Design of High Frequency Single and Double Gate Laterally-Contacted InGaAs/InAlAs HEMTs

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ABSTRACT
In this paper, two developed designs of InGaAs/InAlAs high electron mobility transistors (HEMTs) have been studied. The proposed laterally contacted HEMTs satisfy the desired high frequency characteristics and are good candidates for high frequency applications. Two kinds of HEMTs have been designed and simulated: single-gate laterally contacted HEMT (SGLC-HEMT) and double-gate laterally contacted HEMT (DGLC-HEMT). The proposed SGLC-HEMT exhibits 111 GHz current-gain cut-off frequency. By using double-gate design, the current-gain cut-off frequency has been increased to 256 GHz. The simulation results show that the maximum oscillation frequency for the proposed SGLC and DGLC HEMTs, are 410 GHz and 768 GHz, respectively. Maximum value of transconductance (gm) for SGLC-HEMT is obtained 620 mS/mm while it is 1130 mS/mm for DGLC-HEMT.

1. INTRODUCTION
Nowadays, high electron mobility transistor (HEMT), due to its attractive characteristics is one of the inseparable elements in electronics. They have high transconductance (gm), low saturation voltage and are able to work at higher frequencies than conventional transistors [1, 2]. By developing the fabrication technology to sub-micron, HEMTs with gate lengths equal to 100 nm and less, exhibit good characteristics such as high gm, high current-gain cut-off frequency (fT), and large maximum oscillation frequency (fmax). Though fT is of great interest for digital circuits, enhancement in fmax is also required for analog and power applications [3]. The main cause of reduction in gm with increasing Lg is its inability to maintain the desired aspect ratio (α=Lg/d) [4], where d is the distance between the gate electrode and hetero-interface. For a SG-HEMT with 300 nm gate, fT and fmax have been reported as 108 GHz and 349 GHz, respectively [5]. Also, for a DG-HEMT with 50 nm gate length, the fT and fmax have been reported as 162 GHz and 417 GHz, respectively [6]. Until 2014, the fastest HEMTs with fT = 664 and fmax = 681 GHz have been fabricated based on InAlAs/InGaAs/InAlAs heterostructures [7]. These large values of frequencies can be obtained due to the high electron mobility (μe) and high saturation drift velocity of electrons in these heterostructures. The electron mobility, μe can be increased by reducing the molar fraction of In in a InGaAs quantum well (QW) because of the increase in the effective electron mass [8]. In addition, μe in HEMT, PHEMT, and metamorphic HEMT (MHMET) can be increased by some methods such as improving the structural quality of the spacer layer in the barrier [9], using a well-designed heterostructure [8, 10], and improving the fabrication technology [11]. With the goal of improving the HEMT performance, several researches have been conducted on increasing the maximum oscillation frequency [12, 13], designing and fabricating good contacts [14-16], surface passivation [17, 18], and etc. Engineering of the transistor contacts has always been an attractive topic [19]. In this paper, the effects of the lateral source/drain contacts on the device performance have been investigated. The single gate and double
gate HEMTs with lateral contacts have been simulated and their high frequency characteristics have been compared.

Figure 1: The conventional top-contacted structures (SG-HEMT and DG-HEMT).

InGaAs/InAlAs single gate laterally contacted HEMT (SGCL-HEMT) and double gate laterally contacted HEMT (DGCL-HEMT) have been designed and studied with the goal of obtaining very high $f_T$ and $f_{max}$. A brief explanation of InGaAs/InAlAs HEMTs have been presented in Section 2. Designed SGCL-HEMT and DGCL-HEMT structures are introduced in Section 3. Simulation results and discussions are presented in Section 4 and finally the paper is concluded in Section 5.

2. InGaAs/InAlAs HEMTs

In this paper we focus on InGaAs/InAlAs HEMTs. Two of most important parameters of III-V semiconductors that dictate their functionality in a device are the bandgap and the lattice constant. By exploiting the bandgap difference of III-V materials, it is possible to increase carrier concentration in the channel of transistor. This is done by forming a heterostructure using a doped wider bandgap material (e.g., InAlAs) and an undoped lower bandgap material (e.g., InGaAs). Bandgap of InGaAs and InAlAs are 0.76 eV and 1.48 eV, respectively [20]. Electrons fall into a trap due to formation of quantum well near the junction. Because channel is formed in InGaAs layer and this layer is donor-free, impurity scattering is absent at the channel which causes high mobility of electrons.

