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Noise characteristics of AlInN/GaN HEMTs at microwave frequencies

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Abstract—The microwave noise parameters measured on AlInN/GaN HEMTs devices with different gate length values are presented in this paper. 0.15- μm HEMTs achieve a maximum current density of 700 mA/mm at $V_{GS} = 0$ V and a measured extrinsic transconductance of 350 mS/mm. The current gain cutoff frequency and the maximum oscillation frequency are 40 GHz and 70 GHz, respectively. At 10 (20) GHz, the device exhibits a minimum noise figure of 0.8 dB (1.8) dB with an associated power gain of 14 (8.8) dB. Below 8 GHz, the gate leakage current and a generation-recombination noise source with a very short time constant limit the noise performance.

Keywords—AlInN/GaN HEMTs; microwave noise parameters.

I. INTRODUCTION

Nitride-based High Electron Mobility Transistors (HEMT) can be used in robust low-noise receivers with high power-handling properties [1]. In these technologies, AlInN/GaN HEMTs are promising devices for power applications at microwave frequencies [2]. Lattice-matched heterostructure offers a high channel charge density compared to the AlGaIn/GaN technology and a record current gain cutoff frequency (f_T) value of 370 GHz was reported in [3]. Furthermore, the absence of strain is an attractive feature for improving the reliability of the devices. The first noise characteristics of this type of device are reported in [4]. A minimum noise figure of 1.5 dB is measured at 20 GHz with a high associated power gain of 13.5 dB. The latter point is attractive compared to other nitride-based transistors to design multi-stage low-noise amplifiers (LNA). However, this technology suffers from a high gate leakage current and from the presence of traps and threading dislocations [5]–[7]. Trapping-detrapping processes with distributed time constants have been also reported in [8] from 100 kHz to 1 GHz. The transconductance and

the output conductance exhibit frequency dispersion in this frequency range which, could be largely increased at high field due to Frenkel-Poole effect.

The noise characteristics of AlInN/GaN HEMTs grown on a SiC substrate are investigated at microwave frequencies. This technology is currently in development at III-V Lab, and several structures from different wafers with different gate length (L_g) values have been characterized. The device

technology is described in Section II. DC and small-signal results are reported in Section III. The noise characteristics are then presented in Section IV.

II. DEVICE TECHNOLOGY

Three different AlInN/GaN HEMTs devices have been studied. The dimensions and the main frequency characteristics of the different samples are reported in Table I. Fig. 1 shows the variations of the minimum noise figure (NF_{min}) and associated gain (G_a) of these devices versus the inverse of the gate length value measured at 12 GHz. As expected, the sample #A exhibits the best noise performance ($NF_{min} = 1$ dB) at 12 GHz. This is mainly due to an increase of the transconductance when the gate length is reduced which also increases the operation frequency as reported in Table I. We will focus our paper on sample #A. Fig. 2 presents the cross section of this transistor.

TABLE I. CHARACTERISTICS OF ALINN/GAN HEMTs

	L_g (μm)	W_g (μm)	f_T (GHz)	f_{MAX} (GHz)
#A	0.15	2×75	41	70
#B ^a	0.25	2×100	24	46
#C	0.70	2×100	15	25

^a. Additional information are available in [9] for device technology

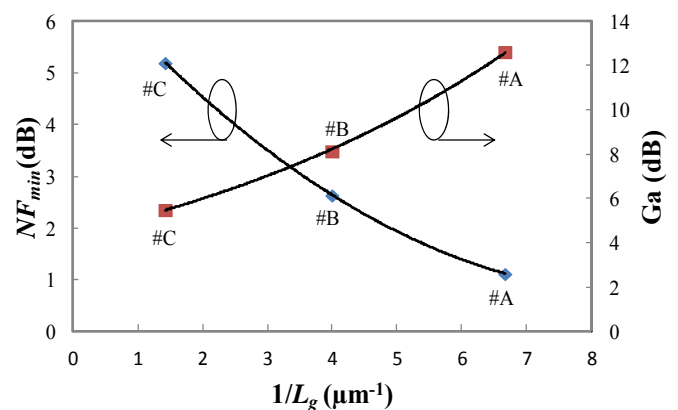


Fig. 1. Minimum noise figure and associated gain versus the inverse of gate length at 12 GHz for different samples biased for low-noise conditions.

