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Use of a spacer layer and doping, 0.5 µm AlInAs/InGaAs to improve mobility of HEMT

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ABSTRACT

In this article, we optimize the performance of a high electron mobility In0.53Ga0.47As/In0.52Al0.48As transistor with a 0.5 m gate length and delta doping. Here, we have improved the mobility of the HEMT using variables like spacer layer fluctuation and delta doping. We simulate the -doped In0.53Ga0.47As/In0.52Al0.48As HEMT's conduction band discontinuities, threshold voltage, trans-conductance, cut-off frequency, and high density two-dimensional electron gas. Analysis has been done on the parameters affecting the conduction band discontinuities, high density 2DEG, and HEMT performance optimization.

Keyword*- High Electron Mobility Transistor, HEMT, 2DEG, InAlAs/InGaAs Hetrostructure, Delta Doping, Spacer Layer*

1. INTRODUCTION

Due to improved electron mobility and velocity at high electron density in a device channel, high electron mobility transistor (HEMT) technology is widely employed for high frequency applications. It provides high output gain, low noise, trans-conductance (gm), cutoff frequency f_t, and device current I_D values [2]. The main assessment trends for this technology involve looking into heterostructures with larger conduction band offset values (Ec). We employ Ultrafast III-V (InAlAs/InGaAs/GaAs) modulation doped FET technology in high-speed monolithic microwave integrated circuits (MMIC). High electron mobility transistors (HEMTs) made of InAlAs/InGaAs are crucial components in a variety of devices, from RADAR to cell phones. InGaAs/InAlAs quantum wells are now the foundation of many innovations.

These applications are connected to the larger sheet carrier density in the 2DEG quantum well and the enhanced transport characteristics of InGaAs. Since this doping method produces high-density 2DEG systems, "delta" doping, also known as planar or sheet doping, is receiving a lot of attention these days. When compared to ordinary FETs and HEMTs without delta doping, field-effect transistors (FETs) made with delta-doped materials would have higher drain current capabilities, easier control of the threshold voltage Vth, a larger breakdown voltage, and higher intrinsic trans-conductance (gm). By adjusting the trans-conductance and cut-off frequency, these desirable qualities will have a significant impact on the performance of short channel devices for gate lengths.

The rest of this paper is structured as follows: In Section II, a two-dimensional (2D) model of HEMT has been created. Conduction band simulation and 2DEG across channel were used to characterize the HEMT model in Section IV. The model is formulated with -doping in Section III. In section V, we use spacer layer thickness and -doping variations to optimize the performance of lattice matched doped In0.53Ga0.47As/In0.52Al0.48As quantum well HEMTs grown by MBE on an InP substrate (here and elsewhere in our paper, we use the abbreviations InAlAs for In0.52Al0.48As and InGaAs for In0.53Ga0.47A After adjusting the value of the doping and spacer layer, research has been done on the conduction band bending and electrical characteristics of 2DEG across the channel.. The simulations have been performed using the heterojunction device simulator Nextnano[3] and ATLAS. Finally conclusion is drawn in Section VI.

2. DEVICE STRUCTURE

In Fig. 1 the InAlAs/InGaAs HEMT 2D model is shown. Such a structure can be grown by using 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].

To enhance carrier confinement in the channel and create a low leakage isolation floor, the undoped InAlAs buffer layer is employed. The 2DEG that emerges from the difference in band-gap between InGaAs and InAlAs is the most significant aspect of the InGaAs channel layer in HEMT devices. The electrons are then constrained to a thin sheet of charge known as the 2DEG by a potential barrier. The 2DEG has less Coulomb scattering than a MESFET, which has a doped channel and hence many ionised donors, leading to an extremely high mobility device structure.

There is an InAlAs spacer layer in the remaining portion of the HEMT structure. InAlAs may have modulation doped thin layers or Si-delta doped layers. It serves as an electron source. We introduce a -doping layer (da) that is 8x1018 /cm3 doped and very thin, of the order of 3, supplying all the electrons for 2DEG. It is known as a "-doped," "planar doped," or "pulse doped HEMT" for such a construction. There is no doping when a Schottky layer (di) is inserted. The contact performance beneath the electrodes is improved by the InGaAs contact layer.

