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Improved InAlGaP-based heterostructure field-effect transistors

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Abstract
This investigation proposes the improved double δ-doped InGaP/InGaAs heterostructure field-effect transistor (HFET) grown by metalorganic chemical vapour deposition. The extrinsic transconductance ($g_m$) and saturation current density ($I_{max}$) of the double δ-doped InGaP/InGaAs HFET are superior to those of the previously reported single δ-doped InGaP/InGaAs HFETs. The first n-InAlGaP/GaAs HFET is also investigated because it has a high Schottky barrier, a large high band gap and a large conduction-band discontinuity ($\Delta E_C$). Even without indium in the channel of the InAlGaP/GaAs HFET, $g_m$ and $I_{max}$ are as high as 170 mS mm$^{-1}$ and 410 mA mm$^{-1}$, respectively. The $g_m$ values of these two HFETs remain large even when the gate voltages are positive. Moreover, the breakdown voltages of the two examined HFETs both exceed 40 V.

1. Introduction
AlGaAs/InGaAs high electron mobility transistors (HEMTs) have been established to display excellent power performance at microwave frequencies, but their noise figures remain inferior to those of InGaP/InGaAs HEMTs. The noise performance of InGaP/InGaAs HEMTs is improved by the absence of donor-related deep levels. AlGaAs contains $DX$ centres, which are responsible for large threshold voltage shifts and drain $I$–$V$ collapse at low temperature. Accordingly, the absence of deep traps in doped InGaP makes InGaP an alternative to AlGaAs in HEMTs. However, a heterostructure with a larger conduction-band discontinuity ($\Delta E_C$) is required to provide a larger sheet charge density and reduce the knee voltage, which are essential for low-voltage power application. In 1996, Lu et al developed the first n-InGaP/GaAs heterostructure field-effect transistors (HFETs) [1]. Numerous researchers have presented a series of InGaP/InGaAs HEMTs [2–7]. Experimental findings have proven that a high-breakdown voltage can be achieved. Unfortunately, the two-dimensional electron gas (2DEG) densities of the InGaP HEMTs remain limited by their relatively small $\Delta E_C$, which, in turn, limits their current-driving capability [1–7].

The In$_{0.5}$(Al$_{1-x}$)Ga$_x$P/GaAs heterojunctions are excellent alternative materials for use in electronic and optoelectronic devices [8]. The In$_{0.5}$(Al$_{1-x}$)Ga$_x$P/GaAs heterojunction with $x \geq 0.2$ has a larger $\Delta E_C$ ($\geq 0.25$ eV) than the Al$_{0.25}$Ga$_{0.75}$As/GaAs (0.19 eV) or In$_{0.5}$Ga$_{0.5}$P/GaAs heterojunction. Although the value of $\Delta E_C$ for the In$_{0.5}$Ga$_{0.5}$P/GaAs heterojunction is still an issue of debate, evidence indicates that the incorporation of Al can increase both $\Delta E_C$ [9] and the band gap [10]. Hence, In$_{0.5}$(Al$_{1-x}$)Ga$_x$P/GaAs HFETs with $x \geq 0.2$ are expected to have a considerably larger 2DEG sheet density and current drive capability, and better carrier confinement of electrons because they have a larger $\Delta E_C$. The other advantages of using In$_{0.5}$(Al$_{1-x}$)Ga$_x$P as the barrier material in an HEMT structure include: (1) a higher breakdown voltage, because of a larger band gap, (2) the fact that the gate leakage current can be significantly reduced because the Schottky barrier is heightened and (3) the high selectivity of etching over GaAs, which improves the gate recess control.

This study develops double δ-doped InGaP/InGaAs and the first n-InAlGaP/GaAs HFETs. The δ-doped HFETs have a superior 2DEG concentration and a high-breakdown voltage [11–14]. For the InGaP/InGaAs HFET proposed
herein, symmetric double δ-doping is adopted to overcome the shortcoming of the low current capability in conventional InGaP-based HEMTs [1–5]. However, because InAlGaP/GaAs heterostructures have the advantages of high ΔEC and high Eg, the n-InAlGaP/GaAs HFET is also investigated. Experimental results demonstrate that both these improved structures have better dc characteristics than the previously reported HFETs [1–8, 17–19].

