Gate-alloy-related kink effect for metamorphic high-electron-mobility transistors

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Gate-metal-related kink effects in InAlAs/InGaAs/GaAs metamorphic high-electron-mobility transistors have been investigated. Improvements on the kink effect have been observed by using the higher Schottky barrier height gate alloys, including Ti/Au, Ni/Au, and Pt/Au, as compared to the use of the conventional Au gate metal. In comparison with gate alloy combinations, the devices with Ti/Au alloy exhibit superior noise characteristics, whereas those with Ni/Au alloy demonstrate the highest power characteristics. With the gate dimensions of 1.2 × 200 μm², the device minimum noise figure, NFmin, is 1.17 dB at 2.4 GHz by using Ti/Au and the output power is 13.14 dBm at 2.4 GHz by using Ni/Au. Significant rf characteristics have also been improved upon that with Au gate. © 2004 American Institute of Physics [DOI: 10.1063/1.1823600]

InAlAs/InGaAs high-electron-mobility transistors (HEMTs) on InP substrate have shown high gain and low noise at millimeter-wave frequencies as compared to GaAs-based pseudomorphic HEMTs. However, the disadvantages of InP substrate including fragility, limited wafer size, and higher cost have made GaAs substrates more suitable for large scale MMIC applications. Trying to realize the lattice-mismatched compounds on GaAs substrate, attempts have lately been made to grow the InAlAs/InGaAs/GaAs metamorphic high-electron-mobility transistors (MHEMTs). Yet, the narrower band gap channel is observed to easily initiate the impact ionization effects, thus, giving rise to the current increase. Moreover, the generated holes through the effective impact ionizations will further result in the kink effects.

The causes of impact-ionization-induced kink effect, consisting of the hole-traps in the buffer, 7 in the barrier, 8 and the decreased source resistance, 9 have been studied. The holes generated from the impact ionization in the channel regime will be injected across the Schottky layer 10 and collected by the gate terminal. It is noted that the gate alloy recipes would dominate the characteristics, including the Schottky barrier height and the interfacial valence band discontinuities, between Schottky layer and channel region. Thus, the kink effect strongly depends on choosing the specific gate metals. In this work, we have investigated the influence of various gate alloys on the kink effect, the breakdown characteristics, the extrinsic transconductance, and high-frequency performance in the MHEMTs.

As indicated in Fig. 1, the studied MHEMT epitaxial structure was grown on semi-insulating GaAs substrate by the molecular beam epitaxy technique. A 0.6 μm InAlGaAs metamorphic graded buffer layer was deposited on the GaAs substrate by keeping its band gap larger than the GaAs substrate (1.42 eV). Upon the graded buffer, a 0.5-μm-thick undoped In0.45Al0.55As barrier layer, a 20 nm undoped In0.53Ga0.47As channel layer, a 4 nm undoped In0.45Al0.55As spacer layer, a silicon planar doping layer, a 25 nm undoped In0.45Al0.55As Schottky layer, and finally a 20 nm Si-doped...
In 0.45 Al0.55 As cap layer were grown, sequentially. Since the band gap of InAlGaAs is designed within the range of 1.7–1.8 eV, which is larger than that of the In0.45 Al0.55 As1.46 eV barrier layer, the leakage current resulting from the substrate layer can be improved.11 The electron mobility and the 2DEG concentration, characterized by Hall measurements under 5000 G at 300 K, were 7658 cm2/V s and 2.9 × 1012 cm−2, respectively. The device processing procedures include: (1) the mesa isolation, performed by chemically wet etching a mesa down to the GaAs substrate; (2) the drain/source ohmic contact metallization, by the rapid thermal annealing of AuGeNi/Au metallurgy; (3) the gate recess etching of n+ In0.45 Ga0.55 As, by wet etching using solution of H3PO4:H2O2:H2O=1:1:30; and (4) gate metal evaporation, by standard photolithography and lift-off techniques. The gate dimensions were 1.2 × 200 μm2.

(1 × 1019 cm−3) In0.45Al0.55As cap layer were grown, sequentially. Since the band gap of InAlGaAs is designed within the range of 1.7–1.8 eV, which is larger than that of the In0.45Al0.55As (1.46 eV) barrier layer, the leakage current resulting from the substrate layer can be improved.11 The electron mobility and the 2DEG concentration, characterized by Hall measurements under 5000 G at 300 K (77 K), were 7658 (30083) cm2/V s and 2.9(3.6) × 1012 cm−2, respectively. The device processing procedures include: (1) the mesa isolation, performed by chemically wet etching a mesa down to the GaAs substrate; (2) the drain/source ohmic contact metallization, by the rapid thermal annealing of AuGeNi/Au metallurgy; (3) the gate recess etching of n+ In0.45Ga0.55As, by wet etching using solution of H3PO4:H2O2:H2O=1:1:30; and (4) gate metal evaporation, by standard photolithography and lift-off techniques. The gate dimensions were 1.2 × 200 μm2.