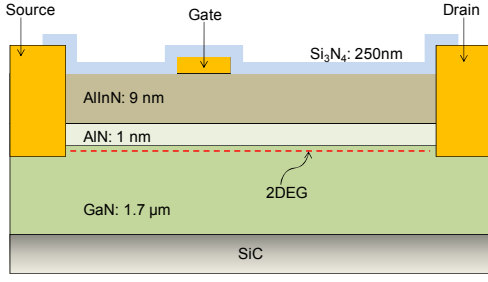


Fig. 2. Cross section of the AlInN/GaN HEMT with 0.15- μm -gate-length.

The layers are grown on a SiC substrate by Low Pressure Metal Organic Chemical Vapour Deposition (LP-MOCVD) using a 2-inch single wafer reactor. The heterostructures consist in a 1.7- μm -thick insulating GaN buffer layer, a 1-nm-thick AlN spacer layer and a 9-nm-thick undoped AlInN layer with 0.2 % of Indium content.

The sheet resistance and the sheet carrier density are evaluated respectively at 330 Ω and $1.52 \times 10^{13} \text{ cm}^{-2}$. Ohmic contacts are formed by rapid thermal annealing of Ti/Al/Ni/Au multilayer at 900 $^\circ\text{C}$ during 30 s under nitrogen ambient, and show an average resistance of 0.45 $\Omega\cdot\text{mm}$. Argon ion implantation is used for device isolation. 150 nm Ni/Pt/Au T-gates are obtained by e-gun evaporation after electron beam lithography. The devices are passivated with a 250-nm-thick Si_3N_4 layer deposited by plasma enhanced chemical vapour deposition. A Ti/Pt/Au multilayer deposited by e-gun is used for interconnections. Multifinger device 3D interconnects are fabricated with plated gold bridge technology on photosensitive BCB.

III. DC AND RF CHARACTERIZATION

DC characteristics have been realized on wafer with a precision semiconductor parameter analyzer (Agilent 4156C). Fig. 3 shows the I-V characteristics of the sample #A. The gate-source voltage (V_{GS}) varies between -4 and 0 V with a step of 0.5 V, while the drain-source voltage (V_{DS}) is comprised between 0 and 10 V. The maximum drain current (I_{DS}) measured at $V_{GS} = 0$ V (I_{DSS}) and $V_{DS} = 10$ V is 700 mA/mm. The peak of the extrinsic transconductance (g_m) obtained at $V_{GS} = -0.5$ V and $V_{DS} = 4$ V is 350 mS/mm. The gate leakage current (I_g) measured at $V_{GS} = -1$ V and $V_{DS} = 5$ V is 45 $\mu\text{A}/\text{mm}$. We obtained 1 and 10 $\mu\text{A}/\text{mm}$ for the samples #B and #C,

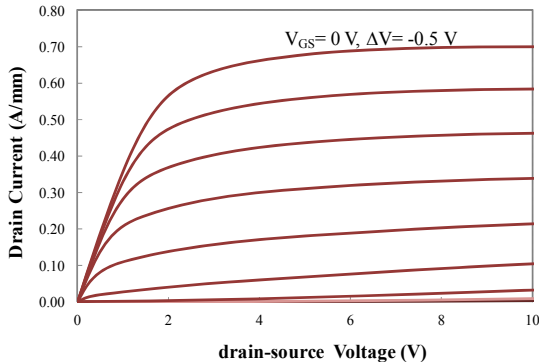


Fig. 3. Drain current (I_{DS}) versus drain-source voltage V_{DS} at different V_{GS} values.

