<table>
<thead>
<tr>
<th><strong>Title</strong></th>
<th>High-frequency microwave noise characteristics of InAlN/GaN high-electron mobility transistors on Si (111) substrate</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Author(s)</strong></td>
<td>Arulkumaran, Subramaniam; Ranjan, K.; Ng, G. I.; Manoj Kumar, C. M.; Vicknesh, S.; Dolmanan, S. B.; Tripathy, S.</td>
</tr>
<tr>
<td><strong>Citation</strong></td>
<td>Arulkumaran, S., Ranjan, K., Ng, G. I., Manoj Kumar, C. M., Vicknesh, S., Dolmanan, S. B., et al. (2014). High-Frequency Microwave Noise Characteristics of InAlN/GaN High-Electron Mobility Transistors on Si (111) Substrate. IEEE Electron Device Letters, 35(10), 992-994.</td>
</tr>
<tr>
<td><strong>Date</strong></td>
<td>2014</td>
</tr>
<tr>
<td><strong>URL</strong></td>
<td><a href="http://hdl.handle.net/10220/25657">http://hdl.handle.net/10220/25657</a></td>
</tr>
<tr>
<td><strong>Rights</strong></td>
<td>© 2014 IEEE. This is the author created version of a work that has been peer reviewed and accepted for publication by IEEE electron device letters, IEEE. It incorporates referee’s comments but changes resulting from the publishing process, such as copyediting, structural formatting, may not be reflected in this document. The published version is available at: [<a href="http://dx.doi.org/10.1109/LED.2014.2343455">http://dx.doi.org/10.1109/LED.2014.2343455</a>].</td>
</tr>
</tbody>
</table>
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 Member, IEEE, C. M. Manoj Kumar, S. Vicknesh, S. B. Dolmanan and S. Tripathy

Abstract—We report for the first time high-frequency microwave noise performances 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)/fMAX(MSG) of 12.24 GHz/µm is the highest value ever reported for InAlN/GaN HEMTs on Si substrate. At VDS=4V and VGS=2.25V, the device exhibited a minimum noise figure (NF min) of 1.16 dB for 10 GHz and 1.76 dB for 18 GHz. Small variation of NF min (<0.5 dB) from 8% to 48% of fMAX (100-636 mA/mm) was observed.

Index Terms—InAlN/GaN, GaN-on-Silicon, HEMT, NF min. 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 InxAl1-xN/GaN HEMT (x~17%) structure can provide more than two times higher Two-dimensional-Electron-Gas (2DEG) sheet carrier density (n2~3x1013 cm-2)[1] and also helps to mitigate the strain induced reliability issues. The combination of high n2 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 regrown 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 (NF min) 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 NF min value of 0.62 dB but with an improved associated gain (Gs) of 15.4 dB when compared to AlGaN/GaN HEMTs (Gs=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 NF min as low as 1.16 dB and 1.76 dB at 10 GHz and 18 GHz respectively. In addition, the product fMAX(U)/Lg=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/AlN/GaN (9-10 nm)/AlN(100 nm)/GaN(1000 nm) heterostructures on (111) oriented high-resistivity (HR) Si substrate exhibiting room temperature 2DEG mobility of 759 cm2/V·s and n2 of 2.7×1013 cm-2. The device fabrication starts with mesa isolation by dry etching process (BCl3/Cl2), 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 footprint 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: (Ld/Wd/Lg/dg=0.8×(2×75)/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 1320 mA/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 (800 mA/mm) [12]. Figure 2(a) shows the small-signal microwave performance of InAlN/GaN HEMTs measured at VDS=-2.4V and VGS=6V. The HEMT exhibited a fT of 64 GHz and a fMAX(U)/fMAX(MSG) of 72/106 GHz without de-embedding. The product
$f_{\text{max}}(U) = 12.24 \ \text{GHz} \cdot \mu\text{m}$ 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·$\mu$m) [13] which could be due to higher 2DEG mobility and lower parasitics. The observation of high gate-leakage ($\Gamma_{\text{Leak}}$) of our devices at 18 GHz is comparable to the reported values for AlGaN/GaN on Si substrate [5]. The measured $f_{\text{max}}$ and $G_s$ for 2-18GHz measured at $V_{GS} = 4$ V and $V_{DS} = 2.25$ 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 SiC substrate[4]. 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 2$\mu$m. Moreover, the observed $G_s$ is slightly better because of the high $n_s$ ($2.74 \times 10^{13}$ cm$^{-2}$) in the InAlN/GaN HEMT structure. However, at lower frequencies (2-8GHz), slightly higher $NF_{\text{min}}$ values and variations were observed. This could be attributed to the shot-noise source due to high gate-leakage current ($I_{\text{Leak}} = 75 \mu$A/mm)[15]. Sanabria et al., have also observed the increase of $NF_{\text{min}}$ with the increase of $I_{\text{Leak}}$ in AlGaN/GaN HEMTs on SiC substrate [15]. The observation of high gate-leakage is common for Schottky-gate based InAlN/GaN HEMTs [17]. This can be improved by using Metal-Insulator-Semiconductor HEMT (MISHEMT) approach reported in AlGaN/GaN MISHEMTs on Si substrate [18].

