Modeling, characterization and optimization of tri-step doped
InAlAs/InGaAs heterostructure, InP based HEMT
for microwave frequency applications

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A new analytical model for tri-step doped InAlAs/InGaAs heterostructure InP based HEMT has been proposed in this paper. Maximum sheet carrier density has been formulated considering the limitation arising from the doping-thickness product. A comparison is made between conventional pulsed doped structure and equivalent tri-step doped structures to validate the model. The conventional pulsed doped device is also optimized for higher sheet carrier concentration/effective parallel conduction voltage/cut-off frequency by varying the Schottky layer thickness for identical carriers using equivalent tri-step doped structure.

I Introduction

The high electron mobility transistors (HEMTs) consisting of InAlAs/InGaAs hetero-structure, lattice matched to InP are known for its high sheet carrier concentration, high carrier mobility and saturation velocity. Eversince their development, several models were proposed to predict the characteristics and to optimize its performance. Introduction of intrinsic layer between the Schottky gate and the n-lnAlAs layer reduces the gate leakage current with improved breakdown voltage. In addition, the increase in Schottky layer thickness with increased doping concentration, enhances the characteristics by improving sheet carrier concentration, higher carrier mobility and high saturation velocity. But, these enhancements are limited by doping-thickness product, if sheet carrier concentration exceeds the doping-thickness product.

In this paper, a model has been formulated for tri-step doped HEMT having different doping concentration and different thicknesses. The conventional, uniformly doped, pulsed doped and delta doped structure are the special cases. The expression of maximum sheet carrier density has been formulated considering the effect of doping-thickness product. The comparison of tri-step doped structure has been done with pulsed doped structure to validate the model. The drain current obtained by tri-step doped structure considering equivalent parameters of conventional pulsed doped structure shows excellent match. The analysis concentrates on the distance of doping from the hetero-junction and gate electrode. Different design criteria have been given to dope the carriers (amount and distance) in different regions to optimize the performance for higher sheet carrier density/parallel conduction voltage/paralllel conduction voltage/cut-off frequency.

2 Theoretical Details

The basic structure of an InAlAs/InGaAs HEMT used in the analysis is a tri-step doped structure, as shown in Fig. 1, consists of InP substrate; InAlAs undoped buffer; undoped InGaAs layer to form the 2DEG channel; InAlAs undoped spacer-layer of thickness, d; and tri-step Si-doped InAlAs layer of thickness d, d, and d, doped with doping density N, N, and N, respectively. The basic charge control equation for two-dimensional electron gas (2DEG) along the channel used for the analysis is given in Ref. 4:

\[ n_1 = \frac{\beta \phi_2 + \sqrt{(\beta \phi_2)^2 + 4\beta / V_g - V(x) - V_{off}}}{2(1 + \beta \phi_3)} \]  

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where $\beta = \frac{q}{q_d}$, $V_g$ is the gate voltage, $d$ the channel depth and $k_1$, $k_2$ and $k_3$ are the fitting parameters used to obtain the equivalent expression for 2DEG sheet carrier density and the quasi-Fermi level for InAlAs/lnGaAs system. The threshold voltage for the tri-step doped structure can be expressed as:

$$V_{\text{th}} = \phi_b - \Delta E_{c} - \frac{q}{2 \varepsilon} \left[ N_d d_1^2 + N_d d_2^2 + N_d d_3^2 \right] + 2 N_d (d_1 + d_2 + d_3)$$

where $\phi_b$ is the Schottky barrier potential ($-0.4$ V for the undoped InAlAs layer); $\Delta E_c$ is the conduction band discontinuity at the InAlAs/InGaAs interface ($-0.52$ eV)

