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Abstract

In this letter, a record performance at 40 GHz obtained on AlGaN/GaN high electron mobility transistor (HEMT) grown on Hydride Vapor Phase Epitaxy (HVPE) Free-Standing GaN substrate is reported. An output power density of 2 W.mm^{-1} associated with 20.5 % power added efficiency and a linear power gain (G_p) of 4.2 dB is demonstrated for 70 nm gate length device. The device exhibits a maximum DC drain current density of 950 mA.mm^{-1} and a peak extrinsic transconductance ($g_{m\,Max}$) of 300 mS.mm^{-1} at V_{DS} = 6 V. A 100 GHz maximum intrinsic cutoff frequency f_T, and a maximum intrinsic oscillation frequency f_{Max} of 125 GHz are obtained from S-parameters measurement. This performance is very promising for HEMTs grown on Free-Standing GaN substrate.

Keywords: free-standing GaN, hydride vapor phase epitaxy (HVPE), AlGaN/GaN, high electron mobility transistor (HEMT), millimeter-wave power density

1. Introduction

Gallium Nitride (GaN) High Electron Mobility Transistor (HEMT) constitutes the best candidate for millimeter wave power applications [1], due to its remarkable material properties such as high breakdown voltage, high saturation velocity, and high thermal conductivity. Most AlGaN/GaN HEMT epilayers are grown on Silicon Carbide (SiC) substrate for high resistivity and good thermal management [2], [3], and on Silicon substrate (Si) because of its low-cost, large area availability, and compatibility with MOS technology [4]. However, during the epitaxial growth, many defects appear in the material (dislocations with density from 10^8 to 10^{10} cm^{-2}), because of the crystal lattice mismatch of 17% (4%) between GaN and Si (SiC) substrate. To this, is added a difference in the thermal expansion coefficient of 54% and 25% with Si and SiC substrates respectively, which can induce noticeable tensile stress responsible for layer cracking. In this paper, the device is fabricated on AlGaN/GaN epilayer grown by Metal Organic Chemical Vapor Deposition (MOCVD) on Hydride Vapor Phase Epitaxy (HVPE) commercial Free-Standing Gallium Nitride (GaN) substrate. This structure presents the advantages of the direct growth of high crystalline quality GaN with threading dislocation density below 10^7 cm^{-2} [5], [6]. The goal of this study is to demonstrate the high microwave power performance at 40 GHz of HEMTs on GaN substrate.

Several studies have been conducted previously to fabricate high-frequency transistors on high quality GaN substrates.

An output power density of 9.4 W.mm^{-1} at 10 GHz [7], and 6.7 W.mm^{-1} at 4 GHz using back-barrier [8] are reported. With an AlN barrier, David J.Meyer et al. obtained 1 W.mm^{-1} at 40 GHz with a cutoff frequency f_T of 165 GHz and a 171 GHz maximum oscillation frequency [9]. Thus, it has been demonstrated that AlGaN/GaN HEMT homo-epitaxial devices present relevant DC characteristics and microwave power performances [10]–[14]. Furthermore, beyond the expected benefit of better reliability on high crystal quality materials, further progress of performance is still achievable by improving the epilayer design and growth as well as the transistor process.

In this letter, DC and RF electrical performances are described and state of the art microwave performance such as a power density of 2 W.mm^{-1} at 40GHz are carried out demonstrating the capability of an AlGaN/GaN HEMT grown on doped Free-Standing GaN substrate.

