



International Journal of Emerging Technologies in Computational and Applied Sciences (IJETCAS)

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Simulation and Optimization of δ -doped AlInAs/InGaAs HEMT for High Frequency Applications

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Abstract: In this paper efforts have been made to simulate and optimize the performance of delta (δ) doped $0.5\ \mu\text{m}$ gate length InP based $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ high electron mobility transistor with the help of some parameters as δ -doping, spacer layer thickness, schottky layer thickness and gate length variation. We perform characterization studies on high density two-dimensional electron gas (2DEG), conduction band discontinuity (ΔE_c), threshold voltage (V_{th}), transconductance (g_m), cut-off frequency (f_T), confined in lattice-matched InP based δ -doped $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ quantum wells HEMT grown by molecular beam epitaxy (MBE) on InP substrate. The impact of parameters variation on the conduction band discontinuity, high density 2DEG and optimization of the performance of HEMT has been analysed. These values then utilize to optimize figure of merit such as transconductance and cut-off frequency of device.

Keywords: High Electron Mobility Transistor (HEMT); 2DEG; InAlAs/InGaAs Hetrostructure; Delta Doping; Spacer Layer

I. Introduction

High electron mobility transistor (HEMT) technology is widely used for high frequency application [1] due to enhanced electron mobility and velocity at high electron density in a device channel. This provide high value of device current I_D , transconductance g_m , cutoff frequency f_T , output gain and low value of noise [2]. Main tendencies of evaluation of this technology corresponds to investigation of heterostrutures with higher value of conduction band offset ΔE_c and, respectively, higher two dimensional electron gas (2DEG).

Ultrafast III-V (InAlAs/InGaAs/GaAs) modulation doped field effect transistor (MODFET) technology are used in high-speed monolithic microwave integrated circuits (MMIC) [3]. InAlAs/InGaAs high electron mobility transistors (HEMTs) play a key role in communication and many type of equipments ranging from cell phones to electronic warfare systems such as radar and radio astronomy [4]. Many technologies are now based on InGaAs/InAlAs quantum well [5]. These applications are subjected to higher transport properties of InGaAs and large sheet carrier density in 2DEG quantum well which is formed near heterointerface. Recently much attention has been paid to “delta” doping, also called planar or sheet doping, because this doping technique can provide high-density 2DEG systems in compound semiconductors. It is expected that field-effect transistors (FET’s) fabricated from δ doped materials will have high drain current capability, large breakdown voltage, easy control of the threshold voltage V_{th} , and high intrinsic transconductance g_m due to small distance between the electron channel and the gate, compared with conventional FET’s and HEMT without delta doping. These advantages will strongly influence the performances of short channel devices for gate lengths [6] in enhancing the performance of device by optimizing the tranconductance and cut-off frequency.

The remainder of this paper is organized as follows: A two dimensional (2D) model of HEMT has been designed in Section II. Model is formulated with δ -doping in Section III. In Section IV, characterization of HEMT model has been performed with simulation of conduction band and 2DEG across channel. In section V, optimization of performance of lattice matched δ doped $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ quantum well HEMT grown by MBE on an InP substrate (here and after in our paper we use abbreviations InGaAs for $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ and InAlAs for $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$) is performed using spacer layer thicknes (d_s), δ -doping (N_D), schottky layer thickness (d_i) and Gate length (L_g) variations. Investigation is done with study of conduction band bending and electronics properties of 2DEG across channel after changing the value of parameters of HEMT model. The simulations are performed using the heterojunction device simulator Nextnano³ and ATLAS. Finally conclusion are drawn in Section VI.

