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High-Frequency Microwave Noise Characteristics of InAlN/GaN High-Electron-Mobility Transistors on Si (111) Substrate

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Abstract— We report for the first time high-frequency microwave noise performance on 0.17- μm -gate $\text{In}_{0.17}\text{Al}_{0.83}\text{N}/\text{GaN}$ 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 (f_T) of 64 GHz and a maximum oscillation frequency [$f_{\text{max}}(\text{U})/f_{\text{max}}(\text{MSG})$] of 72/106 GHz. The product $f_{\text{max}}(\text{U}) \times L_g = 12.24 \text{ GHz} \cdot \mu\text{m}$ is the highest value ever reported for InAlN/GaN HEMTs on Si substrate. At $V_d = 4\text{V}$ and $V_g = -2.25\text{V}$, 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} ($<0.5\text{dB}$) from 8% to 48% of $I_{D\text{max}}$ (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

AlGaIn/GaN high-electron-mobility transistors (HEMTs) are still facing the strain induced reliability problem due to large lattice mismatch ($\sim 18\%$) between AlGaIn barrier and GaN buffer layer. In contrast, lattice matched $\text{In}_x\text{Al}_{1-x}\text{N}/\text{GaN}$ HEMT ($x \sim 17\%$) structure can provide more than two times higher Two Dimensional-Electron-Gas (2DEG) sheet carrier density ($n_s \sim 3 \times 10^{13} \text{ cm}^{-2}$) [1] and also helps to mitigate the strain induced reliability issues. The combination of high n_s and small gate length devices can provide improved DC and RF performances. Yue et al., achieved very high $f_T = 370 \text{ GHz}$ 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 ($R_g = 183 \Omega\text{-mm}$) which leads to poor f_{max} ($\sim 28 \text{ GHz}$). Sun et al., reported f_T of 113 GHz and f_{max} 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 G_a can eliminate the requirement of additional gain building blocks. Excellent microwave noise performance for AlGaIn/GaN HEMTs on SiC [4] and Si substrates [5-7] have already been reported.

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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 (G_a) of 15.4 dB when compared to AlGaIn/GaN HEMTs ($G_a = 11.2\text{dB}$) [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 $\text{In}_{0.17}\text{Al}_{0.83}\text{N}/\text{AlN}/\text{GaN}$ 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 $f_{\text{max}}(\text{U}) \times L_g = 12.24 \text{ GHz} \cdot \mu\text{m}$ 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 $\text{In}_{0.17}\text{Al}_{0.83}\text{N}$ (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 $\text{cm}^2/\text{V}\cdot\text{s}$ and n_s of $2.74 \times 10^{13} \text{ cm}^{-2}$. The device fabrication starts with mesa isolation by dry etching process (BCl_3/Cl_2), followed by conventional Ti/Al/Ni/Au (20/120/40/50 nm) ohmic contact (825 $^\circ\text{C}/30 \text{ s}$). The extracted contact resistance R_c is $0.36 \Omega\text{-mm}$. 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 L_g was confirmed by cross-sectional high-resolution transmission electron microscopy image (See the inset of Figure 1). The device dimensions for this study are: $(L_{\text{sg}}/W_g/L_g/L_{\text{gd}} = 0.8/(2 \times 75)/0.17/1.7 \mu\text{m})$. 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 $I_{\text{DS}}-V_{\text{DS}}$ measurements with pulse width of 200 ns and pulse period of 1 ms using DiVA 265 system [12].

III. RESULTS AND DISCUSSIONS

Figure 1 show the $I_{\text{DS}}-V_{\text{DS}}$ and transfer characteristics of the InAlN/GaN HEMTs on Si substrate. The devices exhibited a maximum drain current density ($I_{D\text{max}}$) of 1320 mA/mm and a maximum extrinsic transconductance, g_{mmax} of 363 mS/mm. The observed current density is almost double than that of similar AlGaIn barrier thick GaN HEMTs (800 mA/mm) [12]. Figure 2(a) shows the small-signal microwave performance of InAlN/GaN HEMTs measured at $V_g = -2.4\text{V}$ and $V_d = 6\text{V}$. The HEMT exhibited a f_T of 64 GHz and a $f_{\text{max}}(\text{U})/f_{\text{max}}(\text{MSG})$ of 72/106 GHz without de-embedding. The product

Figure 1. I_{DS} - V_{DS} and transfer characteristics of InAlN/GaN HEMTs ($W_g/L_g/L_{gd} = (2 \times 75)/0.17/1.7 \mu\text{m}$) on Si Substrate

$f_{\text{max}}(U) \times L_g = 12.24 \text{ GHz} \cdot \mu\text{m}$ is the highest ever reported for InAlN/GaN HEMT on Si substrate. However, the $0.144 \mu\text{m}$ gate InAlN/GaN HEMTs on SiC substrate exhibited better product values ($25 \text{ GHz} \cdot \mu\text{m}$) [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_{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_d) [14].