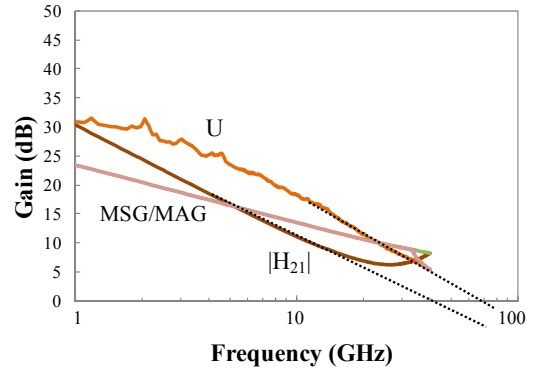


Fig. 4. Microwave performance of AlInN/GaN HEMT with 0.15- μm -gate-length at $V_{DS} = 5$ V and $V_{GS} = -1$ V.

respectively.

The scattering parameters have been measured with a network analyzer (Agilent N5230C). Fig. 4 shows the microwave performances against frequency for the sample #A measured at $V_{GS} = -1$ V and $V_{DS} = 5$ V. The extrapolation of the current gain ($|H_{21}|$) with -20 dB/decade yields to a current gain cutoff frequency of 40 GHz. A maximum oscillation frequency (f_{MAX}) value of 70 GHz is also obtained by extrapolating the Mason's gain (U). The maximum stable gain (MSG) and the maximum available gain (MAG) are also plotted in this figure.

IV. MICROWAVE NOISE CHARACTERIZATION

The noise figure (NF) of a linear two-port is given by the following relation

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

where NF_{min} , R_n and Γ_{opt} are the noise parameters. Γ_s is the reflection coefficient presented at the input of the two-port and Γ_{opt} corresponds to the value of Γ_s obtained for minimum noise figure condition. R_n is the equivalent noise resistance and is directly linked to the noise voltage at the input of the device. The microwave noise parameters have been measured using the multiple impedances technique between 4 and 26 GHz, with a home-made experimental test set [10] and with updated instruments. The automated test bench is controlled with a GPIB interface. Thirteen values of Γ_s well distributed over the Smith chart are generated with a microwave automated tuner (MT986A) and the corresponding noise powers are measured with a noise figure analyzer (Agilent N8975A). The noise parameters are then extracted with an appropriate algorithm method. Additional information related to the experimental setup and extraction procedure can be found elsewhere [10].

Fig. 5 represents the variations of the four microwave noise parameters against frequency at $V_{DS} = 5$ V and $V_{GS} = -1$ V for the sample #A. The variations of NF_{min} reported in Fig.5a clearly indicate a non standard behavior. Experimental data are adjusted with the following expression

$$NF_{\min} = a_0 + a_1 f + a_2 f^2 + \frac{a_3}{f^2} \quad (2)$$

where a_0 , a_1 , a_2 , and a_3 are fitting parameters. The coefficient a_0 is related to the shot noise source due to the gate leakage current. Electrons injected from the gate to the channel flow into the source and the drain when a negative V_{GS} is applied, inducing the gate and drain shot noise [11]. The presence of an excess noise source up to a few GHz (related to the coefficient a_3 in (2)) is not very usual. This has been previously reported by others in AlGaIn/GaN HEMTs [12], [13]. This could be attributed to trapping-detrapping processes with very short time constants (around 1 ns). We have reported in previous work [8] that these effects are present in this technology and directly impact the frequency behavior of the extrinsic transconductance and output conductance. Below 8 GHz, the variations of NF_{\min} could then be attributed to a combined effect of a shot noise source, a generation-recombination (g-r) noise source, and the frequency dispersion of the transconductance and output conductance. Above 8 GHz NF_{\min} increases with frequency due to diffusion noise in the channel [14]. We measured a minimum noise figure and an associated gain around 0.8 dB and 14 dB at 10 GHz, respectively. The values at 20 GHz are 1.8 dB and 8.8 dB, respectively. The noise performances are slightly lower, than those of AlGaIn/GaN HEMTs featuring the same gate length value [12], [15]. However, the associated gain exhibits higher values compared to AlGaIn/GaN heterostructures, as previously observed in [4] for 0.1- μm devices.

Fig. 5.b represents the variations of R_n versus frequency. This parameter continuously decreases from 42 to 13 Ω when the frequency grows. This is attributed to the presence of a g-r

noise source below 8 GHz and to the interconnections between the test pads and the intrinsic device. The latter effect is also observed on the phase of Γ_{opt} plotted in Fig.5d, where significant variations versus frequency are reported (150° at 26 GHz). The magnitude of Γ_{opt} presented in Fig. 5.c slightly varies around 0.5 with frequency.

