage 20 GHz HEMT amplifier which was used by Nobeyama Radio Observatory in Nagano, Japan as a Low noise amplifier (LNA) in a 45m radio telescope [7].

HEMT finds its wide application in wireless communication systems, satellite systems, optical communication systems and military applications [8-11]. HEMT based biosensors have been developed using AlGaN/GaN HEMT for detection of C-reactive protein and uric acid [12, 13]. 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 [14]. 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 [15-21].

In the recent past, many researchers have shown interest in analysis and simulation of optically illuminated MOSFETs and MODFET's [1-3, 22]. None have offered flexibility to the user that the proposed C–Interpreter function does 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.

II. Device Model and Structure

High mobility (8000-12000 cm^2/V-s), large conduction band discontinuity (0.52 eV at 300 K) and high saturation velocity ($2.6*10^7$ cm/s) in InAlAs/InGaAs HEMT leads to higher sheet carrier concentration in the 2DEG and hence, higher current density and transconductance improving the overall device performance in terms of frequency and noise [23-24]. There has been a continuous demand for always-on devices that can operate at higher frequencies and better performance in terms of noise. Reducing the device length has resulted in improved device performance. Cutoff frequency of 562 GHz and a maximum oscillation frequency of 330 GHz have been obtained for InAlAs/InGaAs/InP at a gate length of 25 nm [25]. Further reduction in the gate length of the device is limited by the various short channel effects. There are several other ways in which the device performance can be improved. Optical illumination seems to be one such tool, where we illuminate

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the device by an optical source and increase the concentration of the mobile charge carriers.

The device under consideration is 100 nm InAlAs/InGaAs/InP HEMT fabricated by *Whichmann* [26] presented in Figure 1. The device has a cutoff frequency of about 400 GHz obtained from Monte Carlo simulations. The device is optically illuminated using an optical laser source in a direction transverse to the interface. The behavior of the device under such condition is analyzed by using ATLAS Device Simulator.

Atlas is a 2D-3D device simulator that simulates the DC, AC and transient behavior for electrical, thermal and optical performance of semiconductor devices. It characterizes the physics behind any semiconductor device by solving a set of fundamental equations: Poisson's equation, Carrier continuity equations and Transport equations [26].

The device is divided into five regions in the simulation program and the properties of each region such as doping, semiconductor material used are specified by using a set of statements in the input deck. Drift diffusion model is employed to determine the carrier statistics and the device modeling uses (a) fixed minority carrier lifetime (Shockley-Read-Hall/SRH) (b) temperature dependent mobility (Concentration dependent mobility/CONMOB) and (c) field dependence mobility for modeling the velocity saturation [27]. Numerical solution employing all these models has been carried out using Gummel Newton Iteration scheme to obtain the potential, carrier concentration and drain to source current. To account for the behavior of the device under optical illumination, Atlas uses the inbuilt luminous module.

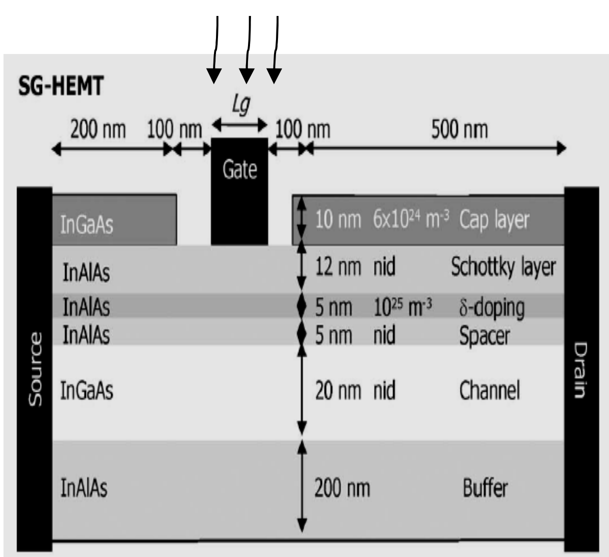

Figure 1. InAlAs/InGaAs/InP HEMT under optical illumination

Luminous is a 2D or 3D module in the Atlas framework to incorporate optoelectronic effects in the device simulation. Luminous calculates the photo generation rates by profiling the optical energy within the semiconductor device, which is finally used to simulate the optoelectronic effects in the devices.

In this work, the optical behavior of the device is analyzed using User defined arbitrary photo generation. It uses a C-INTERPRETER function written by the user in the text file. The Atlas program uses the F.RADIATE parameter to seek the photo generation rate from the C-INTERPRETER function. The F.RADIATE parameter is defined using the BEAM statement in the input deck of the Atlas Device Simulator.

The C-INTERPRETER function is defined in the text file and it should have the same path as the input deck file [27]. The photogeneration rate can be approximated to be a constant or considered to be position dependent in the device which appears to be more appropriate. This paper simulates the optical performance of the device under consideration using the later approach i.e., a position dependent photogeneration approach.