Figure 3(b) shows the optimal noise reflection coefficient [$\Gamma_{\text{opt}}$] and phase angle $\Delta \Gamma_{\text{opt}}$ for different frequencies of $f$.

InAlN/GaN HEMTs on Si substrate. The measured $|\Gamma_{\text{opt}}|$ and $\Delta \Gamma_{\text{opt}}$ 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 $\Gamma_x$ is the equivalent noise resistance which is an important parameter to estimate the overall noise figure of the device. $NF = NF_{\text{min}}$ when $\Gamma_{\text{opt}} = \Gamma_s$. The observed $\Gamma_x$ (see inset of Figure 3a) of our device is 25$\Omega$ at 10 GHz. However, the $\Gamma_x$ at 18 GHz is only 20$\Omega$. This contributes to the small degradation of $NF$ when the source impedance is mismatched to the optimum termination.

$$NF = NF_{\text{min}} + \frac{4R_n}{50} \left( \frac{1}{1 - |\Gamma_s|^2} \right) \left( 1 + |\Gamma_{\text{opt}}|^2 \right)$$

Figure 4 shows the $NF_{\text{min}}$ for 10 and 18GHz over a wide range of $I_D$. The $NF_{\text{min}}$ variation with $I_D$ is $\frac{NF_{\text{min(high)}} - NF_{\text{min(low)}}}{|I_{DS(max)} - I_{DS(min)}|}$ 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 SiC and Si substrates.

<table>
<thead>
<tr>
<th>Affiliation [Ref.]</th>
<th>HEMT Structure</th>
<th>Lg [$\mu$m]</th>
<th>NF (dB)(@10 GHz)</th>
<th>NF (dB)(@100 GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNRS [9]</td>
<td>AlN/GaN on Si</td>
<td>0.15</td>
<td>1.0 (1.2)</td>
<td>-1.18</td>
</tr>
<tr>
<td>ETH-Z [8]</td>
<td>AlN/GaN on SiC</td>
<td>0.15</td>
<td>0.6 (1.2)</td>
<td>-1.18</td>
</tr>
<tr>
<td>Triquint [10]</td>
<td>AlN/GaN on SiC</td>
<td>0.15</td>
<td>0.6 (1.2)</td>
<td>-1.18</td>
</tr>
<tr>
<td>Tufts University</td>
<td>AlN/GaN on Si</td>
<td>0.25</td>
<td>0.85</td>
<td>-0.74</td>
</tr>
<tr>
<td>ETH-Z [8]</td>
<td>AlN/GaN on SiC</td>
<td>0.15</td>
<td>0.6 (1.2)</td>
<td>-1.18</td>
</tr>
<tr>
<td>CNRS [9]</td>
<td>AlN/GaN on Si</td>
<td>0.15</td>
<td>1.0 (1.2)</td>
<td>-1.18</td>
</tr>
<tr>
<td>Tece Work</td>
<td>AlN/GaN on Si</td>
<td>0.15</td>
<td>1.0 (1.2)</td>
<td>-1.18</td>
</tr>
</tbody>
</table>

*aMesa-ololution by Implantation, *bRegrown Ohmic Contacts with Field-Plate, *cUnsual Sn
substrates. No significant increase of InAlN/GaN HEMTs on SiC and AlN/GaN HEMTs on Si [5].

18 GHz is 1.76 dB which is comparable to the reported current collapse of InAlN/GaN HEMTs on SiC [22]. In addition, the process related current collapse is also suppressed by the optimized Si passivation with ammonium sulfide ([NH₄]₂S) pre-treatment [11,12,23].

IV. CONCLUSIONS

Microwave noise performances (2-18 GHz) were investigated on 0.17-μm T-gate InAlN/GaN HEMTs on HR-Si substrate. The f_{max} (U)×L_g = 12.24 GHz·μm is the highest value ever reported for InAlN/GaN HEMTs on Si substrate. The NF_{min} for 18 GHz is 1.76 dB which is comparable to the NF_{min} of InAlN/GaN HEMTs on SiC and AlN/GaN HEMTs on Si substrates. No significant increase of NF_{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 NF_{min} with improved G_{m} can be achievable from InAlN/GaN HEMTs by suppressing the gate-leakage current.

REFERENCES


