Investigation of High Frequency Noise and Power in AlGaN/GaN HEMTs

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Abstract. AlGaN/GaN HEMTs with gate length and width of L_G=1 µm and W_G=2x75µm respectively were grown on sapphire substrate. DC, RF, load-pull characteristics, noise parameters and isothermal noise temperature were measured, simulated and analyzed. A small signal circuit was extracted from measured *s*-parameters in a broad frequency range (0.1-30 GHz). Extracted peak transit frequency f_T=7 GHz is in agreement with reported values [1]. Noise sources were analyzed in terms of PRC [2] and Pospieszalski [3] noise models. The relatively high noise figure (NF_{min}) was explained by high channel noise and large source and drain resistances. The peak value of the simulated electric field distribution along the channel exceeded 250 kV/cm and that is much higher than necessary for occupation of upper conduction band valleys (150 kV/cm). Measured isothermal noise temperature (T_N) in AlGaN/GaN channel exhibited the presence of intervalley and real space transfer related noise. T_N in AlGaN/GaN with 27% of Al fraction was found higher (x5) compared to that with 15% what can be explained by nonequilibrium phonon effects [4]. Very high (60%) power added efficiency (PAE) in matched source and load conditions at 1 GHz frequency was obtained.

Keywords: AlGaN/GaN HEMT, Noise parameters, Noise temperature, Load-pull, GT, PAE.
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INTRODUCTION

Wide bandgap GaN based HEMT can operate at high breakdown electric fields, offering very high linearity and survivability. Featuring reduced scattering due to electron confinement in 2D channel, AlGaN/GaN HEMTs exhibit very low microwave noise: for the gate length (L_G=0.12 µm) NF_{min}=0.98 dB at 18 GHz [5], for L_G=0.2 µm NF_{min}=1.5 dB, 26 GHz [6] and NF_{min}=0.5 dB, 8 GHz for L_G=0.25 µm [7]. Therefore GaN based HEMTs are excellent devices for high power, high temperature and low noise applications. Such features can be beneficial for broadband power applications as well for the very linear low noise front-end LNAs, featuring high reliability for power overdrive. A 36 dBm *CW* power overdrive on a LNA was reported in [8]. Perfect survivability was demonstrated with 33 dBm *CW* power stress for 12 h on a GaN based LNA featuring $NF<1.8$ dB in 3-7 GHz range [9].

In this work we present high frequency noise and power analysis of AlGaN/GaN HEMTs with $L_G=1$ µm.

DEVICE UNDER TEST AND EXPERIMENTAL

AlGaN/GaN HEMTs were grown by a Veeco Gen 930 Molecular Beam Epitaxial (MBE) system using solid sources for group III and plasma source for nitrogen. The top AlGaN/GaN layers were grown on top of a 4 µm thick semi-insulating GaN template on c-face sapphire substrate. The HEMTs have two gate stripes of width $W_G=0.75$ µm and length $L_G=1$ µm. Thickness of AlGaN and GaN are 29 nm and 218 nm, respectively, both un-intentionally doped throughout the whole structure. Al mole fraction was 27% and sheet carrier density and mobility were $N_s=9.94*10^{12}$ cm^{-2} and $\mu=1231$ cm^2/Vs at room temperature, and $N_s=1.12*10^{13}$ cm^{-2}, $\mu=2848$ cm^2/Vs at $T_0=77$ K. On-wafer DC, AC ($\Delta f=0.1$-30 GHz) standard characteristics were measured with HP4142, HP8510C, using Agilent ICCAP 2006 software and Suss Microtech semiautomatic RF-probestation PA200. Noise parameters and power characteristics (in source-load matching conditions for PAE) were measured in the 1-5 GHz range with automated tuner system ATS MT993B from Maury Microwaves. Contact resistance was extracted from measured TLM structure resistances and was found to be $R_C=20$ Ω. Hot electron noise of the gate-less AlGaN/GaN channel was measured in isothermal conditions with a pulsed gated radiometer at 10 GHz spot frequency versus applied bias. De-embedding of pad parasitics from measured *s*-parameters was performed using 1-step ("open" dummy) method. Noise parameters were de-embedded with the correlation matrix technique. Small-signal model parameters (SSM) were extracted from standard DC and *s*-parameters with ICCAP routine.