The noise parameters have been also measured at several bias points to find the optimum bias conditions for minimum noise figure operation. Fig. 6 represents the variations of NF_{\min} at 12 and 26 GHz versus the ratio I_{DS}/I_{DSS} . The drain-source voltage is fixed at $V_{DS}=5$ and 10 V. The minimum noise figure is achieved with a ratio of around 0.3-0.4, corresponding to a drain current value of 200 mA/mm. This value is in agreement with previous work realized on AlGaIn/GaN devices [16], [17]. This bias point is also very close to the peak of the transconductance. Fig. 7 shows the variations of NF_{\min} versus the drain-source voltage measured at a fixed V_{GS} value (-1 V). The variations of the transconductance are also plotted on the same graph. The noise figure exhibits a minimum value at $V_{DS} = 5$ V, which corresponds to the peak value of the transconductance. Above $V_{DS} = 5$ V, NF_{\min} increases due to several factors: reduction of g_m , rise of I_{DS} , and increase of the dissipated power.

The noise performance of AlInN/GaN HEMTs could be improved by reducing the gate leakage current, which represents the limiting factor. This could be achieved by improving the Schottky contact or by using an oxide layer inserted between the AlInN barrier and the gate (MOSHEMT) [18], [19]. This has been demonstrated with 0.7- μm -gate-length devices. The reduction of the gate leakage current directly impacts the minimum noise figure in the “low-

