Investigation of breakdown voltage in InAlAs/InGaAs/InP HEMTs with different structures

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Abstract: InAlAs/InGaAs/InP high electron mobility transistors have higher mobility comparing to structures without indium. But existence of indium causes smaller $E_g$ and as a result smaller breakdown voltage. However, increasing percentage of indium results in higher mobility and as a result higher current and transconductance. Therefore decreasing percentage of indium causes higher breakdown voltage at the sometime lower transconductance. One of the most important parameters that limit maximum output power of transistor is breakdown voltage. In this paper, InAlAs/InGaAs/InP HEMTs with different structures are simulated and a structure with a good transconductance and breakdown voltage is introduced.

Keywords: HEMT, InGaAs, breakdown voltage, channel

Classification: Electronic materials, semiconductor materials

References


[7] J. S. Ayubi-Moak, D. K. Ferry, S. M. Goodnick, R. Akis, and M. Saraniti, “Simulation of ultrasubmicrometer-gate $\text{In}_{0.52}\text{Al}_{0.48}\text{As}/\text{In}_{0.75}\text{Ga}_{0.25}\text{As}/\text{InP}$ pseudomorphic HEMTs using a full-band Monte Carlo simulator,” *IEEE Trans. Electron Devices*, vol. 54, no. 9, pp. 2327–2338, Sept. 2007.


1 Introduction

In recent years HEMTs are used for high frequency and microwave circuits usually. The first HEMT was built with GaAs as channel and AlGaAs as barrier [1]. Increasing percentage of Al increases conduction band discontinuity. AlGaAs lattice match with GaAs very good and there is no crystal defect. However, this is for percentage of Al less than 30% and there are DX center traps for percentages of larger than 30% which decreases performance of transistor. The conduction band discontinuity for $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}/\text{GaAs}$ is 0.25 eV. Adding indium will increase the conduction band discontinuity. Also InGaAs has higher saturation velocity than GaAs. Therefore InAlAs/InGaAs/InP structure was introduced. HEMTs with InGaAs channel have high mobility and high current density [2] and they are high speed transistors. In recent years there performance was improving and extrinsic maximum transconductance ($G_{m,\text{max}}$) of 1.65 S/mm and a current gain cutoff frequency ($f_T$) of 610 GHz was achieved for 15 nm-gate HEMTs on GaAs substrates [3].

Whereas breakdown voltage confines output power of transistor, so we have investigated breakdown voltage of InAlAs/InGaAs/InP HEMT with different structures, and in next section these structures which are used for simulation are described. Results of simulation are shown in section three and conclusion is in last section.

2 Simulated structures

All structures that are simulated consist of InAlAs/InGaAs/InP. The substrate is made of InP and $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ as buffer layer. InGaAs is used for channel. The thickness of channel in all structures is 18 nm. The spacer and barrier layers are made of $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$. Table I (a) shows different structures which are used for simulation. The first structure is the reference [4] structure where other ones are compared with it. Percentage of indium in the channel layer of this structure is 75% and the concentration in the $\delta$
doped layer is $3.5 \times 10^{12} \text{cm}^{-2}$ [5]. The percentage of indium in the second structure is decreased to 50%, from 75% of the first structure. Decreasing the indium percentage decreases mobility, but it increases $E_g$ which increases the breakdown voltage. Percentage of indium in the channel layer of third structure is 75%. In this structure another $\delta$ doped layer is added in bellow the channel to increase electron concentration in the channel [6]. The doping in this $\delta$ doped layer is $3.5 \times 10^{12} \text{cm}^{-2}$ and the spacer layer thickness for this layer is 4 nm. Finally, the fourth structure has two $\delta$ doped layer, similar to the third structure, but the percentage of indium in the channel is 50%.

Transistors are simulated at 300 K. The gate length of transistors is 70 nm and the barrier height of schottky barrier in the gate is 0.8 V [7]. The conduction band offset in the InGaAs/InAlAs interface is 0.53 eV [7]. A length of structures in channel direction, x direction, is 620 nm and thickness in the perpendicular to the channel and intersects layers, y direction, is 48 nm. The Drift-Diffusion equations with quantum potential are used for simulation [8]. The quantum potential is in such a way that includes quantum effects such as tunneling.

Table I. (a) The different InAlAs/InGaAs/InP simulated structures (b) Compare difference of the breakdown voltage and transconductance

<table>
<thead>
<tr>
<th>Layer</th>
<th>Structure 1</th>
<th>Structure 2</th>
<th>Structure 3</th>
<th>Structure 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cap</td>
<td>In$<em>{0.25}$Ga$</em>{0.75}$As</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barrier</td>
<td>In$<em>{0.25}$Al$</em>{0.75}$As</td>
<td>6 nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\delta$ doped</td>
<td>3.5$\times$10$^{12}$ cm$^{-2}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spacer</td>
<td>In$<em>{0.32}$Al$</em>{0.68}$As</td>
<td>4 nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Channel</td>
<td>In$<em>{0.77}$Ga$</em>{0.23}$As</td>
<td>18 nm</td>
<td>In$<em>{0.77}$Ga$</em>{0.23}$As</td>
<td>18 nm</td>
</tr>
<tr>
<td></td>
<td>In$<em>{0.77}$Ga$</em>{0.23}$As</td>
<td>18 nm</td>
<td>In$<em>{0.77}$Ga$</em>{0.23}$As</td>
<td>18 nm</td>
</tr>
<tr>
<td>Spacer</td>
<td>--------------</td>
<td>--------------</td>
<td>--------------</td>
<td>--------------</td>
</tr>
<tr>
<td>$\delta$ doped</td>
<td>3.5$\times$10$^{12}$ cm$^{-2}$</td>
<td>3.5$\times$10$^{12}$ cm$^{-2}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buffer</td>
<td>In$<em>{0.25}$Al$</em>{0.75}$As</td>
<td></td>
<td>InP Substrate</td>
<td></td>
</tr>
<tr>
<td>Breakdown Voltage (V)</td>
<td>4.0</td>
<td>8.0</td>
<td>4.1</td>
<td>8.1</td>
</tr>
</tbody>
</table>

