n⁺-GaAs/p⁺-InAlGaP/n⁺-InAlGaP Camel-Gate High-Electron Mobility Transistors

Yu-Shyan Lin,a,z Dong-Hai Huang,b Wei-Chou Hsu,b Tzong-Bin Wang,b Rong-Tay Hsu,c and Yu-Huei Wuc

aDepartment of Materials Science and Engineering, National Dong Hwa University, Hualien 974, Taiwan
bInstitute of Microelectronics, Department of Electrical Engineering, National Cheng-Kung University, Tainan, Taiwan
cLand Mark Optoelectronics Corporation, Tainan, Taiwan

This investigation proposes InAlGaP/InGaAs camel-gate high-electron mobility transistors with inverted δ-doping layers (CAMHEMTs). CAM-HEMTs with various gate metals, including Au, Pt/Au, Ti/Au, and Ni/Au, are investigated. The CAM-HEMT with the Ni/Au gate metal exhibits the benefits of a large gate voltage swing (3.6 V), a high two-terminal gate-source breakdown voltage (≥20 V), a small gate leakage current, and a high temperature-insensitive threshold voltage. These characteristics are attributable to the inverted δ-doping layer, the large conduction-band discontinuity of the InAlGaP/InGaAs heterojunction, the large bandgap of InAlGaP and the high camel-gate barrier with the Ni/Au gate metal.

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Over the past several years, InGaP/InGaAs high-electron mobility transistors (HEMTs) have become one of the most important semiconductor devices used in microwave applications.1-3 Several research groups have been reported to improve the breakdown voltage of the heterostructure field-effect transistors (HFETs) without decreasing the current drivability, such as buried gate HFETs,4 metal-insulator-semiconductor FETs,5 and camel-gate FETs.6-8 In particular, the CAMEFET provides several advantages, such as (i) the elimination of metallurgical difficulties associated with metal-semiconductor contacts; (ii) the relative ease of adjustment of the built-in voltage, and (iii) the potential for improving reliability at high temperatures. For high power applications, the device should have a high breakdown voltages and high current driving capability. The driving currents are directly related to the sheet charge density in the channel. An effective way to increase the sheet charge density is to use material systems with a large conduction-band discontinuity.9,10 In principle, a larger conduction-band discontinuity corresponds to a larger sheet charge density, so the current driving capacity is greater. The larger conduction-band discontinuity in HEMTs also reduces the output conductance and the real space transfer, improving the performance of the device.

Our previous studies demonstrated the use of alternative InAlAsSb/InGaAs,11,12 InAlGaP/GaAs,13 InAlAsSb/InAlGaP/CdSb,14,15 and InAlGaP/GaAs16 materials systems used in microwave devices. Recently, Liu et al. presented a series of GaAs/InGaP CAMFETs.8,10 However, no study has focused on GaAs/InAlGaP CAMFETs. Therefore, this work presents high-electron mobility transistors with the quaternary camel-gate and inverted δ-doping layer (CAM-HEMTs). The n⁺-GaAs/p⁺-InAlGaP/n⁺-InAlGaP camel gate is employed to replace the GaAs homojunction camel gate,6,8 the GaAs/AlGaAs heterojunction camel gate,6,7 the GaAs/InGaP heterojunction camel gate,7 and the conventionally used Schottky gate.8,11,12,13,14 The high-barrier gate can effectively prevent electron injection into the channel. The good carrier confinement in the InAlGaP/InGaAs/InAlGaP heterostructure channel also reduces the substrate leakage current at elevated temperatures. The experimental data demonstrate the excellent output characteristics of the CAM-HEMT because of the design of the camel gate and the use of the InAlGaP/InGaAs heterojunction.

**Experimental**

The CAM-HEMT was grown by metalorganic chemical-vapor deposition (MOCVD). The CAM-HEMT was grown on a Cr-doped semi-insulating GaAs substrate as the following layers −0.5 μm undoped GaAs buffer layer, δ-doping layer (n+ = 3.5 × 10¹² cm⁻²), 30 Å undoped In₀.₅Ga₀.₅As spacer layer, 90 Å undoped In₀.₅Ga₀.₅As channel layer, 600 Å n⁺-In₀.₅Ga₀.₅As spacer layer, 100 Å p⁺-In₀.₅Ga₀.₅As spacer layer, and 200 Å n⁺-GaAs (n = 4 × 10¹⁸ cm⁻³). Figure 1 illustrates the cross section of the CAM-HEMT. The growth pressures of all of the layers were 100 Torr. The growth temperatures for InAlGaP and InGaAs were 700 and 650°C, respectively. Trimethylindium (TMI), trimethylaluminum (TMA), trimethylgallium (TMG), arsine (AsH₃) and phosphine (PH₃) were used as sources of In, Al, Ga, As, and P, respectively. Standard photolithography and lift-off methods were used to fabricate devices. The etchants for InAlGaP and GaAs were HCl and H₂PO₄:H₂O₂:H₂O (1:1:30), respectively. The etching rates of InAlGaP and GaAs were 50 and 15 Å/s, respectively. The etching solutions perform high-selectivity etching between InAlGaP and GaAs. Au/GeNi/Au metal was used as the source and drain ohmic contacts. For comparison, four metals, including Au, Pt/Au, Ti/Au, and Ni/Au, were evaporated as the gate contact metals. The source, drain, and gate contact metals were deposited on the
n⁺-GaAs layer. After these contacts were formed, the CAM-HEMT was dipped in the etchant to recess the partial n⁺-GaAs layer, which is not protected by the gate metal. The gate areas were 1.5 × 125 μm. The source-drain spacing was 5 μm. All the device characteristics of this proposed CAM-HEMT were measured using an HP-4156 semiconductor parameter analyzer.