Transconductance can be obtained by differentiating the drain current with respect to gate voltage at constant drain voltage and corresponding cut-off frequency can be obtained from the expression:

$$f_c = \frac{g_m}{2 \pi C_g}$$

in which $g_m$ is the transconductance and $C_g$ is the channel-gate capacitance and for fully depleted case, it is given by:

$$C_g = \frac{\varepsilon}{d}$$

## 2.1 Calculation of maximum 2DEG sheet carrier density

The maximum value of 2DEG sheet carrier density depends on the transfer of carriers from different doping regions, doping density and the thickness of the regions in tri-step doped, to the quantum well, and has been analyzed in further part of the work. If all the carriers are transferred from region 1 to the quantum well, then the maximum sheet carrier concentration is given by:

$$n_{\text{sat}} = \sqrt{\frac{2.1 \varepsilon N_{\text{dil}} (\Delta E_c - E_f) - N_d d_s}{q}}$$

and the corresponding depletion width is given by:

$$d_{\text{pe}} = d_s + \frac{n_{\text{sat}}}{N_d}$$

if number of carriers or the depletion width from the above calculation exceeds the doping thickness product ($N_d d_s$) or the thickness of the region 1 then the 2DEG quantum well could extract electrons from region 2, and the maximum sheet carrier density is then given by:

$$n_{\text{sat}} = N_d d_1 - N_d (d_2 + d_1) + \sqrt{A_1}$$
in which:

\[
A_1 = \frac{N_d^2}{2}(d_s + d_1)^2 - 2N_dN_d_2 d_1 d_s \\
- N_dN_d_2 d_1^2 + \frac{2\pi N_2}{q}(\Delta E_c - E_f)
\]

and the corresponding depletion width from the hetero-interface is given by:

\[
\text{dep}_1 = \frac{n_{\text{sw}1} - N_d d_1}{N_d^2} + d_s + d_1 \quad \ldots(8)
\]

If depletion width exceeds the sum of thicknesses of region 1 and 2 or doping thickness product \((N_d, d_1 + N_d, d_2)\) then, carriers are also transferring from region 3 and the maximum sheet carrier concentration is then given by:

\[
n_{\text{sw}1} = B_1 + \sqrt{B_1^2 + C_1 + D_1} \quad \ldots(9)
\]

in which:

\[
B_1 = N_d d_1 + N_d, d_1 - N_d, (d_s + d_1 + d_2) \\
C_1 = N_d, N_d, d_1^2 + 2N_d, N_d, d_1 d_2 + N_d, d_1 d_2^2 \\
D_1 = \frac{2N_d, \Delta E_c}{q}(\Delta E_c - E_f) - N_d^2 d_1^2 - N_d^2 d_2^2 \\
- 2N_d, N_d, d_1 d_2
\]

and the corresponding depletion width from the hetero-interface is given by:

\[
\text{dep}_2 = \frac{n_{\text{sw}2} - N_d, d_2}{N_d^2} + d_s + d_2 \quad \ldots(10)
\]

In general, maximum sheet carrier concentration is given by:

\[
n_{\text{sw}} = \begin{cases} 
  n_{\text{sw}1} & \text{if } d_s \leq \text{dep}_1 \leq d_s + d_1 \\
  n_{\text{sw}2} & \text{if } d_s + d_1 \leq \text{dep}_2 \leq d_s + d_2 \\
  n_{\text{sw}3} & \text{if } d_s + d_1 + d_2 \leq \text{dep}_3 \leq d_s + d_2 
\end{cases} \quad \ldots(11)
\]

and the corresponding depletion width is given by:

\[
\text{dep} = \begin{cases} 
  \text{dep}_1 & \text{if } d_s \leq \text{dep}_1 \leq d_s + d_1 \\
  \text{dep}_2 & \text{if } d_s + d_1 \leq \text{dep}_2 \leq d_s + d_1 + d_2 \\
  \text{dep}_3 & \text{if } d_s + d_1 + d_2 \leq \text{dep}_3 \leq d_s + d_2 
\end{cases} \quad \ldots(12)
\]

2.2 Comparison with pulsed doped structure

Doping variation in pulsed doped structure is given by:

\[
N(y) = \begin{cases} 
  0 & \text{if } 0 \leq y \leq d_s \\
  N_d & \text{for } d_s \leq y \leq d_s + d_1 \\
  0 & \text{for } d_s + d_1 \leq y \leq d_s + d_1 + d_2 \\
  N_d & \text{for } d_s + d_1 + d_2 \leq y \leq d 
\end{cases} \quad \ldots(13)
\]

where \(d_s\) is the spacer layer thickness and \(d_1\) is the doping layer thickness, where doping variation of tri-step doped structure is given by:

\[
N(y) = \begin{cases} 
  0 & \text{for } 0 \leq y \leq d_s \\
  N_d & \text{for } d_s \leq y \leq d_s + d_1 \\
  N_d & \text{for } d_s + d_1 \leq y \leq d_s + d_1 + d_2 \\
  N_d & \text{for } d_s + d_1 + d_2 \leq y \leq d 
\end{cases} \quad \ldots(14)
\]