The equation for the position dependent photo generation rate is expressed as [27]

$$G = \frac{P\lambda}{(y+b)hc}(1 - e^{-\alpha(y+b)}) \tag{1}$$

where, G is the electron hole pair generation rate, P is the optical beam density specified in the solve statement, λ is the optical wavelength, α is the absorption coefficient of the material, b is the vertical coordinate of the beam origin defined in the beam statement and y denotes the vertical depth in the device.

Using equation 1, the photo generation rate is evaluated at each node in the device. This photo generation rate is incorporated into the continuity equation as [27]

$$\frac{\partial n}{\partial t} = \frac{1}{q}\Delta J_n + G_n - R_n \tag{2}$$

where, n is the electron concentration, J_n is the electron current density, G_n and R_n are the electron generation and recombination rates respectively. Similar equation holds for the holes. This continuity equation is used in the drift diffusion model to evaluate the device drain to source current [27]. The complete process is summarized in the flow chart in Figure 2.

III. RESULTS AND DISCUSSION

Using equation 1 and Table I, photogeneration rate is evaluated at each node in the device. This generation rate is used in the continuity equation to calculate the device drain to source current under optical illumination. Figure 3, represents the drain current variation gate voltage at a constant drain to source voltage under dark and optical illumination using position dependent photo generation rate. As observed threshold voltage is reduced under optical illumination as compared to dark conditions. The drain current variation with drain voltage for different gate voltages is plotted in Figure 4.

TABLE I. PARAMETERS FOR GENERATION RATE

Parameters	Value
Optical Source wavelength (λ)	623 nm
Incident optical power density (P)	10 Watt/cm^2
Planck's constant (h)	$6.634*10^{-34}$ m^2 kg s^{-1}
Velocity of wave (c)	$3*10^8$ m/s
Absorption coefficient (α)	10^6 /m

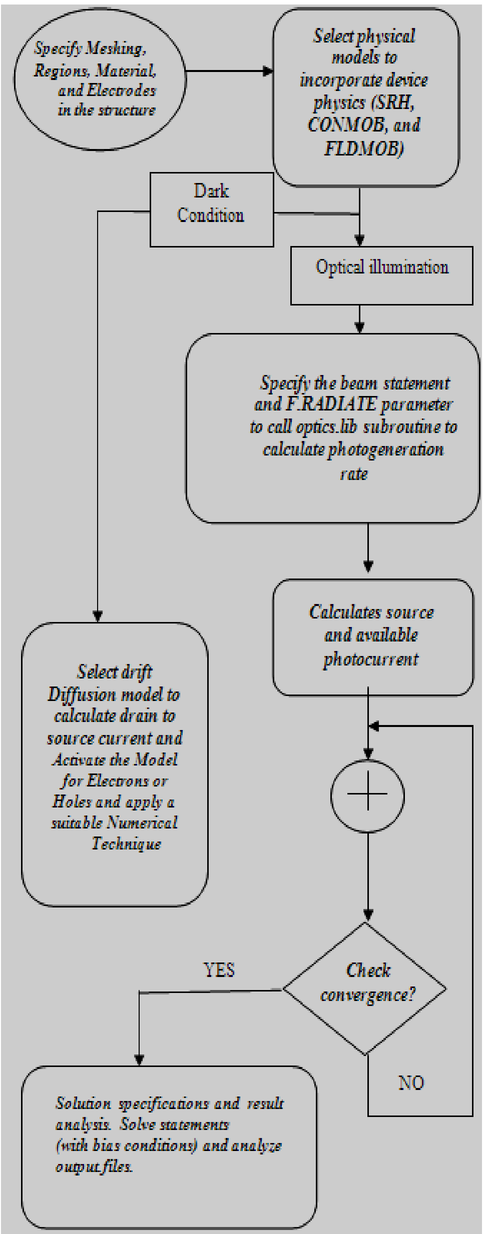

Figure 2. Flow chart for simulation of InAlAs/InGaAs/InP HEMT under optical illumination.

Increasing the gate to source voltage, results in greater drain to source current magnitude. At a constant gate to source voltage, the drain to source current varies linearly for smaller values of drain to source bias. As the drain to source bias increases, the drain to source current saturates.