For lattice matching, the mole fraction of In$_x$ for In$_x$Ga$_{1-x}$As and In$_x$Al$_{1-x}$As compounds should be 0.53 and 0.52, respectively.

3. Proposed Laterally Contacted HEMTs

The conventional structures of the InGaAs/InAlAs HEMTs (SG-HEMT and a DG-HEMT) have been shown in Error! Reference source not found.. As can be seen in Error! Reference source not found., the HEMTs are top contacted and the source and drain electrodes are positioned on the top of the structures.

In this paper, we have investigated the effect of the source and drain design on the device performance. If we change the position of the source and drain contacts from top of the device to the sides of the device, new HEMT designs would be achieved. We have proposed laterally contacted source and drain HEMTs as shown in Error! Reference source not found.. As illustrated in Error! Reference source not found., the proposed InGaAs/InAlAs HEMTs have the same heterostructures as their top contacted counterparts. But, the top contacts have been replaced by lateral contacts which will change the transistors behavior. Simulations show that the lateral contacts affect the device performance considerably. The structures of the designed SGCL-HEMT and DGCL-HEMT and their dimensions used in simulations are shown in Error! Reference source not found.. As depicted in Error! Reference source not found., a 200 nm buffer layer of In$_{0.52}$Al$_{0.48}$As on SiC substrate layer has been used to isolate the channel from substrate layer effects in SGCL-HEMT. In$_{0.53}$Ga$_{0.47}$As channel layer with 20 nm thickness on the buffer layer forms a two-dimensional electron gas (2-DEG).

To supply excess electrons to the channel, a heavily doped (1018 cm$^{-2}$) 5 nm thick delta-doped layer, has been introduced. In order to reduce the cumblic interaction between diffused electrons in channel and the ionized donors of delta-doped layer, a very thin In$_{0.52}$Al$_{0.48}$As layer (2 nm) as a spacer has been located between channel layer and delta-doped layer. Schottky layer with thickness of 15 nm has been designed on top of delta doped layer. To avoid the parallel conduction effects, this layer is undoped. Finally, highly doped (1018 cm$^{-2}$) In$_{0.53}$Ga$_{0.47}$ as a cap
layer with 10 nm thickness has been introduced to make good Ohmic source and drain contacts.

The main idea in HEMTs is conduction through an undoped channel with a special heterojunction design to increase the mobility and switching speed of the transistor (electrons in the 2-DEG channel do not undergo impurity scattering and hence exhibit high mobility and velocity). If in addition to the channel, another conduction path exists (parallel conduction), it will slow down the device. That is why the Schottky layer with thickness of 15 nm on top of delta doped layer should be undoped to avoid parallel conduction.

Each layer's mission in the proposed HEMT is as follows. The schottky layer is an intrinsic (undoped) InAlAs to avoid the parallel conduction effects. Below that, a thin heavily doped (5nm) layer of InAlAs (delta-doped layer), is introduced to supply excess electrons to the channel. A spacer layer of InAlAs with 2nm thickness is used as a sandwiched between the channel and delta doped layer in order to reduce the coulombic interaction between diffused electrons in channel and the ionized donors of delta doped layer.

Two-dimensional electron gas (2-DEG) is formed in undoped narrowband InGaAs layer of 20nm. A buffer layer of 200nm was used to isolate the channel from being affected by the substrate effects. AllInAs layers have to be undoped (schottky layer and spacer layer). If an AllnAs layer is doped (delta doped layer), its electrons should fall from doped InAlAs and trap in InGaAs (undoped channel) due to formation of quantum well near the junction. This way the conduction is limited to the channel and parallel conduction are eliminated to avoid slowing down the transistor.

In our proposed design, source and drain electrodes has been placed at sides of the structure. The drain-source spacing of 1.5 μm is used for simulation study.