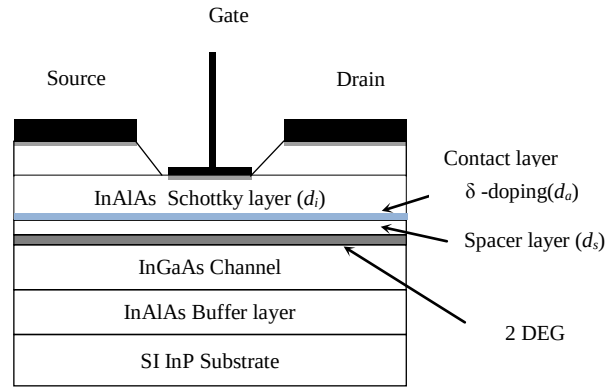
II. Device Structure

The InAlAs/InGaAs HEMT 2D model is shown in Fig. 1. Such structure can be grown by molecular beam epitaxy (MBE) or less commonly by metal organic chemical vapor deposition (MOCVD) and chemical beam epitaxy (CBE) on semi insulating InP material [7].

The undoped InAlAs buffer layer is employed to improve carrier confinement in the channel and create a low leakage isolation floor. The most important point about the InGaAs channel layer in the HEMT devices is the 2DEG that results from the band-gap difference between InGaAs and InAlAs. A potential barrier then confines the electrons to a thin sheet of charge known as the 2DEG. In contrast to the MESFET, which has a doped channel and consequently lots of ionized donors, the 2DEG has significantly less Coulomb scattering, resulting in a very high mobility device structure.

The remainder of the HEMT structure contains an InAlAs spacer layer (d_s). The doping in InAlAs can be modulation doped thin layer or Si-delta doping. It serves as the source of electrons. We introduce a δ -doping layer (d_a) which is very thin of the order of 3 Å with very high doping as $8 \times 10^{18} / \text{cm}^3$, supply all the electrons for 2DEG. This type of structure is called δ -doped or Planar doped or Pulse doped HEMT. A Schottky layer (d_i) is introduced which is undoped. InGaAs contact layer enhance the contact performance below electrodes.

Fig. 1. InP based HEMT model



III. Theoretical Consideration

This model extended to predict the device behaviour of HEMT. The basic structure of an InAlAs/InGaAs HEMT used in the analysis is a δ -doped structure, as shown in Fig. 1. Threshold voltage is also called as off voltage (V_{off}) [4]. This voltage is defined as voltage required to turn off the HEMT device. It is equivalent to the threshold voltage (V_{th}) for depletion mode MOSFET. Model used in the analysis is a δ -doped structure, in which d_s , d_a and d_i are the thicknesses of spacer layer, doped layer and Schottky layer respectively. The threshold voltage of δ -doped structure depends on d_a and d_i and is given by:

$$V_{off} = V_{th} = \phi_b - \Delta E_C - \left(\frac{qN_D d_a^2}{2\epsilon} \right) \left(1 + \frac{2d_i}{d_a} \right) \quad (1)$$

Here ϕ_b is schottky barrier height of InAlAs ($\phi_b \approx 0.7V$), ΔE_C is conduction band offset, q is electron static charge, N_D is δ -doping, ϵ is dielectric constant. 2DEG carrier density n_s play a important role in HEMT structure. According to the linear charge control model the charge across the channel is linearly dependent on the gate voltage V_{GS} . We assume that full InAlAs is depleted. The charge across the channel is given by

$$Q_{ch} = C_s (V_{GS} - V_{off})$$

(2)

where $C_s = \epsilon A/d$ and V_{GS} is gate to source voltage of HEMT and d is given by:

$$d = d_i + d_a + d_s \quad (3)$$

So 2DEG carrier density is given by:

$$n_s = \frac{\epsilon}{qd} (V_{GS} - V_{off}) \quad (4)$$

Drain current and transconductance of HEMT is much affected by 2DEG. The value of drain current is obtained as:

$$I_D = \frac{\mu_n C_s W}{2L} (V_{GS} - V_{off})^2 \quad (5)$$

Transconductance can be obtained by differentiating the drain current with respect of gate voltage, is given by:

$$g_m = \frac{\partial I_D}{\partial V_{GS}} = \frac{\mu_n C_s W}{L} (V_{GS} - V_{off}) \quad (6)$$

If C_{gs} is channel gate to source capacitance, corresponding cut off frequency (f_T) can be obtained from the expression

$$f_T = \frac{g_m}{2\pi C_{gs}} \quad (7)$$

IV. Simulations and Discussion

Simulated 2D structure of $0.5\mu\text{m}$ gate length HEMT model using ATLAS tool is shown in Fig. 2. Simulated current-voltage characteristics is shown in Fig. 3. Parameters and details of layers are mentioned in Table-1. Fig. 3(a) shows the variation of drain current I_D with gate voltage V_{GS} . The variation of drain current with drain voltage at different gate voltages is shown in Fig. 3(b).

