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<td>Author(s)</td>
<td>Arulkumaran, Subramaniam; Ranjan, K.; Ng, G. I.; Manoj Kumar, C. M.; Vicknesh, S.; Dolmanan, S. B.; Tripathy, S.</td>
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High-Frequency Microwave Noise Characteristics of InAlN/GaN High-Electron-Mobility Transistors on Si (111) Substrate

S. Arulkumaran, Senior Member, IEEE, K. Ranjan, G. I. Ng, Senior Members, IEEE, C. M. Manoj Kumar, S. Vicknesh, S. B. Dolmanan and S. Tripathy

Abstract—We report the first time high-frequency microwave noise performance on 0.17-µm-gate In0.17Al0.83N/GaN high-electron-mobility transistors (HEMTs) fabricated on Si(111). The HEMTs exhibited a maximum drain current density of 1320 mA/mm, a maximum extrinsic transconductance of 363 mS/mm, an unity current gain cut-off frequency (fT) of 64 GHz and a maximum oscillation frequency (fmax) of 72/106 GHz. The product fmax(U)/lo(S) = 12.24 GHz·µm is the highest value ever reported for InAlN/GaN HEMTs on Si substrate. At VDS=4V and VG=-2.25V, the device exhibited a minimum noise figure (NFmin) of 1.16 dB for 10 GHz and 1.76 dB for 18 GHz. Small variation of NFmin (<0.5 dB) from 8% to 48% of IDmax (100-636 mA/mm) was observed.

Index Terms—InAlN/GaN, GaN-on-Silicon, HEMT, NFmin, Cut-off frequency, Maximum Oscillation frequency, linearity.

I. INTRODUCTION

AlGaN/GaN high-electron-mobility transistors (HEMTs) are still facing the strain induced reliability problem due to large lattice mismatch (~17%) between AlGaN barrier and GaN buffer layer. In contrast, lattice matched InxAl(1-x)N/GaN HEMT (x~17%) structure can provide more than two times higher Two Dimensional-Electron-Gas (2DEG) sheet carrier density (n3=3x1013 cm-2)[1] and also helps to mitigate the strain induced reliability issues. The combination of high n3 and small gate length devices can provide improved DC and RF performances. Yue et al., achieved very high fT=370 GHz with 30 nm-gate-length T-gate InAlN/GaN HEMT on SiC substrate with re-grown ohmic contacts [2]. However, the devices suffered from high gate-resistance (RG=183 Ω-mm) which leads to poor fmax (~28 GHz). Sun et al., reported fT of 113 GHz and fmax of 105 GHz for 0.1-µm-gate InAlN/GaN HEMTs on high-resistivity (HR) Si substrate [3]. For low-noise receiver module, small minimum noise figure (NFmin) with higher Gs can eliminate the requirement of additional gain building blocks. Excellent microwave noise performance for AlGaN/GaN HEMTs on SiC[4] and Si substrates[5-7] have already been reported.

Recently, few groups have also reported the microwave noise performances of InAlN/GaN HEMTs on SiC substrates [8-10]. At 10 GHz, Sun et al., reported a 0.1-µm-gate InAlN/GaN HEMT with NFmin value of 0.62 dB but with an improved associated gain (Gm) of 15.4 dB when compared to AlGaN/GaN HEMTs (Gm=11.2 dB) [6]. However, to the best of our knowledge, no microwave noise performance has been reported using InAlN/GaN HEMTs on Si substrate. In this work, we report the first microwave noise performance of lattice-matched In0.17Al0.83N/GaN HEMTs on Si substrate with NFmin as low as 1.16 dB and 1.76 dB at 10 GHz and 18 GHz respectively. In addition, the product fmax(U)/lo(S) = 12.24 GHz·µm is also the highest value ever reported for InAlN/GaN HEMTs on Si substrate.

II. DEVICE FABRICATION

The HEMTs were fabricated on MOCVD grown un-doped In0.17Al0.83N(9-nm)/AlN(1-nm)/GaN(1000-nm)/AlN(100-nm) heterostructures on (111) oriented high-resistivity (HR) Si substrate exhibiting room temperature 2DEG mobility of 759 cm2/V·s and n3 of 2.74x1013 cm-2. The device fabrication starts with mesa isolation by dry etching process (BCl3/C2H4) followed by conventional Ti/Al/Ni/Au (20/120/40/50 nm) ohmic contact (825 °C/30 s). The extracted contact resistance Rc is 0.36Ω-mm. Subsequently, Ni/Au (150/350 nm) T-gate was formed with 0.17-μm foot-print and 0.5-μm gate-head using electron beam lithography. Finally, the devices were passivated with 120-nm thick SiN by PECVD. The process details can be found in [11]. The device gate-length Lg was confirmed by cross-sectional high-resolution transmission electron microscopy image (See the inset of Figure 1). The device dimensions for this study are: (Lg=W/Lg=0.8/(2x75)/0.17/1.7 µm). The device DC, RF and high-frequency microwave noise characteristics were carried out using Keithley 2636A, HP8510C and ATN NP5 microwave noise setup with HP8970B, respectively. The current collapse of InAlN/GaN HEMTs was measured by pulsed IDS-VDS measurements with pulse width of 200 ns and pulse period of 1ms using DiVA 265 system [12].