In order to achieve a high frequency InGaAs/InAlAs HEMT, we propose the DGLC-HEMT structure. The high frequency performance of this transistor is verified in the upcoming sections of the paper. As seen in Error! Reference source not found.(b), compared to SGLC-HEMT, in DGLC-HEMT structure, all layers except buffer layer are duplicated symmetrically around the central channel. In order to fabricate the double gate device, first, like SGLC-HEMT, all layers are introduced. Then, by using transfer substrate technique [21] and removing buffer and substrate layers, all SGLC-HEMT layer are introduced to the back side of the wafer. T-gate contacts are introduced by using SiO$_2$ insulators. Thickness and doping concentration of different layers of the simulated SGLC-HEMT and DGLC-HEMT are tabulated in Table 1.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness (nm)</th>
<th>Doping (cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cap</td>
<td>10</td>
<td>1e18</td>
</tr>
<tr>
<td>Schottky</td>
<td>15</td>
<td>------</td>
</tr>
<tr>
<td>Delta-Doped</td>
<td>5</td>
<td>1e18</td>
</tr>
<tr>
<td>Spacer</td>
<td>2</td>
<td>------</td>
</tr>
<tr>
<td>Channel</td>
<td>20</td>
<td>------</td>
</tr>
</tbody>
</table>

4. Results and Discussions

In this section, the InGaAs/InAlAs SGLC-HEMT and DGLC-HEMT have been simulated. The channel lengths have been chosen so that the results can be compared to other works. The parameters such as the drain current, transconductance ($g_m$), current-gain cut-off frequency ($f_T$) and maximum oscillation frequency ($f_{max}$) have been calculated and compared. The comparison of the results at the end of the paper proves the efficacy of the proposed designs.
A. SGLC-HEMT

The devices have been simulated by means of SILVACO-ATLAS. Two models have been included in the simulations: field dependent mobility model (FLDMOB) and carrier quantization model (QUANTUM) [20]. Parameters used for modeling the devices are tabulated in Table 2.

The input current-voltage curve and transconductance ($g_m$) characteristics at drain voltage of 0.5 V for SGLC-HEMT are presented in Figure 4.

The frequencies $f_T$ and $f_{\text{max}}$ of the transistors have relations as below:

$$f_T = \frac{g_m}{2\pi(C_{gs} + C_{gd})}$$

$$f_{\text{max}} = f_T \sqrt{\frac{R_{ds}}{4R_{in}}} = \frac{f_T}{\sqrt{4C_{gs}R_{in}}}$$

where $C_{gs}$ is gate to source capacitance, $C_{gd}$ is gate to drain capacitance, $g_{ds}=1/R_{in}$ is drain to source conductance and $R_{in}$ is the input resistance.

![Graphs of I–V and g_m characteristics for SGLC-HEMT](image1)

Figure 4: a) $I_D$–$V_{GS}$ characteristic and b) $g_m$ for SGLC-HEMT in $V_{GS}$=0.5 V.

For the purpose of a fair comparison to other works, the channel length of the SGLC-HEMT is 300 nm. The drain current is 365 mA/mm at $V_{GS}$=1 V. The obtained maximum value of $g_m$ is 620 mS/mm at $V_{GS}$=0.05 V.

Table 2: Parameters Used in Simulations

<table>
<thead>
<tr>
<th>Material</th>
<th>$E_g$ (300 K)</th>
<th>Affinity</th>
<th>$N_C$ (300 K)</th>
<th>$N_V$ (300 K)</th>
<th>Electron Mobility (cm$^2$/Vs)</th>
<th>$V_{sat}$</th>
<th>Gate metal Work Function</th>
<th>Source and Drain Contacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>In$<em>{x}$Al$</em>{1-x}$As ($x=0.52$)</td>
<td>1.48 eV</td>
<td>4.2</td>
<td>5.3e17</td>
<td>1.09e19</td>
<td>4100</td>
<td>2.1e7</td>
<td>4.69 eV</td>
<td>Ohmic</td>
</tr>
<tr>
<td>In$<em>{x}$Ga$</em>{1-x}$As ($x=0.53$)</td>
<td>0.76 eV</td>
<td>4.72</td>
<td>2.18e17</td>
<td>8.44e18</td>
<td>10000</td>
<td>3.2e7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Gain (dB) vs Frequency [GHz]

![Graph of Gain vs Frequency for SGLC-HEMT](image2)

Figure 5: Current gain and unilateral power gain for calculation of $f_T$ and $f_{\text{max}}$ for SGLC-HEMT.

However, these parameters ($f_T$ and $f_{\text{max}}$) can be calculated based on the frequency dependent current gain and unilateral power gain, as well. In order to calculate $f_T$ and $f_{\text{max}}$ the current-gain and unilateral power gain versus frequency have been plotted in Error! Reference source not found.