Conduction band structure of HEMT model (parameters and layers thickness are given in Table 2) which is simulated using nextnano³ is shown in Fig. 4. A notch is formed at 55.3nm (interface in between InAlAs and InGaAs) due to their band gap difference. The band bending in conduction band is shown in Fig 4. Conduction band offset (ΔE_c) is shown which found to be 0.50eV (theoretically it is equal to 0.52eV) represent band bending in this heterostructure device.

The electron density concentration in heterostructure interface of HEMT model is shown in Fig. 5. As we observe that electron density is found to be very high at the interface of wider band gap and narrower band gap material. Here the electron density is very high at distance between 55.3nm to 105.3nm. It represent that electron from the higher band gap layer (InAlAs) are transferred to lower band gap layer (InGaAs) which is called channel layer. This channel layer consist the electron density approximately $1.5 \times 10^{18}/\text{cm}^3$. This confinement of electron is representing the 2DEG (Two Dimensional Electron Gas) across channel.

Table 1. Parameters For 2d Hemt Model Simulation

Parameters	d_i	d_a	d_s	Φ_b	ΔE_c	ϵ_r
Value	30 nm	1 nm	3 nm	0.4eV	0.52eV	13.5

Fig. 2. 2D HEMT model

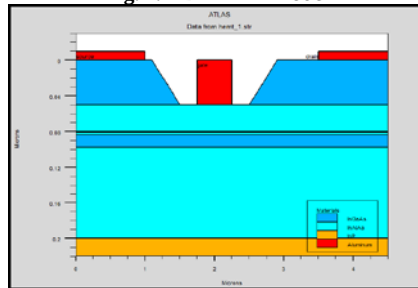


Fig. 3. (a) I_D - V_{GS} characteristics (b) I_D - V_{DS} characteristics of HEMT model

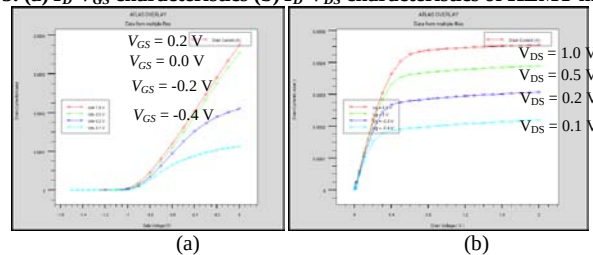


Fig. 4. Simulated Conduction Band Diagram with 2DEG formation and Band bending

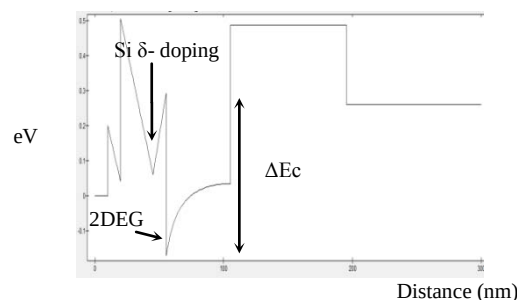
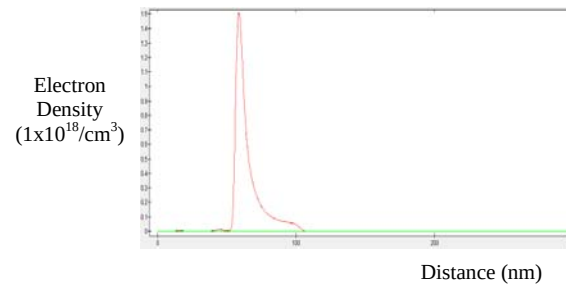


Fig. 5 Simulated plot of Electron Density Vs Distance



V. Optimization

A. Using Spacer Layer Thickness

A thin spacer layer is introduced at the interface of doped InAlAs and undoped InGaAs such that electron in 2DEG channel don't see the effect of dopant in doped InAlAs layer. This layer is undoped and thickness of this layer is affecting 2DEG [8]. Scattering due to dopant is not affecting 2DEG. So spacer layer is physically separating donor from 2DEG and increasing the mobility. The electron density variation of electron density of 2DEG with respect to spacer layer thickness is shown in Fig. 6. We cannot make this spacer layer very thick because less transfer of electron from doped layer to 2DEG.