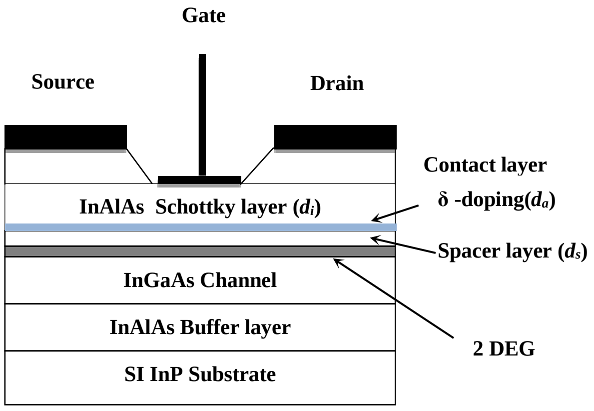


Fig. 1. InP based HEMT model

3. THEORETICAL CONSIDERATION

This model is used to predict the device behavior and characteristics 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 known as off voltage (Voff) [4]. This voltage is defined as the voltage needed to make HEMT device turn off. It is analogous to the threshold voltage (Vth) for depletion mode MOSFET. This model is used in the analysis is a δ- doped structure, in which ds, da and di represents the thicknesses of spacer layer, doped layer and Schottky layer respectively. The threshold voltage of δ-doped structure depends on da and di and is given by:

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

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

$$Q_{ch} = C_s\left(V_{GS} - V_{off}\right) \tag{2}$$

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

$$d = d_i + d_a + d_a + d_s \tag{3}$$

So 2DEG carrier density is given by:

$$n_s = \frac{\varepsilon}{qd}\left(V_{GS} - V_{off}\right) \tag{4}$$

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

$$I_D = \frac{\mu_n C_S W}{2L}\left(V_{GS} - V_{off}\right)^2 \tag{5}$$

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

$$g_m = \frac{\partial I_D}{\partial V_{GS}} = \frac{\mu_n C_S W}{L}\left(V_{GS} - V_{off}\right) \tag{6}$$

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

$$f_T = \frac{g_m}{2\pi C_{gs}} \tag{7}$$

4. SIMULATIONS AND DISCUSSION

2D structure simulation result of 0.5μm gate length High electron mobility transistor model that is obtained by using ATLAS tool is shown in Fig. 2. Current-voltage characteristics have been shown in Fig. 3. Parameters and details of layers are recorded in Table-1. Fig. 3(a) shows the variation of drain current I_D with gate voltage V_{GS} and Fig. 3(b) shows the variation of drain current with drain voltage for different gate voltages.

Fig. 4 depicts the conduction band structure of the HEMT model, which was simulated using nextnano and whose parameters and layer thickness are listed in Table 2. At the interface of InAlAs and InGaAs, a notch forms at 55.3 nm. Figure 4 depicts the band bending in the conduction band. Band bending in this heterostructure device is represented by the conduction band offset, which was determined to be 0.50 eV.

Fig. 5 depicts the HEMT model's heterostructure interface's electron density concentration. At the intersection of materials with a broader band gap and a narrower band gap, a very high electron density has been observed. The electron density is extremely high at this location between 55.3 and 105.3 nanometers. It shows that electrons are transmitted from the higher band gap layer (InAlAs) to the lower band gap layer (InGaAs), also referred to as the channel layer. This channel layer has an electron density of 1.5 x 1018/cm3 or less. The 2DEG (Two Dimensional Electron Gas) across channel is represented by this electron confinement.

Table I. 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

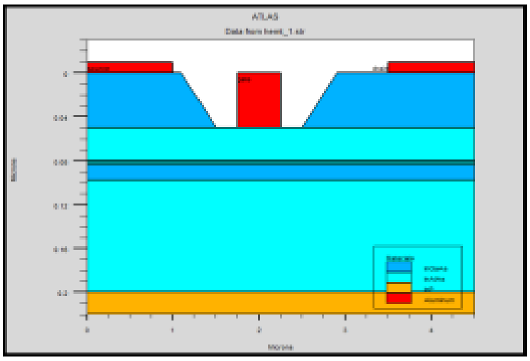
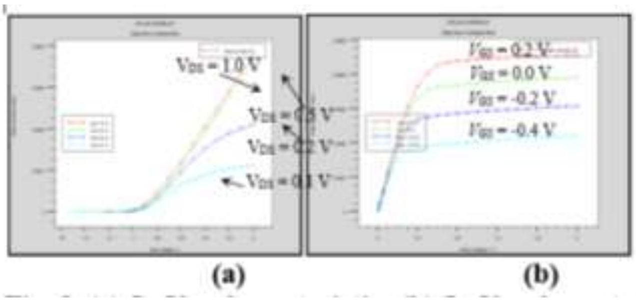