The effect of the gate length on the device performance has been discussed in the following lines. By decreasing the gate length to 100 nm, the effects of the short gates on the characteristics of SGLC-HEMT have been studied. Drift diffusion equations have been
solved again to obtain the input current-voltage (\(I_D-V_{GS}\)) and \(g_m\) characteristics as shown in Error! Reference source not found.. As the gate length decreases, unlike \(I_D\) and \(g_m\), frequency characteristics such as \(f_T\) and \(f_{max}\) are improved. However, the frequencies of unity current gain and unity unilateral power gain are limited by short-channel effects [22] and the performance enhancement due to device scaling is restricted [23]. That is because maintaining the desired channel aspect ratio (\(\alpha=L_g/d\)) is difficult (\(d\) is the vertical distance from gate to the channel) [24]. Also HEMT devices may show short-channel effects due to other non-idealities such as gate leakage current, traps, and impact ionization [23].

In comparison to 300 nm gate length, \(I_D\) and the maximum \(g_m\) have been decreased about 11% and 8%, respectively, as shown in Error! Reference source not found..

Figure 6: a) \(I_D-V_{GS}\) b) \(g_m\) for 100 nm channel length SGLC-HEMT in \(V_{DS}=0.5\) V.

Figure 7: Current gain and unilateral power gain for calculation of \(f_T\) and \(f_{max}\) for 100 nm channel SGLC-HEMT.

The short channel effects most are demonstrated in devices with gate length less than 100 nm [5]. In order to improve the HEMT performance in short channels, a second gate can be added to the transistor. This will be explained in the next section.

B. DGLC-HEMT

The solution to degraded characteristic parameters of the HEMTs (such as the decreased \(g_m\)) due to short channel is to use double gate HEMT (DG-HEMT) which also provides the benefit of having much larger \(f_T\) and \(f_{max}\).

A DG-HEMT can be designed by removing the substrate in SG-HEMT and replacing it with duplicated layers around the channel as shown in Error! Reference source not found.. DG-HEMTs, due to
more control of carriers transfer in channel and also maintaining the desired aspect ratio, are suitable to improve HEMTs characteristics. Our proposed high frequency InGaAs/InAlAs HEMT is double gate and laterally contacted. The simulations for DGLC-HEMT are presented in the following lines.

The input current-voltage and transconductance curves for $V_{DS}=0.5$ V are shown in Error! Reference source not found.. As shown in Figure 8, $I_D$ at $V_{GS}=1$ V is 583 mA/mm and maximum $g_m$ is 1130 mS/mm which are about 60% and 82% greater than SGLC-HEMT, respectively.

Simulations results show outstanding increases in $f_T$ and $f_{max}$ values. As shown in Figure 9, $f_T$ is about 256 GHz. Also $f_{max}$ is 768 GHz which have significant improvements compared to SGLC-HEMTs.

Figure 9: Current gain and unilateral power gain for calculation of $f_T$ and $f_{max}$ in DGLC-HEMT.

The results show that the DGLC-HEMT structure is an ideal candidate for high frequency applications. As shown in Error! Reference source not found., the current gain and the unilateral gain decrease more slowly than conventional HEMTs and reach unity (0 dB) in much higher frequencies than conventional designs.

This means that the proposed InGaAs/InAlAs DGLC-HEMT is a transistor suitable for high frequency applications.

C. Comparison

In this section by comparing the obtained results to each other and to the previously reported InGaAs/InAlAs HEMTs, the superior performance of the proposed SG and DG laterally contacted HEMTs has been proved. The obtained results for SGLC-HEMT and DGLC-HEMT have been tabulated in Table 3.

As illustrated in Table 3, for SGLC-HEMT, shortening the channel length results in the degradation of the drain current and the transconductance, however, the current-gain cut-off frequency ($f_T$) and the maximum oscillation frequency ($f_{max}$) have become higher.

This is similar to the gain bandwidth trade off that exist between the gain and the cutoff frequency of the transistors. As discussed previously, the short channel effects limit the performance of the HEMTs and this problem can be solved by using a double gate HEMT.

For double gate HEMTs, all of the parameters have been improved compared to the single gate HEMTs. In order to present an illustrative comparison, we have compared the results of gain and frequency characteristics obtained for the proposed SGLC-HEMT and DGLC-HEMT with previous works on InGaAs/InAlAs HEMTs as shown in Table 4.