Comparing these two structures for same number of carriers gives:

\[
N_d = 0 \\
d_s + d_1 = d_s \\
\text{and} \quad N_d, d_1 + N_d, d_2 = N_d, d_2 \quad \ldots(15)
\]

Substituting the values given in Eq. (15) in Eq. (2), the threshold voltage for tri-step doped structure with identical carriers in dopant region with pulsed doped structure and is obtained as:

\[
V_{\text{eff}} = \phi_b - \Delta E_c - \frac{q d_1}{2e} \left[ N_d, d_1 + N_d, (d_1 + 2d_1) \right] + k_1 \quad \ldots(16)
\]

Case: \(d_1 = d_1 = d_2/2\) then:

\[
V_{\text{eff}} = \phi_b - \Delta E_c - \frac{q d_1}{4e} \left[ N_d + N_d, \left(1 + \frac{4d_1}{d_s} \right) \right] + k_1 \quad \ldots(17)
\]

for \(N_d = N_d, d_s = N_d\) the expression given in Eq. (17) reduces to:
\[ V_{\text{eff}} = \phi_b - \Delta E_c - \frac{qN_d d_a}{2e} \left( 1 + \frac{2d_1}{d_a} \right) + k_1 \]

which is the same as reported in Ref. 4 for pulsed doped structure, thus, showing the validity of the proposed model.

3 Result and Discussion

Variation of drain current with drain voltage for various value of gate voltage is shown in Fig. 2 for tri-step doped structure and pulsed doped structure. The doping in region 3 is assumed to be zero so that, region 3 can replace Schottky layer of pulsed doped structure. The region 2 and region 1 together form the dopant region in pulsed doped structure, where, for simplicity, thicknesses are assumed to be equal. The variation has been plotted for three different cases, considering identical carriers in the dopant region. In case 1, the doping in region 1 and 2 are assumed to be the same as pulsed doped structure, i.e. \(2 \times 10^{13} \text{ m}^{-2}\). The drain current obtained for equivalent tri-step doped structure shows excellent matching with the published results \(^{3,4}\) for pulsed doped structure. For case 2, doping in region 1 has increased to \(3 \times 10^{13} \text{ m}^{-2}\), and for identical carriers doping in region 2 changes to \(1 \times 10^{13} \text{ m}^{-2}\). This variation will lead to increase in sheet carrier density resulting in increased drain current. For case 3, doping concentration in region 1 has reduced to \(1 \times 10^{13} \text{ m}^{-2}\) and in region 2, doping has increased to \(3 \times 10^{13} \text{ m}^{-2}\). This variation will lead to decrease in sheet carrier density resulting in reduced drain current, as shown in Fig. 2. This shows that, for same number of carriers, altering the distance between carriers and the quantum well, will result in the variation of sheet carrier density, which will affect the drain current. The greater the distance, the lesser will be the sheet carrier density. Moreover, the alteration of doping concentration leads to variation in threshold voltage of the device. For case 1, 2 and 3, threshold voltage is found to be \(-0.696\), \(-0.732\) and \(-0.66\) V, respectively. So, increasing the doping concentration nearer to the hetero-interface or increasing the gate-doping separation, leads to increase in threshold voltage of the device resulting in increase in the effective gate voltage \(V_{\text{gc}}\). This could be another factor, which affects the drain current of the device.