Fig. 2. 2D HEMT model



(a) **(b)**

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

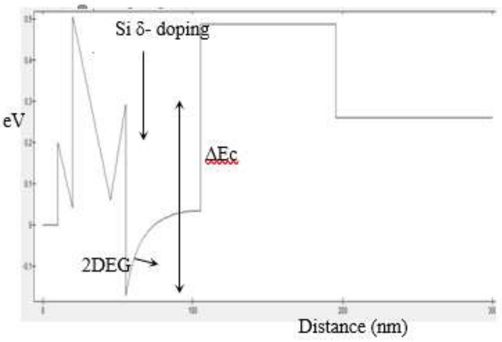


Fig. 4. Simulated Conduction Band Diagram with 2DEG formation and Band bending

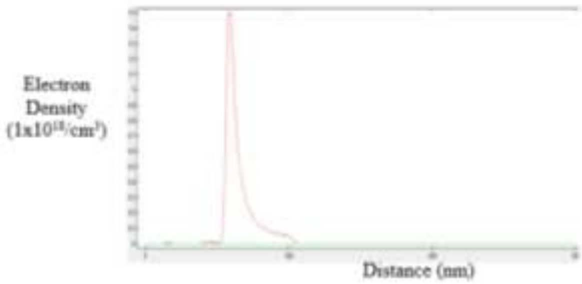


Fig. 5 Simulated plot of Electron Density Vs Distance

5. OPTIMIZATION

A. Using Spacer Layer Thickness

A thin spacer layer is placed at the interface of doped InAlAs and undoped InGaAs so that electron in 2DEG channel do not see the effect of dopant in doped InAlAs layer. Thickness of this layer is affecting 2DEG [8]. Scattering due to dopant is not affecting the 2DEG. Therefore spacer layer is separating donor from 2DEG and increasing the mobility. Electron density variation of 2DEG with respect to spacer layer thickness is shown in Fig. 6. We can't make this spacer layer very thick because less number of electron transfer from doped layer to 2DEG.

When we increase spacer layer thickness, *d* increases. As a result of this decline in HEMT performance, total capacitance Cs and transconductance gm are also decreased. Consequently, spacer thickness is limited to 1–5 nm. Figure 7 displays the relationship between spacer layer thickness and the HEMT model's threshold voltage (vth) change. The threshold voltage shifts more negatively as the thickness of the spacer layer is increased.

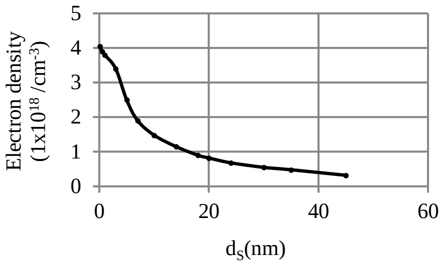


Fig. 6. Spacer layer thickness Vs Electron density

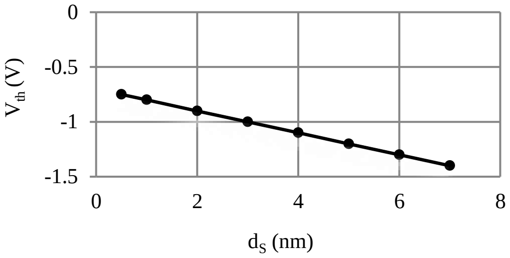


Fig. 7. Variation of threshold voltage with spacer layer thickness(d_s)

B. Using Delta Doping

We are aware that raising the doping ND of the -doped layer will enhance the electron concentration in 2DEG [8]. In this model, a 4.5x1012 cm-2 silicon doping is added at a distance of 35 nm to cause band bending. Figures 4 and 5 depict the effect of delta doping and the related electron concentration, respectively. We determine the relevant 2DEG electron densities using various ND values. In Fig. 8, these variances are depicted. We also notice that the electron density of the matching 2DEG across the channel layer would increase slowly following the initial rapid increase up to 4.5x 1012 cm-2 delta doping. 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. As δ-doping increases, more band bending takes place.

Fig. 9 shows variation of threshold voltage (v_{th}) with δ-doping (N_D). It is found that the 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). Because the drain current is growing as delta doping is increased, the conductance increases. We notice that for high ND, transconductance is really high. Fig. 11 depicts the variation of cut-off frequency (fT) with -doping (ND). Cut-off frequency rises as -doping in the -doped layer is increased (da). The current gain cut-off frequency in this analysis at 2x1019/cm3 doping is 70 GHz, which is greater than the cut-off frequency for lower doping.