Figure 2(a) shows typical current–voltage characteristics of the studied device with Au and Ni/Au gate-alloys at 300 K. The device with Au gate shows significant kink effect. The drain current increases rapidly above the threshold voltage (VGS = −2 V) and at high drain voltage (VDS > 1.5 V) due to impact ionization and kink effect. However, the drain current remains low and almost constant at the threshold voltage (VGS = −2.5 V). The dependence of the extrinsic transconductance (gm) on the gate voltage of the studied MHEMT with Au and Ni/Au gate metals is shown in Fig. 2(b). Sharper transconductance profile near the threshold voltage and poorer gate voltage swing, due to the kink effect, have been observed for the Au gate as compared to that of Ni/Au gate-alloy. This is attributed to the fact that Ni/Au has larger barrier height than Au. Though the larger barrier height may reduce the discontinuity of valence band, making the holes easier to be injected into the gate, the depletion region under gate will be significantly extended, consequently decreasing the carrier population in the channel. Figure 3 shows the calculated band diagram and the respective electron concentration at thermal equilibrium by the self-consistent method. We have observed that the increase of barrier height (ΔΦB) is larger than the decrease of valence band discontinuity (ΔEVB). Due to the dominant influence of the barrier height, the electron concentration is decreased and the kink effect is improved. The typical “bell-shaped” behavior observed at different drain-source voltages with Au and Ni/Au gate, shown in Fig. 4, is related to the occurrence of impact ionization in the channel.12 Due to the present high electric field in the gate-to-drain region at high VDS, significant hot-electron phenomena take place in the channel regime. In particular, electrons can obtain enough energy to further generate electron–hole pairs through effective impact ionizations.13 The peak gate current density with Ni/Au gate, in Fig. 4(b), is significantly improved as compared to that of Au gate, in Fig. 4(a). It is the evidence to reduce the impact ionization using gate metal with high barrier height. Therefore, the hole concentration is decreased to prevent the kink effect.

Table I lists the comparisons of dc and rf characteristics for employing various gate alloys. Au-gate has the highest peak extrinsic transconductance value due to the kink effect. In addition, thanks to the highest barrier height by using Pt/Au gate alloy, it demonstrates the lowest saturation drain current density, IDSS at VGS=0 V, the highest gate-to-drain breakdown voltage, VGBP, defined at IDSS=1 mA/mm, and the

![Figure 2](image1.png)

**FIG. 2.** (a) Current–voltage characteristics at 300 K. (b) Extrinsic transconductance as a function of the gate-source bias at 300 K.

![Figure 3](image2.png)

**FIG. 3.** Schematic band diagram of the studied MHEMT with lower (Au, solid line) and higher (Ni/Au, dash line) barrier height.
threshold voltage, $V_{th}$. Because the kink effect can be significantly suppressed by using Ti/Au, Ni/Au, and Pt/Au alloys, their noise characteristics, the minimum noise figure, $NF_{min}$, all excel over that by using Au-gate. Moreover, the Ti/Au gate alloy demonstrates the best $NF_{min}$ performance due to its lowest contact resistance. The best output power ($P_{out}$) is achieved by using the Ni/Au metal due to the integrated performance of current drive, $I_{DSS}$, and breakdown characteristics, $V_{GD}$. The values of unity current gain cut-off frequency ($f_T$) for Ti/Au, Ni/Au, and Pt/Au gate-alloys are all above 20 GHz and demonstrate better high-frequency characteristics than that of Au-gate.

**TABLE I. Comparisons of dc and rf characteristics by using different gate alloys.**

<table>
<thead>
<tr>
<th>Gate Metal</th>
<th>Au</th>
<th>Ti/Au</th>
<th>Ni/Au</th>
<th>Pt/Au</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q\Phi_p$ (eV)</td>
<td>0.485</td>
<td>0.606</td>
<td>0.608</td>
<td>0.730</td>
</tr>
<tr>
<td>$I_{DSS}$ (mA/mm)</td>
<td>433</td>
<td>415</td>
<td>421</td>
<td>394</td>
</tr>
<tr>
<td>$g_m$ (mS/mm)</td>
<td>280</td>
<td>220</td>
<td>206</td>
<td>200</td>
</tr>
<tr>
<td>$V_{GD}$ (V)</td>
<td>$-10.5$</td>
<td>$-10.6$</td>
<td>$-11$</td>
<td>$-9.5$</td>
</tr>
<tr>
<td>$V_{th}$ (V)</td>
<td>$-2.47$</td>
<td>$-2.24$</td>
<td>$-2.24$</td>
<td>$-1.95$</td>
</tr>
<tr>
<td>$NF_{min}$ (dB, at 2.4 GHz)</td>
<td>2.16</td>
<td>1.17</td>
<td>1.2</td>
<td>1.29</td>
</tr>
<tr>
<td>$f_T$ (GHz)</td>
<td>17.2</td>
<td>21.8</td>
<td>23.8</td>
<td>20.2</td>
</tr>
<tr>
<td>$P_{out}$ (dBm, at 2.4 GHz)</td>
<td>11.26</td>
<td>11.74</td>
<td>13.14</td>
<td>12.97</td>
</tr>
</tbody>
</table>

In summary, comparisons between the MHEMT characteristics with various gate-alloys have been made. The dominant influences of Schottky height on improving the kink effect and the resulting device performance have also been investigated. Both the kink effect and impact ionization effect can be significantly improved by using the high barrier height gate-alloys, including Ti/Au, Ni/Au, and Pt/Au, resulting in the comprehensively superior device gain, threshold, noise, power drive, breakdown and high-frequency characteristics.

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