When we increase spacer layer thickness value of insulating material thickness, d increases. So total C_s is reduced and transconductance g_m is reduced. It decreases performance of HEMT [8]. Therefore spacer thickness should be up to 1nm to 5nm. The effect of spacer layer thickness on threshold voltage of HEMT model (Fig. 2) is shown in Fig. 7. When spacer layer increase threshold voltage become more negative.

Fig. 6. Spacer layer thickness Vs Electron density

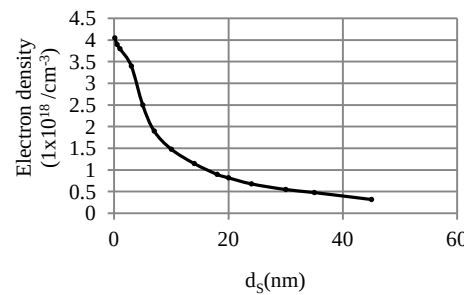
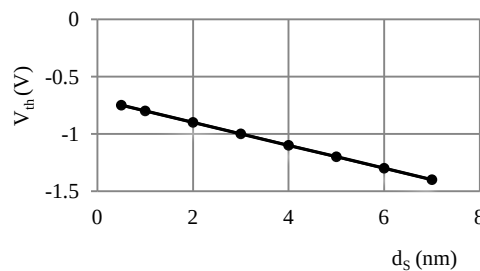


Fig. 7. Variation of threshold voltage with spacer layer thickness(d_s)



B. Using Delta Doping

We know that we can increase the electron concentration in 2DEG by increasing the doping N_D of δ -doped layer [9]. In this model we add at distance = 35 nm, a silicon δ doping of $4.5 \times 10^{12} \text{ cm}^{-2}$ which leads to band bending. The effect of delta doping is shown in Fig. 4 and the corresponding electron concentration is shown in Fig. 5. We take different values of N_D and find corresponding electron densities of 2DEG. These variations are shown in Fig. 8. We also observe that electron density of corresponding 2DEG across channel layer is going to increase very fast initially up to $4.5 \times 10^{12} \text{ cm}^{-2}$ delta doping, after that increase in 2DEG electron density is slower. After observing band structure on corresponding values of delta doping we found that 2DEG well is going to deeper so more electron confinement is there in 2DEG. There is more band bending takes place as δ -doping increase. Fig. 9 shows variation of threshold voltage (V_{th}) with δ -doping (N_D). Here we found that threshold voltage is going to more negative when we are increasing the δ -doping. Fig. 10 shows the variation of transconductance (g_m) with δ -doping (N_D). Transconductance increase as we increase delta doping, because drain current is increasing. We observe that transconductance is very high at high N_D . Variation of cut-off frequency (f_T) with δ -doping (N_D) is shown in Fig. 11. Cut-off frequency is increasing after increasing the δ -doping in δ -doped layer(d_a). In this analysis at δ -doping of $2 \times 10^{19} \text{ cm}^{-3}$, we found current gain cut-off frequency 70 GHz, which is higher than cut-off frequency at lower δ -doping.