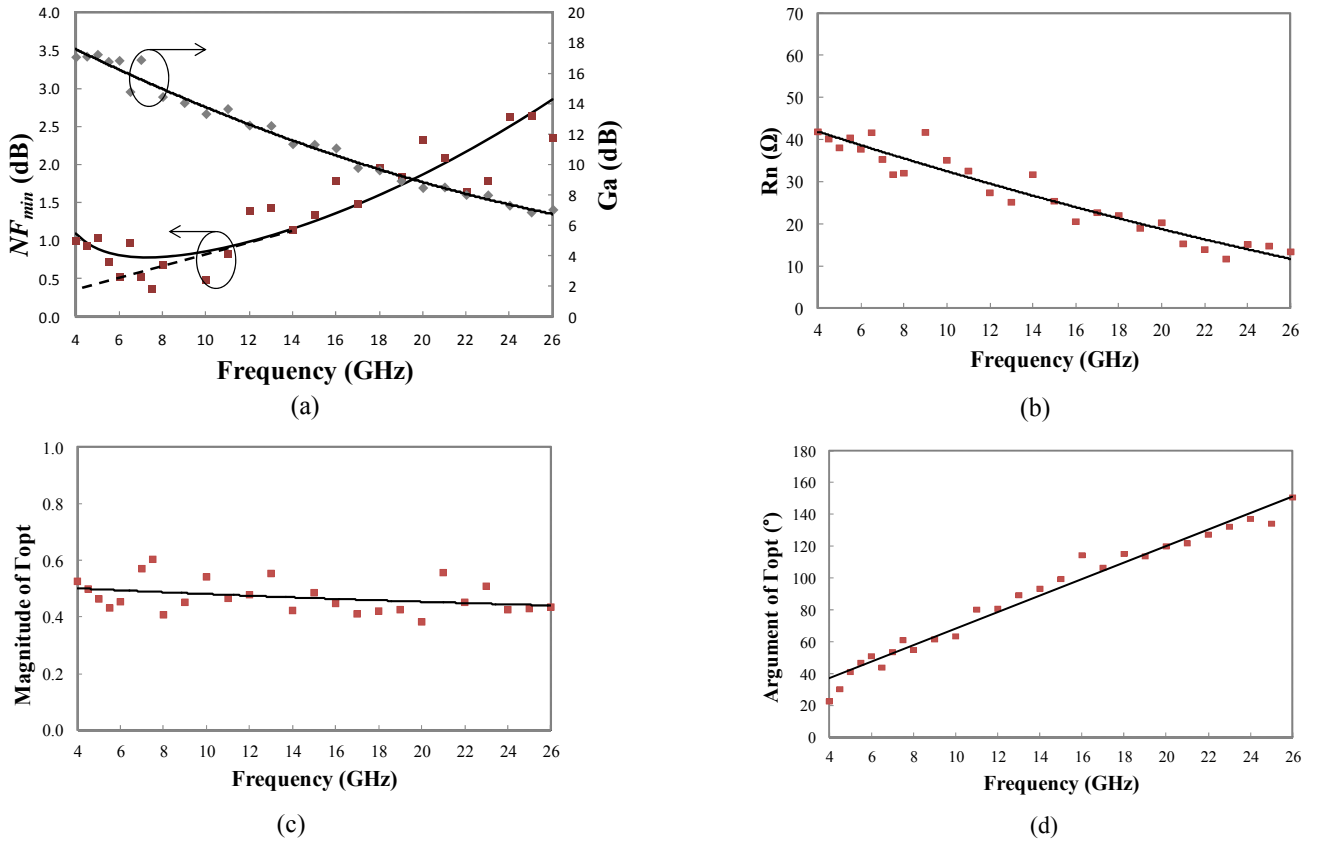


Fig. 5. Noise parameters versus frequency at $V_{DS} = 5$ V and $V_{GS} = -1$ V. (a) Minimum noise figure and associated gain. (b). Equivalent noise resistance. (c). Magnitude of the optimum reflection coefficient. (d). Argument of the optimum reflection coefficient.

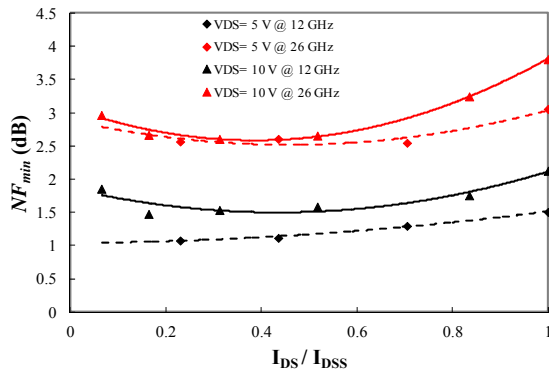


Fig. 6. Minimum noise figure versus the ratio $I_{D_s}/I_{D_{SS}}$ for the 0.15- μm AlInN/GaN HEMT at 12 and 26 GHz with $V_{D_S} = 5\text{ V}$ and 10 V.

frequency” range: NF_{min} is drastically reduced from 3.1 dB (#C) to 1.2 dB (MOSHEMT) at 4 GHz.

V. CONCLUSION

The microwave noise parameters of different AlInN/GaN HEMTs have been presented in this paper. The noise figure in these devices is higher than the one of AlGaIn/GaN heterostructures with the same gate length value. However the measured associated power gain presents higher values which is in agreement with previous work. The main limiting factor is the gate leakage current which must be reduced to improve the overall noise performance of this technology. We have also observed the presence of an unusual excess noise source below 8 GHz which could be attributed to trapping-detrapping processes with short time constants.

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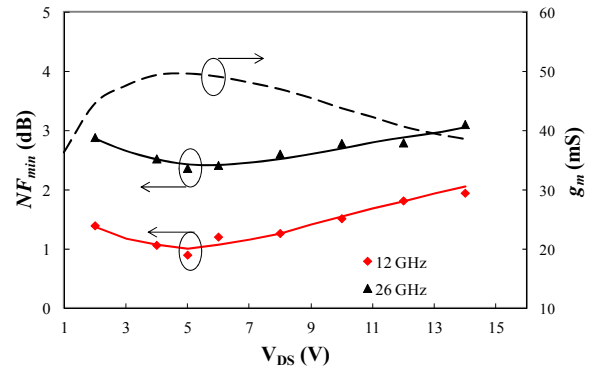


Fig. 7. Minimum noise figure and transconductance versus the drain-source voltage for the 0.15- μm AlInN/GaN HEMT at 12 and 26 GHz with $V_{G_S} = -1\text{ V}$.

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