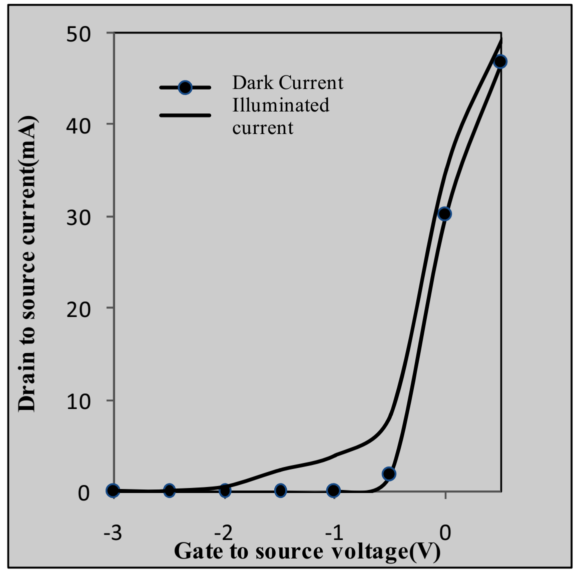

Figure 3. Drain current variation with gate voltage under illumination and dark condition for a 100 nm InAlAs/InGaAs HEMT at V_{ds}=0.5 V (λ=0.623µm and Pop=10 Watt/cm^2).

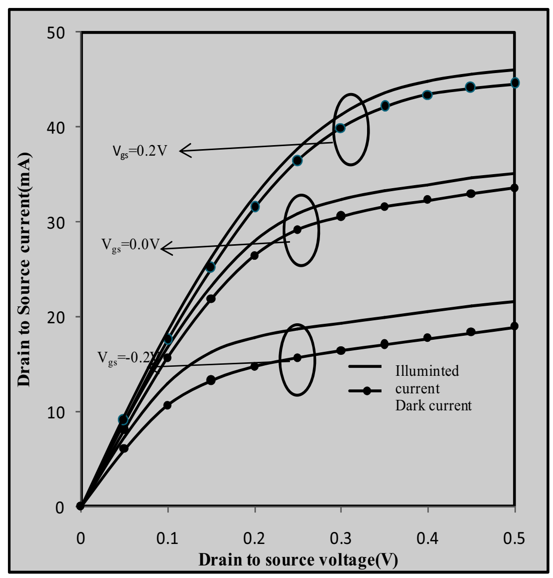

Figure 4. Drain current variation with drain voltage under illumination and dark condition for a 100 nm InAlAs/InGaAs HEMT (λ=0.623 µm and Pop=10Watt/cm^2.

This is because, the device attains pinch off condition where the drain depletion width pinches off with the channel width. This is because, the device attains pinch off condition where the drain depletion width pinches off with the channel width. Further, under illumination the drain to source current is higher as compared to dark suggesting improvement in the device performance. Thus, optical illumination is a useful tool to improve the current ratings of the device.

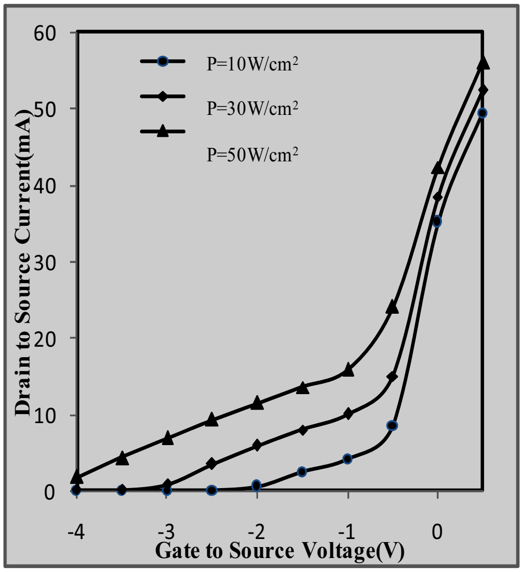

Figure 5. Drain current versus gate voltage for a 100 nm InAlAs/InGaAs HEMT. (λ=0.623 μm) at different optical power density.

With increase in the optical power density the threshold voltage of the device reduced or the device is turned on at a lower gate to source voltage as shown in Figure 5. This is because, when we increase the optical power density the number of electron hole pair generated in the device increases.

IV. Conclusion

Optoelectronic effects are simulated in 100 nm InAlAs/InGaAs using the Atlas Device Simulator. Under illumination, analysis is carried out using user defined C-INTERPRETER function. The C-INTERPRETER function gives the flexibility to define a constant photo generation rate or a position dependent photo generation rate. In this paper, the position dependent approach is investigated which provides extra ability to control the generation rate as a function of depth in the device, the beam density and the wavelength of the optical signal used.

The threshold voltage is attained at gate to source voltage (V_{gs}=-2V) compared to dark threshold (V_{gs}=-0.6V). The threshold voltage can be further reduced by increasing the incident optical power density and wavelength of optical source. The simulation technique used, gives us freedom to utilize any optical source for optical illumination. This would be helpful in studying the possible use of this device in always–on connectivity for IOT applications. Since, under the effect of optical illumination the drain to source current is higher and the threshold voltage is significantly reduced the device can be used in high frequency, wireless connections in IOT applications. 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.

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