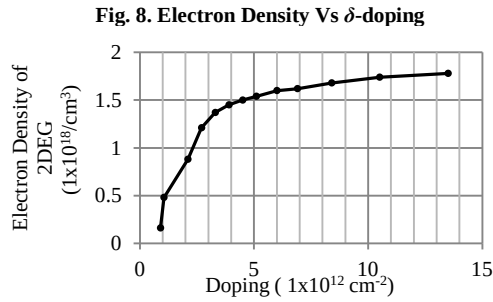


Fig. 9. Variation of threshold voltage (V_{th}) with δ -doping (N_D)

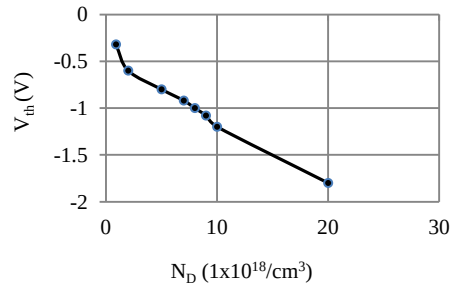


Fig. 10. Variation transconductance (g_m) with δ -doping (N_D)

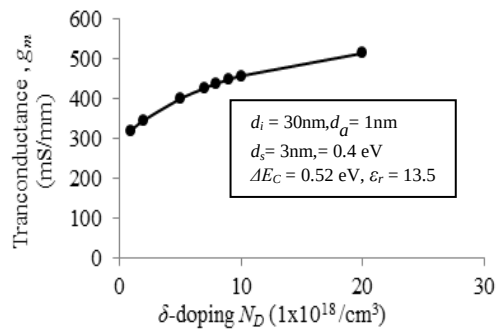


Fig. 11. Variation of cut-off frequency (f_T) with δ -doping (N_D)

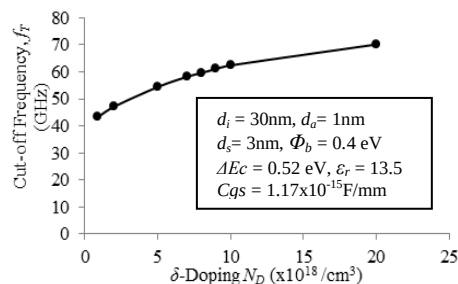


Table II. Parameters For 2deg And ΔE_c Simulation

Material-Layer	Distance(nm)
Metal, $\Phi_b = 0.2\text{eV}$	(0-10)
Contact layer, InGaAs,	(10-20)
Undoped layer(d_i), AlInAs,	(20-45)
δ -Doped layer(d_o), AlInAs	(45-45.3)
Spacer layer(d_s), AlInAs,	(45.3-55.3)
Channel layer, InGaAs,	(55.3-105.3)
Buffer layer, AlInAs,	(105.3-195.3)
SI substrate, InP	(195.3-300)

C. Using Schottky Layer Thickness

A schottky layer of thickness (d_i) is generally used to vary the value of C_s . As d_i reduce, the value of C_s increase, therefore the value of drain current and transconductance is also increase. Fig. 12 shows the variation of threshold voltage (V_{th}) with schottky layer thickness (d_i). In this analysis we found that threshold voltage (V_{th}) is becoming more neagtive when schottky layer thickness (d_i) is increasing.

The variation of transconductance (g_m) with schottky layer thickness (d_i) is shown in Fig. 13. Transconductance is high at less Schottky layer thickness because of increasing in the drain current. As transconductance is increasing after reducing the schottky layer thickness, the value of current gain cut-off frequency (f_T) is also increasing as shown in Fig 14. In this analysis, we observe that cut-off frequency is 116 GHz at 5 nm schottky layer thickness.

Fig. 12. Variation of threshold voltage (V_{th}) with schottky layer thickness (d_i)

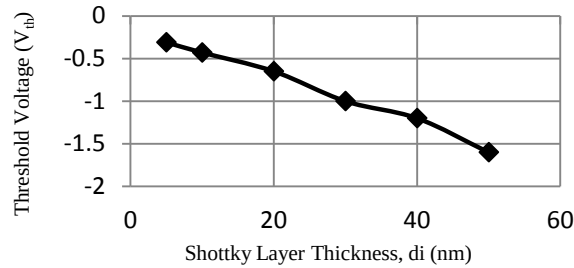


Fig. 13. Variation of transconductance (g_m) with schottky layer thickness (d_i)