III. RESULTS AND DISCUSSIONS

Figure 1 show the IDS-VDS and transfer characteristics of the InAlN/GaN HEMTs on Si substrate. The devices exhibited a maximum drain current density (IDmax) of 1320mA/mm and a maximum extrinsic transconductance, fmax of 363 mS/mm. The observed current density is almost double than that of similar AlGaN barrier thick GaN HEMTs (800mA/mm) [12]. Figure 2(a) shows the small-signal microwave performance of InAlN/GaN HEMTs measured at Vg=-2.4V and VDS=6V. The HEMT exhibited a fT of 64 GHz and a fmax(U)/fmax(MSG) of 72/106 GHz without de-embedding. The product
$f_{\text{max}}(U) \times L_g = 12.24 \text{ GHz} \cdot \mu \text{m}$ is the highest ever reported for InAlN/GaN HEMT on Si substrate. However, the 0.144$\mu$m gate InAlN/GaN HEMTs on SiC substrate exhibited better product values (25 GHz$\cdot$μm) [13] which could be due to higher 2DEG mobility and lower parasitics. Inset of Fig.2 (a) shows the extracted small-signal equivalent circuit parameters. The improved $f_{\text{max}}$ in our devices are due to the occurrence of low values of gated-drain capacitance ($C_{gd}$), gate resistance ($R_g$) and output conductance ($g_{ds}$) [14].

Figure 3(a) shows the NF$_{\text{min}}$ and $G_s$ for 2-18GHz measured at $V_{ds} = 4$ V and $V_{gs} = 2.25$ V. The HEMTs exhibited NF$_{\text{min}}$ value of 1.16 (1.76) dB with $G_s$ of 11.54(7.5) dB at 10 (18) GHz, respectively. The obtained NF$_{\text{min}}$ at 10 GHz and 18GHz are comparable to the reported values for AlGaN/GaN on Si substrate with the same gate length [5]. The measured NF$_{\text{min}}$ of our devices at 18 GHz is comparable to the NF$_{\text{min}}$ of InAlN/GaN on SiC and AlN/GaN on Si substrate (see Table I). However, the NF$_{\text{min}}$ of the reported AlGaN/GaN HEMTs on SiC[4] at 18 GHz is better with a source-drain gap of 2µm. Moreover, the observed $G_s$ is slightly better because of the high $n_i$ (2.74x10$^{13}$ cm$^{-2}$) in the InAlN/GaN HEMT structure. However, at lower frequencies (2-8GHz), slightly higher NF$_{\text{min}}$

Figure 3(b) shows the optimal noise reflection coefficient $|\Gamma_{\text{opt}}|$ and phase angle $\angle \Gamma_{\text{opt}}$ for 2-18GHz for InAlN/GaN HEMT on Si.

Figure 4 shows the NF$_{\text{min}}$ for 10 and 18GHz over a wide range of $I_{Ds}$. The NF$_{\text{min}}$ variation with $I_{Ds}$ is $\frac{\text{NF}_{\text{min(high)}} - \text{NF}_{\text{min(low)}}}{\text{IDS(max)-IDS(min)}}$ is 1.36 dB-mm/A for 10 GHz and 1.67 dB-mm/A for 18GHz. At the same time, the NF$_{\text{min}}$ variation with $I_D$ is better than AlN/GaN HEMTs [19,20] and InAlN/GaN HEMTs on Si substrate. The measured $|\Gamma_{\text{opt}}|$ and $\angle \Gamma_{\text{opt}}$ values are 0.607 (0.61) and 52.1º(89.6º) at 10 (18) GHz, respectively which are comparable to the InAlN/GaN HEMTs on SiC substrate[8]. The overall noise figure (NF) of a linear two-port network is expressed in equation (1) where $\Gamma_s$ is the input reflection coefficient and $R_s$ is the equivalent noise resistance which is an important parameter to estimate the overall noise figure of the device. $NF = NF_{\text{min}}$ when $\Gamma_{opt} = \Gamma_s$. The observed $R_s$ (see inset of Figure 3a) of our device is 25Ω at 10 GHz. However, the $R_s$ at 18 GHz is only 20Ω. This contributes to the small degradation of NF when the source impedance is mismatched to the optimum termination.

$$NF = NF_{\text{min}} + 4R_n \left( \frac{1 - |\Gamma_s|^2}{1 + |\Gamma_{opt}|^2} \right)$$

Table I: State-of-the-art NF$_{\text{min}}$ and variation of NF$_{\text{min}}$ over $I_D$ in AlN/GaN HEMT on Si, AlGaN/GaN HEMTs and InAlN/GaN HEMTs on SiC and Si substrates.