Threshold voltage is an important parameter for optimization of device, as it enhances the effective gate voltage \(V_{\text{gc}}\) which leads to increase in drain current and transconductance. Contours for threshold voltage for various values of doping-thickness product \((N_d d_a)\) and Schottky layer thickness \((d_s)\) for three cases, by varying the doping in region 1 and region 2 in such a way that, carriers in region 1 and 2 are equivalent to conventional pulsed doped structure as discussed in model formulation which are shown in Fig. 3. In case 1, i.e. conventional pulsed doped structure, doping in region 1 and region 2 is assumed to be the same. In case 2, doping in region 1 is \(3/2\)-times the doping in conventional pulsed doped structure whereas, in case 3, doping in region 1 is \(1/2\)-times that of the conventional doped structure. It can be seen from Fig. 3 that, for all the three cases of constant doping-thickness product, the increase in Schottky layer thickness increases the distance of carriers from the gate electrode thereby, enhancing the threshold voltage of the device. Fig. 3 also shows that, for case 1, i.e. for conventional pulsed doped structure, threshold voltage, say at \(-0.7\) V, can be achieved for Schottky layer thickness of \(100 \text{ Å} \) for doping-thickness product of \(2 \times 10^{13} \text{ m}^{-2}\). This value of Schottky layer thickness reduces to \(70 \text{ Å}\) for case 2.
While for case 3, this value of Schottky layer thickness increases to 120 Å. So, for constant doping–thickness product, same value of threshold voltage can be achieved at lower Schottky layer thickness by increasing the amount of carriers in region 1, as compared to region 2, i.e. more closer to the hetero-interface than the gate electrode. It could be noted from Fig. 3 that, with the decrease in
Schottky layer thickness, at constant threshold voltage, requires lesser change in doping-thickness product with increase in doping density in region 1 as compared to region 2, for constant number of carriers. This effect reduces the doping concentration near the gate electrode with increased sheet carrier density and can be used to reduce gate leakage current, arising due to higher doping concentration near to the gate electrode for the same number of carriers. Varying the Schottky layer thickness and doping-thickness product could lead to change in threshold voltage from -0.4 to -1.6 V.
The effect of increase in threshold voltage leads to the increase in drain current and is shown in Fig. 4 through contours for drain current for various values of doping-thickness product and Schottky layer thickness. It is important to enhance the maximum value of 2DEG sheet carrier density, as lower value of sheet carrier density could cause parallel conduction, i.e., flow of carriers from lower mobility path, resulting in the decrease in drain current, that could lead to decrease in transconductance of the device. So, by enhancing the maximum 2DEG sheet carrier density we can enhance the parallel conduction voltage ($V_p$) thereby, enhancing transconductance of the device by increasing the effective parallel conduction voltage ($V_c-V_m$). Contours for maximum 2DEG sheet carrier density for various values of doping thickness product and Schottky layer thickness have been plotted in Fig. 5. This shows that, increase in doping-thickness product, increases the sheet carrier density of the device. This is because, by increasing the Schottky layer thickness, at constant doping-thickness, the product leads to increase in doping concentration ($N_d$) which resulted in increased sheet carrier density. But, by decreasing the Schottky layer thickness at constant channel depth and spacer layer thickness leads to decrease in doping thickness ($d_i$) that could lead to decrease in doping-thickness product and the carriers in the InAlAs region that could transfer to the 2DEG quantum well.

This can be seen from Fig. 5, for the case of $1 \times 10^{14} \text{ m}^{-2}$ doping-thickness product, as variation of doping concentration from uniformly doped to delta doped structure has not been able to increase the maximum sheet carrier density. This region case can also be seen from Fig. 5 for sheet carrier concentration of $1.5 \times 10^{16} \text{ m}^{-2}$, $2.0 \times 10^{16} \text{ m}^{-2}$ and $2.5 \times 10^{16} \text{ m}^{-2}$ after increasing the Schottky layer thickness to 20, 120 and 190 Å, respectively, for conventional pulsed doped structure. For case 3, these values change to 50, 140 and 190 Å, whereas, for case 2, these values change to 100 and 180 Å, for sheet carrier concentration of $2.0 \times 10^{16} \text{ m}^{-2}$ and $2.5 \times 10^{16} \text{ m}^{-2}$ and for $1.5 \times 10^{16} \text{ m}^{-2}$. This region can be seen throughout from uniformly doped to delta doped structure. These values of Schottky layer thickness together with doping-thickness product are best suited parameters for the devices, as these
devices have no chance of parallel conduction and utilize full carriers in the dopant region (InAlAs). Increasing the Schottky layer thickness beyond this point is not required as at constant doping-thickness product, this variation increases the doping concentration without affecting the maximum sheet carrier density. The decrease in Schottky layer thickness from this point gives rise to parallel conduction. Furthermore, it can also be seen from Fig. 5 that at constant doping-thickness product, altering the doping density in region 1 and 2 can be used to get best-optimized device. For 100 Å of Schottky layer, any optimized device for conventional doped structure has not been found, but, by increasing the doping concentration in region 1 for case 2, an optimized device can be achieved for doping-thickness product of $2 \times 10^6$ m$^{-2}$. Same is the case for 140 Å; where the doping density has to be decreased in the region 1, i.e. for case 3.