RESULTS AND DISCUSSION

Standard DC characteristics of AlGaN/GaN HEMT are presented in Fig.1. Due to the sapphire substrate, self-heating is observed, which reduces the drain current (Fig.1 a, V_{GS} >-4 V). At $V_{DS}=5.5$ V and $V_{GS}>-1.5$ V a kink effect is observed. Peak transit frequency $f_T=6.8$ GHz (Fig.2a) corresponds well with $f_T(L_G)$ dependence [1]. Measured NF_{min} exhibits the minimum value around $V_{GS}=-4.2$ V (Fig.2b).

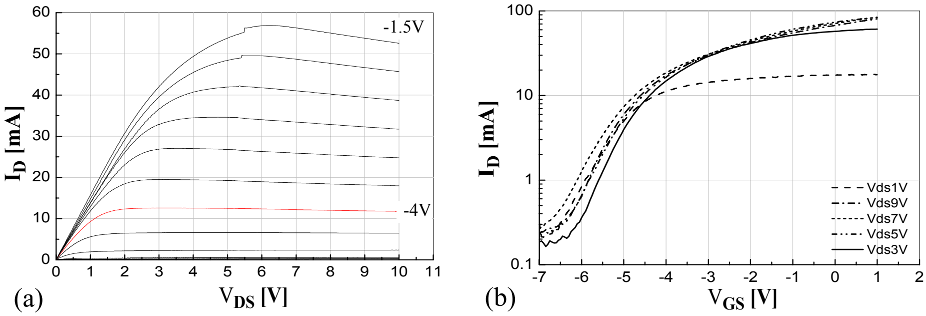

FIGURE 1. Measured (a) $I_D(V_{DS})$, drive V_{GS} /V=-6.5 to -1.5, step 0.5 and (b) $I_D(V_{GS})$.

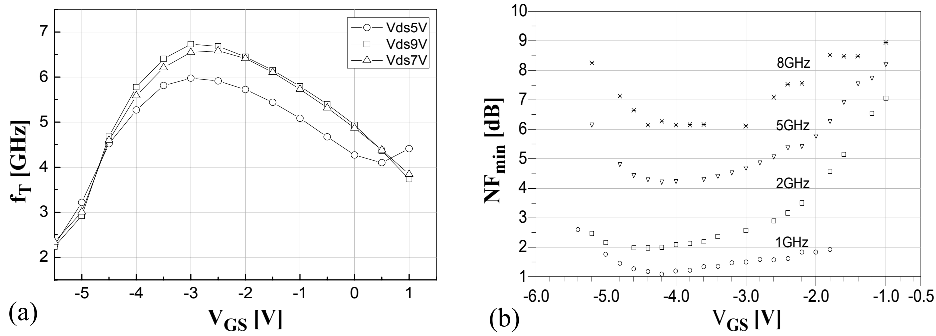

FIGURE 2. (a) Extracted $f_T(V_{GS})$, (b) measured NF_{min} at V_{DS}=2.75 V.

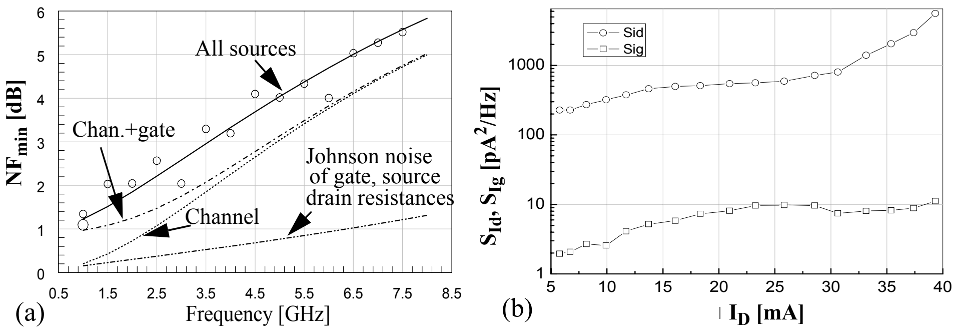

FIGURE 3. (a) NF_{min} at V_{DS}=2.75 V, V_{GS}=-4.2 V, (b) extracted S_{ID} and S_{IG} at V_{DS}=2.75 V.