From the data in Table 4, it is clear that in [5] and [6] all the transistor parameters (transconductance, cutoff frequency and the maximum oscillation frequency) have improved in double gate design compared to the single gate design. As shown in Table 4, the proposed SGLC-HEMT has improved the $f_T$ and $f_{max}$ compared to the previous works. It can also be concluded that the proposed InGaAs/InAlAs DGLC-HEMT which benefits from laterally contacts (compared to top contacts in other works) is a successful design for providing much larger $f_T$ and $f_{max}$ than conventional structures while its $g_m$ is also larger than the single gate HEMTs.

Table 3

<table>
<thead>
<tr>
<th>Device Characteristic</th>
<th>SGLC-HEMT</th>
<th>DGLC-HEMT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel Length (nm)</td>
<td>300</td>
<td>100</td>
</tr>
<tr>
<td>$I_D$ (mA/mm) at $V_{DS}=0.5$ V and $V_{GS}=1$ V</td>
<td>365</td>
<td>325</td>
</tr>
<tr>
<td>Maximum $g_m$ (mS/mm)</td>
<td>620</td>
<td>571</td>
</tr>
<tr>
<td>$f_T$ (GHz)</td>
<td>111</td>
<td>231</td>
</tr>
<tr>
<td>$f_{max}$ (GHz)</td>
<td>410</td>
<td>551</td>
</tr>
</tbody>
</table>

Table 4

<table>
<thead>
<tr>
<th>Device</th>
<th>Channel Length (nm)</th>
<th>$g_m$ (mS/mm)</th>
<th>$f_T$ (GHz)</th>
<th>$f_{max}$ (GHz)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>SGHEMT</td>
<td>300</td>
<td>910</td>
<td>108</td>
<td>349</td>
<td>[5]</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>840</td>
<td>108</td>
<td>346</td>
<td>[6]</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>620</td>
<td>111</td>
<td>410</td>
<td>This work</td>
</tr>
</tbody>
</table>
Since parallel conduction have been prevented, all the current is conducted through the 2DEG formed in the undoped channel which provides a high mobility. Performance improvement of lateral source and drain contacts can be attributed to two main mechanisms. First, in the laterally contacted InGaAs/InAlAs HEMT, the 2-DEG is in direct connection to the source and drain contacts. This helps in improving the current conduction. The carriers can run into the source and drain faster and this makes the device appropriate for high switching speed and high frequency applications. Second, the gate-source and gate-drain capacitances are smaller in laterally contacted HEMTS because the distance between gate and source/drain contacts is larger and because of the same reason the parasitic capacitances are smaller than other designs.

As can be seen in the Table 4, the $f_T$ of the DG-HEMT has been increased from 175 GHz and 179 GHz [5, 6] to 256 GHz in this paper. The DGLC-HEMT could also improve the $f_{max}$ from 448 GHz and 482 GHz in previous works to 768 GHz which is a great improvement. Another interesting point is that the improvement in the $f_T$ and $f_{max}$ compared to other works is much larger for DGLC-HEMT than that of the SGLC-HEMT. The obtained results verify that using laterally source and drain contacts in InGaAs/InAlAs DGLC-HEMT improves its high frequency performance significantly. This work proposes this design as a very high frequency HEMT suitable for high frequency applications.

5. CONCLUSION

Improved designs of InGaAs/InAlAs HEMTs were presented and studied. In order to increase the $f_T$ and $f_{max}$, instead of decreasing the gate length which is a restricted solution because of short channel effects, a very efficient structure was proposed. The designed HEMT benefits from laterally source and drain contacts. The results showed superior performance of the laterally contacted HEMTs compared to top contacted ones. The best frequency response was obtained for DGLC-HEMT. The proposed DG-HEMT design could improve the current-gain cut-off frequency and maximum oscillation frequency to 256 GHz and 768 GHz, respectively. The comparison of the performance of the DGLC-HEMT with SGLC-HEMT and with previously reported double gate HEMTs, verified the significant improvements in DC and AC characteristics of the HEMTs caused by the proposed design.

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Zoheir Kordrostami et al.


[24] Y. Yamashita et al., "Pseudomorphic In0.52Al0.48As/In0.7Ga0.3 As HEMT's with an ultrahigh f of 562 GHz," IEEE Electron Device Lett., vol 23, no. 10, pp. 573-575, 2002.

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