2. Device structure and fabrication

The two structures studied herein were grown by low-pressure metalorganic chemical-vapour deposition (LP-MOCVD). The InGaP/InGaAs HFET comprised a 0.5 µm undoped GaAs buffer layer, a δ-doped GaAs layer, a 100 Å undoped GaAs spacer layer, a 90 Å undoped In0.25Ga0.75As channel layer, a 100 Å undoped GaAs spacer, a δ-doped GaAs layer, an 80 Å undoped GaAs layer, a 400 Å undoped In0.5Ga0.5P Schottky layer, a 50 Å undoped GaAs setback layer and finally a 500 Å n+-GaAs cap layer sequentially grown on a (1 0 0)-oriented Cr-doped semi-insulating GaAs substrate. The growth temperature and pressure of the InGaP/InGaAs HFET were 690 °C and 150 Torr, respectively.

The InAlGaP/GaAs HFET was grown on a Cr-doped semi-insulating GaAs substrate [2° off (1 0 0)] towards [1 1 1]) as layers in the following order: a 0.3 µm undoped GaAs buffer layer, a 1000 Å n-In0.5Al0.5Ga0.5P Schottky layer and a 750 Å n+-GaAs cap layer. A misorientated GaAs substrate was used to reduce the long-range ordering. The growth temperature and pressure of the InAlGaP/GaAs HFET were 725 °C and 150 Torr, respectively. Figures 1(a) and (b) display the approximate conduction-band diagrams of the InGaP/InGaAs and InAlGaP/GaAs HFETs. Trimethylindium (TMI), trimethylaluminium (TMA), trimethylgallium (TMG), arsine (AsH3) and phosphine (PH3) were used as the In, Al, Ga, As and P sources, respectively, to form the two structures of interest. Silane (SiH4) was adopted as the n-type source.

The etchants for InAlGaP and GaAs were H3PO4:HCl (4:1) and NH4OH:H2O2:H2O (5:5:100), respectively. The etchant provides high selectivity of etching between InAlGaP and GaAs. Au/Ge/Ni metal was used to form source and drain ohmic contacts. Ag was then evaporated on Au/Ge/Ni to further reduce the contact resistance. Finally, Au was evaporated on the InAlGaP layer as the Schottky contact metal. The dimensions of the gate were 1.5 × 125 µm2.

3. Results and discussion

The critical thickness (Lc) of pseudomorphic strained layers must be determined to enable them to be grown. With reference to the proposed InGaP/InGaAs HFET, In0.75Ga0.25As has a different lattice constant from GaAs. The maximum thickness at which In0.75Ga0.25As can remain strained, without relaxation that would generate defects or dislocations, is called the critical thickness. The theoretical expression, proposed by Matthews and Blakeslee [15], for the critical thickness of the layer is

$$\varepsilon = \frac{a(1 - \frac{x}{2})[\ln \left(\frac{L_c \sqrt{\pi}}{x}\right) + 1]}{2 \cdot \sqrt{\frac{x}{2} \cdot \pi \cdot L_c}} \cdot (1 + \sigma)$$

where $\varepsilon = 0.07x$, $a$ is the GaAs lattice constant and $\sigma$ is Poisson’s ratio. The thickness is calculated to be 107 Å. Therefore, an InGaAs channel thickness of 90 Å is selected; this value is less than the critical thickness.

A Hall measurement is performed on the sample to determine the carrier mobility and the 2DEG concentration at 5000 G. The 2DEG concentration and mobility of InAlGaP/GaAs HFET are 4 × 1012 cm−2 and 930 cm2 V−1 s−1, respectively, at 300 K. Table 1 lists the Hall measurement results that pertain to this InGaP/InGaAs HFET and the previously reported GaAs/In0.75Ga0.25As structures (x = 0.25) [5, 13]. The InGaP/InGaAs HFET exhibits superior 2DEG concentration and mobility, because of the high quality of the GaAs/InGaAs heterostructure, the double δ-doped structure and the optimum spacer thickness of 100 Å.

Figure 2 shows the two-terminal gate–source $I–V$ characteristics of the HFETs proposed herein at 300 K.

**Table 1. Hall measurements of this InGaP/InGaAs HFET and the previously reported GaAs/In0.75Ga0.25As structures (x = 0.25).**

<table>
<thead>
<tr>
<th>Structure Description</th>
<th>$\mu_n$ (cm2 V−1 s−1)</th>
<th>$\sigma_{2DEG}$ (1012 cm−2)</th>
<th>$\mu_n \times \sigma_{2DEG}$ (1010 V−1 cm−2 s−1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double δ-doped InGaP/InGaAs HFET (proposed herein)</td>
<td>5410</td>
<td>19200</td>
<td>3.85</td>
</tr>
<tr>
<td>Single δ-doped InGaP/InGaAs HFET</td>
<td>2100</td>
<td>7100</td>
<td>3.8</td>
</tr>
<tr>
<td>Inverted δ-doped GaAs/InGaAs HFET</td>
<td>3150</td>
<td>12600</td>
<td>2.9</td>
</tr>
</tbody>
</table>

*a Reference [5].