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

Figure 2. (a) Small-signal characteristics for InAlN/GaN HEMTs ($W_g/L_g/L_{gd} = (2 \times 75)/0.17/1.7 \mu\text{m}$) on Si substrate (b) Benchmarking with state-of-the-art $f_T \times L_g$, $f_{\text{max}} \times L_g$ for InAlN/GaN HEMTs on Si substrate

values and variations were observed. This could be attributed to the shot-noise source due to high gate-leakage current ($I_{g\text{Leak}} = 75 \mu\text{A/mm}$) [15]. Sanabria et al., have also observed the increase of NF_{min} with the increase of $I_{g\text{Leak}}$ in AlGaIn/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 AlGaIn/GaN MISHEMTs on Si substrate [18].

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

Figure 3(a) NF_{min} and G_a versus frequencies (2-18 GHz) (b) Noise reflection $|\Gamma_{\text{opt}}|$ and phase angle $\angle \Gamma_{\text{opt}}$ for 2-18GHz for InAlN/GaN HEMT on Si.

Figure 4. Variation of NF_{min} and G_a over I_D at 10 GHz and 18GHz (b) Pulsed I_{DS} - V_{DS} characteristics for InAlN/GaN HEMT ($W_g/L_g/L_{gd} = (2 \times 75)/0.17/1.7 \mu\text{m}$).

InAlN/GaN HEMTs on Si substrate. The measured $|\Gamma_{\text{opt}}|$ and $\angle \Gamma_{\text{opt}}$ values are 0.607 (0.61) and 52.1° (89.6°) 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 Γ_s is the input reflection coefficient and R_n 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 R_n (see inset of Figure 3a) of our device is 25Ω at 10 GHz. However, the R_n at 18 GHz is only 20Ω . This contributes to the small degradation of NF when the source impedance is mismatched to the optimum termination.

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

Figure 4 shows the NF_{min} for 10 and 18GHz over a wide range of I_{DS} . The NF_{min} variation with $I_{DS} = \{[NF_{\text{min}}(\text{high}) - NF_{\text{min}}(\text{low})]/[I_{DS}(\text{max}) - I_{DS}(\text{min})]\}$ is 1.36 dB-mm/A for 10 GHz and 1.67 dB-mm/A for 18GHz. At the same time, the NF_{min} variation with I_D is better than AlN/GaN HEMTs [19,20] and

Table I: State-of-the-art NF_{min} and variation of NF_{min} over I_D in AlN/GaN HEMT on Si, AlGaIn/GaN HEMTs and InAlN/GaN HEMTs on SiC and Si substrates

Affiliation [Ref.]	HEMT Structure	L_g [μm]	NF_{min} [dB] @10(18) GHz	$(NF_{\text{min}}(\text{low}) - NF_{\text{min}}(\text{high})) / (I_{DS}(\text{max}) - I_{DS}(\text{min}))$ @10GHz [dB-mm/A]
UIUC [4]	AlGaIn/GaN on SiC	0.25	0.75 (0.98)	-1.25
IEMN [5]	AlGaIn/GaN on Si	0.17	1.1 (1.8)	-14.4
Renesas [7]	AlGaIn/GaN/AlGaIn on Si	0.16	0.78 (~1.2)	-
ETH-Z [8]	InAlN/GaN on SiC	0.10	0.62 (1.5)	-
CNRS [9]	InAlN/GaN on SiC	0.15	0.8 (1.8)	-1.18
Triquint [10]	InAlN/GaN on SiC	0.05	0.3	-0.74
NTU [18]	AlGaIn/GaN on Si	0.25	1.25	-8.49
IEMN [19]	AlN/GaN on Si	0.16	1.0 (1.8)	-1.67
This Work	InAlN/GaN on Si	0.17	1.16 (1.76)	1.36

*Mesa-solation by Implantation, #Regrown Ohmic Contacts with Field-Plate, †Insitu SiN

AlGaIn/GaN HEMTs on Si substrate [5,6] with similar gate-length devices (see Table I). However, 50-nm-gate InAlN/GaN HEMTs on SiC with field-plate provided small $NF_{\min}$ variation with I_{DS} which could be attributed to the reduced access resistance by a selectively re-grown ohmic contacts ($R_c=0.1 \Omega\text{-mm}$) [2]. This indicates that InAlN/GaN HEMTs on Si is also promising for wide-bias range and broadband microwave low noise operations. The good $NF_{\min}$ linearity correlates well with the high g_m linearity. As shown in Fig. 1, 80% of the g_m peak value maintains large gate voltage swing (GVS) [18] of 2.85V. This is 83% larger than the 1.55V obtained in AlGaIn/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 ($V_{gs0}=-5 \text{ V}$, $V_{ds0}=0\text{V}$) and drain-lag ($V_{gs0}=-5 \text{ V}$, $V_{ds0}=10\text{V}$) conditions. About 9% of current collapse was observed from the gate-lag and drain-lag at $V_D=6\text{V}$. 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 $\text{In}_{0.17}\text{Al}_{0.83}\text{N/GaN}$ 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 $[(\text{NH}_4)_2\text{S}_x]$ 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 $f_{\max}(U) \times L_g = 12.24 \text{ GHz}\cdot\mu\text{m}$ 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_a 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_a can be achievable from InAlN/GaN HEMTs by suppressing the gate-leakage current.

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