3 Results of simulation

The structure 1 will be investigated first and other structures will be compared to it. Fig. 1 (a) shows conduction band $E_c$ without quantum effect as well as with quantum effect in the y direction. The energy axis in this figure is normalized to 25 meV. Potential of this structure at $V_g = 0.3$ V and
Fig. 1. In the structure: (a) The conduction band $E_c$ without quantum effect (---) and with quantum effect (---) (b) The potential at $V_g = 0.3\,\mathrm{V}$ and $V_d = 1.0\,\mathrm{V}$ (c) The electron concentration in the channel below at $V_g = 0.3\,\mathrm{V}$ (d) The $I_d-V_d$ curve for different gate voltages (e) The $I_d-V_g$ curve at $V_d = 1\,\mathrm{V}$, (f) The transconductance at $V_d = 1.0\,\mathrm{V}$. 
V_d = 1.0 V is shown in fig. 1(b). Fig. 1(c) shows electron concentration in the channel below the gate at V_g = 0.3 V. The concentration is normalized to N_0 = 10^{18} cm^{-3}. Fig. 1(d) shows I_d-V_d curve for different gate voltages. I_d-V_g curve at V_d=1 V is shown in fig. 1(e). The transconductance is shown in fig. 1(f).

Increasing in gate voltage increases channel concentration, transconductance and perpendicular to channel electric field. Conversely, if the gate voltage is decreased, as a result, channel concentration, transconductance and perpendicular to channel electric field will be decreased. Moreover, reason of transconductance decrease is reduction of channel electrons due to the gate voltage decrease.

The breakdown in HEMTs can be due to different effects such as impact ionization, tunneling or surface states. It is important to find the dominant effect in order to control it. The off-state breakdown occurs at a drain-source voltage when the gate voltage is applied in such a way that channel is pinched off [9]. In this case maximum electric field occurs at the edge of gate in drain side and impact ionization is the reason for this breakdown. The breakdown voltage for the first structure is V_d = 4.0 V. The reason for this low breakdown voltage is high percentage of indium in In_{0.75}Ga_{0.25}As which has low E_g and as a result a low critical field E_{crit}. Although this structure has a high current and transconductance, but its breakdown voltage is low.

Now other structures will be investigated to find a structure with high breakdown voltage and a good transconductance. Fig. 2(a) shows the electron density in the channel below at V_g = 0.3 V. It shows that electron density for the structures 3 and 4, which have two δ doped layer, is higher than the other structures. Fig. 2(b) shows I_d-V_d curve for different structure at V_g = 0.3 V. Decreasing percentage of indium will decrease electron mobility and as fig. 2(a) shows, the current for structure 2 is smaller than that of structure 1. Structure 3 and 4 have two δ doped layer which causes more electron density in the channel and as a result more current. The indium percentage in structure 4 is smaller than that of structure 3 and as a result has lower current. Fig. 2(c) shows I_d-V_g curves, at V_d = 1.0 V for different structures. The two structures with two δ doped layer which have higher electron concentration have higher currents. The transconductance of these structures, as shown in fig. 2(d), is higher than other structures. The maximum ε_{mn} for the structures is 1325, 1115, 1690 and 1400 mS/mm respectively.

The calculated breakdown voltage for the structures is 4, 8, 4.1 and 8.1 V respectively. The percentage of indium in the second structure is smaller than the first structure and as a result its E_g is larger and its critical field is larger. Therefore, breakdown voltage of second structure is larger. Although the electron concentration in the third structure is larger than the first structure but the breakdown voltage is calculated for the case that the channel is depleted and therefore their breakdown voltage is almost the same. Percentage of indium in the fourth structure is the same as that of second structure. Although the fourth structure has higher electron concentration
because of its double $\delta$ doping, but its breakdown voltage, as discussed above, is near that of second structure. Table I (b) compares transconductance and off-state breakdown voltage for simulated structures.

(a) 
(b) 
(c) 
(d) 

Fig. 2. In simulated structures: (a) The electron concentration in the channel below at $V_g = 0.3$ V (b) The $I_d$-$V_d$ curve at $V_g = 0.3$ V (c) The $I_d$-$V_d$ curve at $V_d = 1$ V, (d) The transconductance at $V_d = 1.0$ V

4 Conclusion

Transconductance and breakdown voltage of InGaAs/InAlAs HEMTs with different structures are calculated. Another way of increasing breakdown voltage is using a channel with small percentage of indium. But this will decrease its transconductance. It is also shown that adding a second $\delta$ doped layer will increase the transconductance.

Finally, it is shown that having low indium percentage together will two $\delta$ doped layer will have a large breakdown voltage with a reasonable transconductance.