Results and Discussion

Figure 2 depicts the current-voltage characteristics of the CAM-HEMT with an Ni/Au gate. The gate leakage current at VGS = 1 V is as small as 177 μA/mm. The threshold voltage (Vth) of the CAM-HEMT is −7.2 V because of the use of the inverted doping layer. The gate turn-on voltage, measured at a forward gate current of 1 mA/mm, is 1 V. Figure 3 plots the extrinsic transconductance (gms) vs VGS at a bias of VDS = 7 V. The gate voltage swing, defined by a 10% drop in the maximum gms, is as large as 3.6 V, which can reduce the third-harmonic distortion and so serve as a linear amplifier. These characteristics are attributed to the inverted δ-doping and to the large ΔEC at the InAlGaP/InGaAs heterojunction. The design of the inverted δ-doping increases the reversed operating voltage. Moreover, the large ΔEC of the InAlGaP/InGaAs/InAlGaP heterojunction leads to the strong carrier confinement. ΔEC of the In0.53Ga0.47As/In0.25Ga0.75As is approximately 0.43 eV.17,18 This value exceeds those of Al0.3Ga0.7As/In0.2Ga0.8As (0.407 eV) and In0.5Ga0.5P/In0.25Ga0.75As (0.34 eV). Figure 4 displays the gate-source diode characteristics of the CAM-HEMT at 300 K. The breakdown voltage of the InAlGaP/GaAs CAM-HEMT, at which IG = 1 mA/mm, exceeds 20 V. This value is superior to those of the δ-doping InGaP/GaAs CAM-HEMT (7.8 V)3 and the InGaP/GaAs doped channel CAMFET (16.5 V).10 The gate-dominated high-breakdown characteristics are attributed to the use of the high InAlGaP/GaAs camel-gate barrier, which reduces the thermionic-field emission. Table I summarizes the dc output characteristics of the CAM-HEMTs with different gate metals. The CAM-HEMT with Ni/Au gate has the largest two-terminal breakdown voltage and the smallest drain-source leakage current of the four CAM-HEMTs with different gate metals, because the barrier in the CAM-HEMT with the Ni/Au gate is highest. Figure 5 plots the gate current of the CAM-HEMT as a function of the gate-source voltage for VDS from 1.2 to 2 V. The gate current is as low as 8.2 μA/mm at VGS = 4 V and VDS = 2 V. Notably, the gate current does not exhibit the bell-shaped characteristics, which are commonly observed in the InGaAs-based HFETs. Additionally, the temperature dependence of the CAM-HEMT is also investigated. The Vth shift of CAM-pHEMT is very small in the temperature range 300–420 K.

Conclusions

This study proposes a series of InAlGaP/InGaAs CAM-HEMTs with different gate metals. The barrier heights and dc characteristics for the CAM-HEMTs with various gate metals are examined. The

Table I. Comparison of the CAM-HEMTs with various gate metals (Lg = 1.5 μm).

<table>
<thead>
<tr>
<th>Gate metal</th>
<th>Pt/Au</th>
<th>Au</th>
<th>Ti/Au</th>
<th>Ni/Au</th>
</tr>
</thead>
<tbody>
<tr>
<td>qφ (eV)</td>
<td>0.816</td>
<td>0.842</td>
<td>0.852</td>
<td>0.867</td>
</tr>
<tr>
<td>BVφ (V)</td>
<td>9.2</td>
<td>13.8</td>
<td>19</td>
<td>&gt;20</td>
</tr>
<tr>
<td>IDS,leakage (μA/mm) at VDS = 0 V</td>
<td>548</td>
<td>512</td>
<td>283</td>
<td>177</td>
</tr>
<tr>
<td>and VGS = 1 V</td>
<td></td>
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</tbody>
</table>
CAM-HEMT with Ni/Au exhibits a high breakdown voltage, large gate voltage swing, and good thermal stability. Accordingly, the CAM-HEMT developed herein is promising for high-power and high-temperature operations.

**Figure 5.** Gate current vs gate-source voltage of the CAM-HEMT with Ni/Au gate metal for $V_{DS}$ from 1.2 to 2 V at 300 K.

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### References