Contours for effective gate voltage for various value of doping-thickness product ($N_d d_L$) and Schottky layer thickness are shown in Fig. 6. The maximum allowed effective gate voltage is $\phi_a V_{\text{at}}$, whereas, the maximum effective parallel conduction voltage is $V_c V_{\text{at}}$. The variation of threshold voltage leads to change in maximum effective gate voltage, as can be seen from Fig. 3. The contours for effective gate voltage of 0.8 V, for all the three cases, show similar trend with threshold voltage contours for -0.4 V and also shows that, these devices are limited by the doping-thickness product. The same thing can be said about achieving the effective gate voltage of 0.9 V, for case 3. Same optimization points as reported in Fig. 5 can be found from the figure by comparing the contours for effective gate voltage and threshold voltage. From the Fig. 5, maximum optimized value of effective gate voltage obtained is 1.4 V, corresponding to Schottky layer thickness of 185 and 190 Å for case 2 and case 1, respectively. For case 3, maximum effective gate voltage obtained is 1.3 V. These values correspond to the maximum transconductance of 1 S/mm and cut-off frequency of 127 GHz for gate length of 0.25 μm and channel depth of 220 Å. Decreasing the gate length to 0.1 μm, can increase the value to cut-off frequency to 318 GHz.

The contours for penetration depth of conduction band below the Fermi level for various value of doping-thickness product and Schottky layer thickness have been shown in Fig. 7. It is necessary to study the penetration depth, as it gives the extent to which conduction band discontinuity has been used. Moreover, it is a useful parameter for the measurement of channel confinement and mobility of carriers in the quantum well. The maximum penetration depth of the device is the conduction band discontinuity (0.52 eV). The penetration depth increases with the increase in sheet carrier density. Larger the penetration depth, larger will be the confinement, resulting in larger mobility for the carriers. Penetration depth has been calculated from the relationship between 2DEG sheet carrier density and the quasi-Fermi level position ($E_F = k_1 + k_2 n_{0}^{1/2} + n_{0}$). The penetration depth is the measurement of quasi-Fermi level position and the only affected parameter is the sheet carrier density. Since sheet carrier density is limited by doping-thickness product, so, same is the case with penetration depth. Same kind of results can be seen from Fig. 7, for doping variation in region 1, as reported in earlier figures. Doping variation can be used to alter the Schottky layer thickness or the threshold voltage of the device for the same optimized value of sheet carrier density or penetration depth.

4 Conclusion

A new model is developed for tri-step doped InAlAs/InGaAs hetero-structure InP based HEMT. The expression of maximum sheet carrier density has been derived, considering the limitation arising from the doping–thickness product. A comparison has been made between conventional pulsed doped structure and equivalent tri-step doped structures to validate the model and is found to be in excellent agreement. The variation of Schottky layer thickness for identical carriers leads to increase in sheet carrier concentration/effective parallel conduction voltage/transconductance/cut-off frequency. Alteration of doping in equivalent tri-step doped structure can optimize the conventional pulsed doped structure for better performance. Maximum values of sheet carrier density, effective gate voltage, transconductance, cut-off frequency obtained from the analysis are $2.6 \times 10^{16}$ m$^{-2}$, 1.4 V, 1 S/mm and 318 GHz, respectively.
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