*b Reference [13].
The InAlGaP/GaAs HFET exhibits an extremely low-leakage current, even the use of the n-doped Schottky layer. The gate–source breakdown voltages ($BV_{gs}$) of the two studied HFTs, defined as the voltages at which the gate current density reaches 1 mA mm$^{-1}$, exceed 40 V. Figure 3 plots the extrinsic transconductance ($g_m$) versus the gate voltage of the InGaP/InGaAs and InAlGaP/GaAs HFTs at 300 K. The $g_m$ values of these two HFTs remain large, even when the gate voltages are positive. Therefore, an FET can be operated with a single power supply. The $g_m$ values of InGaP/InGaAs and InAlGaP/GaAs HFTs are 154 and 170 mS mm$^{-1}$, respectively. The $I_{max}$ values of the InGaP/InGaAs and InAlGaP/GaAs HFTs are 350 and 410 mA mm$^{-1}$, respectively. Table 2 compares this InGaP/InGaAs HFET with the previously reported HFTs of the same gate length [4, 5]. This double $\delta$-doped InGaP/InGaAs HFET proposed herein is superior to the single $\delta$-doped InGaP/GaAs HFTs. These facts demonstrate that the symmetrically $\delta$-doped HFET provides a higher 2DEG concentration and mobility than the single $\delta$-doped InGaP/GaAs HFTs. Table 3 compares the characteristics of this n-InAlGaP/GaAs HFET with those of the previously reported n-InGaP/GaAs FETs ($L_g = 1.5 \mu m$).

### Table 2. Comparison of the characteristics of this double $\delta$-doped InGaP/InGaAs HFET with the previously reported single $\delta$-doped InGaP/InGaAs HFTs ($L_g = 1.5 \mu m$).

<table>
<thead>
<tr>
<th></th>
<th>$g_m$ (mS mm$^{-1}$)</th>
<th>$I_{max}$ (mA mm$^{-1}$)</th>
<th>$BV_{gs}$ (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double $\delta$-doped InGaP/In$<em>{0.23}$Ga$</em>{0.77}$As HFET (proposed herein)</td>
<td>154</td>
<td>350</td>
<td>$&gt;40$</td>
</tr>
<tr>
<td>Single $\delta$-doped InGaP/In$<em>{0.23}$Ga$</em>{0.77}$As HFET$^a$</td>
<td>82</td>
<td>215</td>
<td>$&gt;40$</td>
</tr>
<tr>
<td>Single $\delta$-doped InGaP/In$<em>{0.17}$Ga$</em>{0.83}$As HFET$^b$</td>
<td>72</td>
<td>160</td>
<td>$&gt;40$</td>
</tr>
</tbody>
</table>

$^a$ Reference [4].

$^b$ Reference [5].

### Table 3. Comparison of the characteristics of this n-InAlGaP/GaAs HFET with those of the previously reported n-InGaP/GaAs FETs ($L_g = 1.5 \mu m$).

<table>
<thead>
<tr>
<th></th>
<th>$g_m$ (mS mm$^{-1}$)</th>
<th>$I_{max}$ (mA mm$^{-1}$)</th>
<th>$BV_{gs}$ (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>n-InAlGaP/GaAs HFET (proposed herein)</td>
<td>170</td>
<td>410</td>
<td>$&gt;40$</td>
</tr>
<tr>
<td>n-InGaP/GaAs FET$^a$</td>
<td>87.9</td>
<td>320</td>
<td>$&gt;40$</td>
</tr>
<tr>
<td>n-InGaP/GaAs $t$-HEMT$^b$</td>
<td>120</td>
<td>$\sim$250</td>
<td>26</td>
</tr>
<tr>
<td>n-InGaP/GaAs $f$-HEMT$^b$</td>
<td>100</td>
<td>$\sim$300</td>
<td>14</td>
</tr>
</tbody>
</table>

$^a$ Reference [1].

$^b$ Reference [2].

4. Conclusion

This investigation proposes an improved double $\delta$-doped InGaP/InGaAs and the first n-InAlGaP/GaAs HFTs grown by LP-MOCVD. These two improved structures provide the benefits of high drain current densities, high $g_m$, low-leakage currents and high-breakdown voltages. These results demonstrate that the HFTs developed herein are appropriate for high-power applications.
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Acknowledgment

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