$NF_{min}(V_{DS})$ dependence shows an increase of NF_{min}=(1.3 dB at V_{DS}=1.5 V to 2.5 dB at 8 V) which is related to significant self-heating in devices on sapphire substrate. The lattice temperature can reach 300°C [10]. The relatively high NF_{min} value is related to the channel noise (Fig.3a, decomposed noise sources). The extracted spectral density of drain current fluctuations (S_{Id}=450 pA^2/Hz at V_{GS}=-4.2 V) using PRC model [2] corresponds well to the drain temperature [3] T_D=4800 K. Nevertheless, due to an increasing correlation between gate and drain current noise with V_{GS} (C=0.87 at V_{GS}=-1.5 V), PRC model yields better agreement than T_D, gate temperature (T_G) based. Electric field distribution

($E_X(x)$), obtained from 2D microscopic device simulations exhibited a rapid increase of $E_X(x)$ =250 kV/cm at the gate/drain edge. Such value is sufficiently high not only for the intervalley redistribution (MC simulations yield a threshold electric field of 150 kv/cm for GaN and at E_X=270 kV/cm an electron fraction in the L valley $n_L > n_\Gamma$), but also for hot phonon related effects, which decrease the drift velocity [1],[11]. The al fraction controls the barrier height and thus the carrier concentration in 2D channel. For higher concentration nonequilibrium phonon effects are more pronounced [1],[11] and therefore higher noise is expected. This statement is supported by the measured isothermal (500 ns pulses) noise temperature (T_N) dependence upon effective electric field (E_{eff}) for two different Al fractions (Fig.4a). Note that the device with 27% Al corresponds to our DUT and the measurements were taken for the gateless HEMT, therefore measurement frequency 10 GHz does need to be matched with f_T. Measured PAE at 1, 3, 5 GHz at matched conditions (Γ_S=0.87 angle(<)18°, Γ_L=0.81<5.8°) was 61%, 45% (Γ_S=0.81<38°, Γ_L=0.79<14°) and 30% (Γ_S=0.81<48°, Γ_L=0.735<19°) respectively, featuring a transducer gain G_t [dB]=20, 13, 6 (Fig.4b).

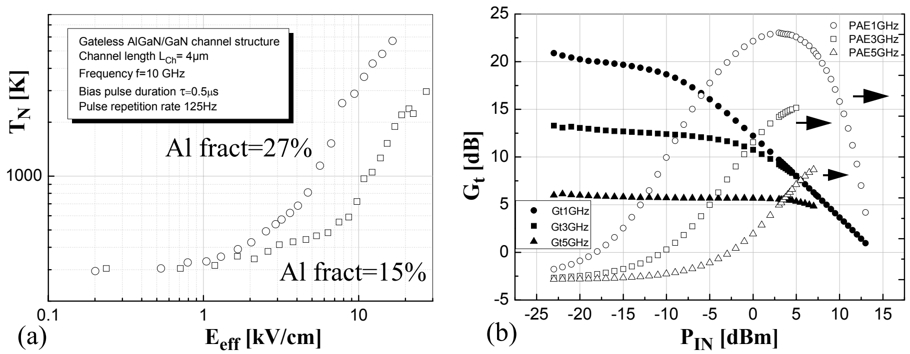

FIGURE 4. (a) T_N at f =10 GHz, (b) G_t and PAE at V_{DS}=5 V, V_{GS}=-5 V, f [GHz]=1, 3, 5.

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