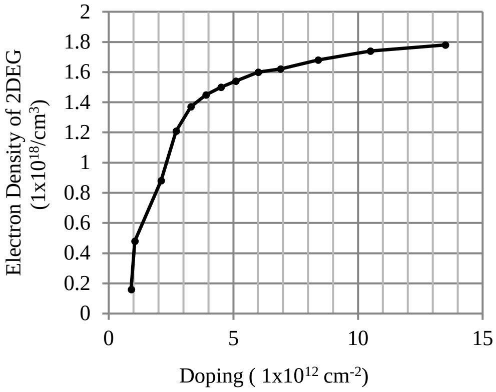


Fig. 8. Electron Density Vs δ-doping

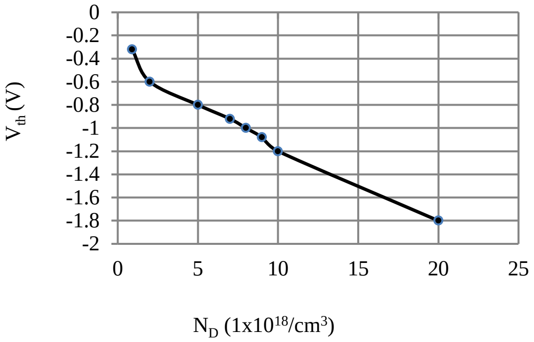


Fig. 9. Variation of threshold voltage (v_{th}) with δ-doping (N_D)

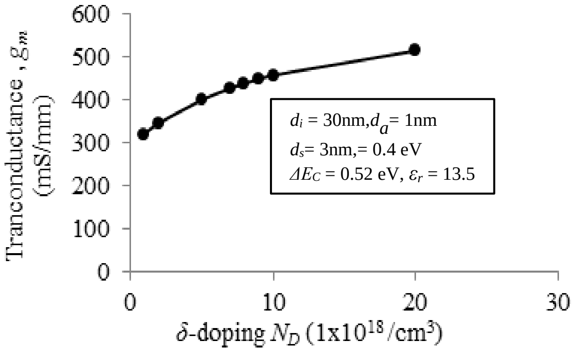


Fig. 10. Variation transconductance (g_m) with δ-doping (N_D)

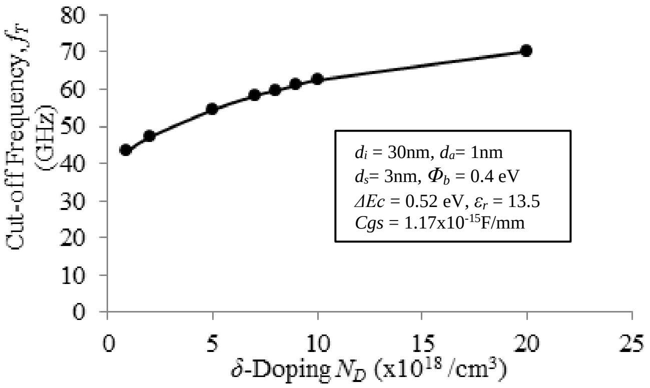


Fig. 11. Variation of cut-off frequency (f_T) with δ-doping (N_D)

Table II. Parameters For 2deg And Δe_c Simulation

Material-Layer	Distance(nm)
Metal, Φ_b = 0.2eV	(0-10)
Contact layer,InGaAs,	(10-20)
Undoped layer(d_i),AlInAs,	(20-45)
δ-Doped layer(d_a),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)

5.CONCLUSION

In this paper, a 2-dimensional model for the InAlAs/InGaAs HEMT is constructed. InAlAs/InGaAs HEMT simulation with a 0.5 m gate length has been seen. Conduction band structure and electron density across the channel have been used to investigate variations in spacer layer thickness and -doping for improving HEMT device performance. As a result, spacer layer thickness is used to increase HEMT mobility. With conduction band discontinuities, 2DEG electron density across channel and threshold voltage V$_{th}$, the impact of spacer layer thickness change is seen. For best performance, the spacer layer should be as thick as possible. By adjusting the -doping, the improvement of gadget attributes has been researched. The final transconductance value recorded is 510 mS/mm, and the cut-off frequency is 70 GHz.

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