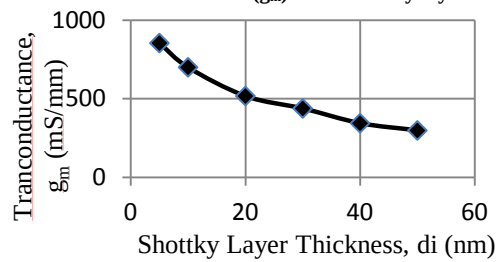
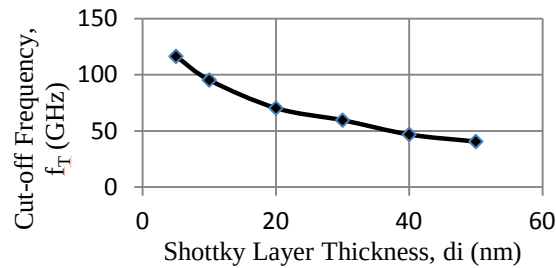


Fig. 14. Variation of cut-off frequency (f_T) with schottky layer thickness (d_i)



C. Using Gate Length

The performance of HEMT improve with reduced dimensions, specially the gate length as we approach the ballistic transport. Maximization of performance such as current gain cut-off frequency can be done after varying the gate length [6]. Fig. 14 shows the variation of threshold voltage as we reduce the gate voltage. The increase in current gain cut-off frequency could be achieved through the scaling down of the device i.e. the reduction of the gate length. In this analysis we found that the value of cut-off frequency is increases as gate length is decreased as shown in Fig. 15.

Fig. 15. Variation of threshold voltage (V_{th}) with gate length (L_g)

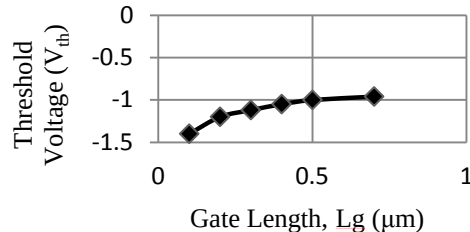
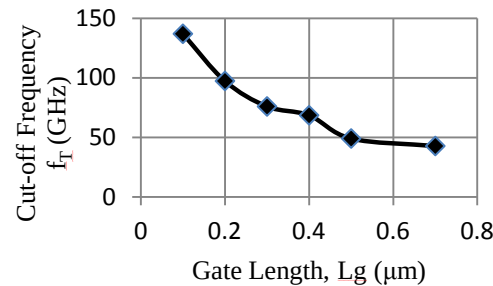


Fig. 16. Variation of cut-off frequency (f_T) with gate length (L_g)



VI. Conclusion

In this paper a 2D model is successfully developed for δ -doped InAlAs/InGaAs heterostructure InP based HEMT. The expression for high electron density has been derived. The characterization of 0.5 μm gate length InP based InAlAs/InGaAs HEMT has been done. Variation of spacer layer thickness and δ -doping for optimizing of performance of the HEMT device has been analyzed with the help of conduction band structure and electron density across the channel. Spacer layer is used to improve in mobility of channel. The effect of spacer layer thickness variation is investigated after observing conduction band discontinuity, 2DEG electron density across channel and threshold voltage. The thickness of spacer layer should be optimum to increase the performance. The improvement of device characteristics, like channel confinement using delta doped structure through various contours of sheet carrier density, threshold voltage, etc., have been studied by varying the δ -doping. Highest observed transconductance and cut-off frequency is 510 mS/mm and 70 GHz respectively. Schottky layer thickness variation effect on performance of device is observed. When schottky layer thickness reduces, the performance parameters as threshold voltage become more positive, transconductance increases and current gain cut-off frequency is increases. At 5 nm thickness of schottky layer, the observed transconductance and current gain cut-off frequency is 850 mS/mm and 116 GHz respectively. As we reduce the device geometry such as gate length, the performance of the device is also affecting. This effect of gate length variation is observed with variation on threshold voltage and current gain cut-off frequency. The maximum cut-off frequency observed is 138 GHz at 0.1 μm gate length. Therefore this HEMT model with delta doping has very good performance in communication compare to other HEMT model [4] in high frequency application.

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