<table>
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<tr>
<th>Affiliation</th>
<th>HEMT Structure</th>
<th>$L_g$ [μm]</th>
<th>NF$<em>{\text{min}}$ [dB] [$I</em>{ds} = 100\mu\text{A}$]</th>
<th>NF$<em>{\text{min}}$ [$I</em>{ds} = 25\mu\text{A}$]</th>
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<td>IEMN [5]</td>
<td>AlGaN/GaN on SiC</td>
<td>0.15</td>
<td>4.8 (+1.8)</td>
<td>4.7 (+1.8)</td>
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<tr>
<td>NTU [18]</td>
<td>AlGaN/GaN on Si</td>
<td>0.25</td>
<td>2.5</td>
<td>2.4</td>
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<td>Triquint [10]</td>
<td>AlGaN/GaN on Si</td>
<td>0.05</td>
<td>0.3</td>
<td>0.04</td>
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<td>Renesas [7]</td>
<td>AlGaN/GaN on SiC</td>
<td>0.18</td>
<td>0.78 (+1.0)</td>
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<tr>
<td>ETH-Z [8]</td>
<td>AlN/GaN on SiC</td>
<td>0.10</td>
<td>0.62 (+1.6)</td>
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<tr>
<td>CNES [8]</td>
<td>AlN/GaN on SiC</td>
<td>0.15</td>
<td>0.8 (+1.8)</td>
<td>-1.18</td>
</tr>
<tr>
<td>BAE [15]</td>
<td>AlN/GaN on Si</td>
<td>0.10</td>
<td>0.3 (+1.8)</td>
<td>-1.07</td>
</tr>
<tr>
<td>This Work</td>
<td>AlN/GaN on Si</td>
<td>0.17</td>
<td>1.16 (+1.76)</td>
<td>1.36</td>
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*Mesa-epitaxy by Implantation, *Grown by Oppenloy on 200μm Si.
AlGaN/GaN HEMTs on Si substrate [5,6] with similar gate-length devices (see Table 1). However, 50-nm-gate InAlN/GaN HEMTs on SiC with field-plate provided small $N_{\text{min}}$ variation with $I_{DS}$, which could be attributed to the reduced access resistance by a selectively re-grown ohmic contacts ($R_\text{a}=0.1$ Ω-mm) [2]. This indicates that InAlN/GaN HEMTs on Si is also promising for wide-bias range and broadband microwave low-noise operations. The good $N_{\text{min}}$ linearity correlates well with the high $g_m$ linearity. As shown in Fig. 1, 80% of the $g_m$ peak value maintains a large gate voltage swing (GVS) [18] of 2.85V. This is 83% larger than the 1.55V obtained in AlGaN/GaN HEMT on Si substrate [12].

Figure 4(b) shows the pulsed $I_{DS}$-$V_{DS}$ characteristics (width=200ns, period=1ms) of InAlN/GaN HEMTs on Si substrate under gate-lag ($V_{GS}=5$ V, $V_{DS}=0$V) and drain-lag ($V_{DS}=5$ V, $V_{GS}=10$V) conditions. About 9% of current collapse was observed from the gate-lag and drain-lag at $V_{DS}=6$V. The percentage of current collapse by gate-lag is better [21] and comparable [22] to the reported current collapse of InAlN/GaN HEMTs on sapphire substrates. The observation of small gate-lag is due to the lattice-matched In$_{0.17}$Al$_{0.83}$N/GaN HEMT structure, which is confirmed by Leach et. al.[22]. In addition, the process related current collapse is also suppressed by the optimized SiN passivation with ammonium sulfide [(NH$_4$)$_2$S]$^x$ pre-treatment [11,12,23].

IV. CONCLUSIONS

Microwave noise performances (2-18GHz) were investigated on 0.17-μm T-gate InAlN/GaN HEMTs on HR-Si substrate. The $f_{\text{max}}$ for 18 GHz is 1.76 dB which is comparable to the $N_{\text{min}}$ of InAlN/GaN HEMTs on SiC and AlN/GaN HEMTs on Si substrates. No significant increase of $N_{\text{min}}$ and decrease of $G_m$ with the increase of $I_D$ (100-636 mA/mm) were observed. Hence, the preliminary results reported in this work shows that InAlN/GaN HEMTs can be a promising candidate for low-noise and high-linearity receiver circuit applications. Further improvement in $N_{\text{min}}$ with improved $G_m$ can be achievable from InAlN/GaN HEMTs by suppressing the gate-leakage current.

REFERENCES