2. Material growth and device technology

2.1 Material growth

From commercial Hydride Vapor Phase Epitaxy (HVPE) Free-Standing (2-inches diameter) GaN substrates ($\rho \leq 30$ mΩ.cm) supplied by Saint-Gobain Lumilog, a sufficiently thick and resistive 10 µm GaN buffer layer is grown by Metal Organic Chemical Vapor Deposition (MOCVD) in a close-coupled showerhead Aixtron reactor. This thick buffer is needed to minimize leakage current and to limit the coupling of the conductive substrate with the AlGaN/GaN heterostructure, and thus lowering RF dielectric losses. As in ref [15], growth conditions are chosen to obtain 3 µm carbon rich resistive GaN layer before the growth of 7 µm unintentionally doped (UID) GaN. The HEMT active layers consist of a 11 nm thick $Al_{0.26}Ga_{0.74}N$ barrier capped with 3 nm thick in-situ grown SiN layer. A 1.5 nm thick AlN exclusion layer is used to reduce alloy scattering and to improve carrier confinement within the 2D electron gas (2DEG) (Fig. 1 (a)). The direct growth of AlGaN/GaN layers permits the suppression of the nucleation layer, which is considered as a thermal barrier [16]. X-ray diffraction performed on the structure shows that the high quality of the free-standing GaN substrates is well replicated: full width at half maximum for the (002) and (302) rocking curves are 98" and 200" respectively.

This structure produces a 2DEG with a total charge density of 8.5 × 10^{12} /cm^2 and an electron mobility of 2200 cm^2/V.s obtained from Hall effect measurement. This mobility and charge density translate to a 2DEG sheet resistance of 356 Ω/sq at room temperature.

2.2 Device technology

The device fabrication starts with alignment marks made by Inductively Coupled Plasma (ICP) etching. Using a Cl_2/Ar plasma chemistry, alignment marks are etched to a depth of 650 nm. The process continues with the deposition of ohmic contacts metallization Ti/Al/Ni/Au (12/200/40/100 nm) by e-beam evaporation after in-situ-Argon (Ar) ion beam etching (IBE), where more than half of the barrier layer is etched to set the metallic sequential closer to the 2D conduction channel without degrading the UID-GaN layer. This is followed by rapid thermal annealing (RTA) at 850 °C for 30 s under nitrogen atmosphere. Then, devices are isolated by N+ ion multiple implantations. An average contact resistance as low as $R_C = 0.34$ Ω.mm is measured by a transmission line model on different patterns. T-shaped gate based on Ni/Au (40/300 nm) evaporated metallization with 70 nm footprint (Fig. 1 (b)) are patterned by electron-beam lithography process using optimized (PMMA/COPO/PMMA) tri-layer resist stack. 400 °C annealing for 20 min under nitrogen atmosphere is done in order to improve Schottky contact behavior by reducing the trapping phenomena under the gate [17]. Then, Si_3N_4 passivation is performed by Plasma-Enhanced Chemical Vapor Deposition (PECVD) at 340 °C. Finally, a Ti/Au stack is deposited by evaporation to access transistor contacts. Device under test (DUT) in this paper features a two-finger configuration with a gate length L_g = 70 nm, a gate width W = 2 x 50 µm and source-to-drain spacing L_{SD} = 1.3 µm. Fig. 1 (b) and Fig. 1 (c) shows a Scanning Electron Microscope (SEM) view of the T-shaped gate obtained on a device with 500 nm source-to-gate spacing.

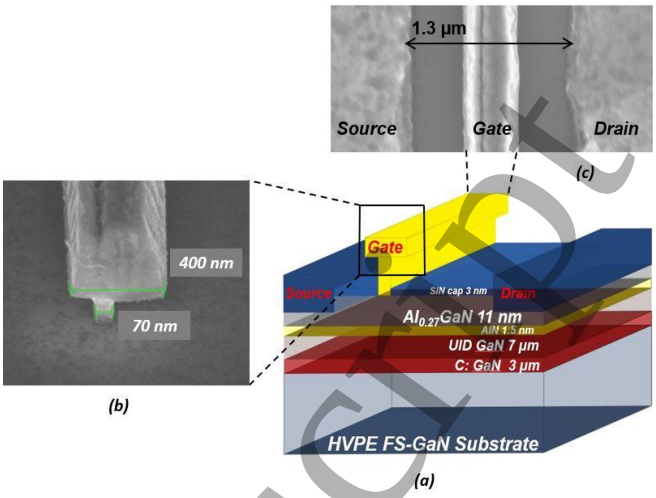

Fig. 1. (a) 3D schematic of the as-fabricated AlGaN/GaN HEMT on Free-Standing GaN substrate before passivation with SiN, (b) SEM image after gate lift-off (c) SEM top view of the device after gate fabrication

3. Measurements and results

3.1 DC Characteristics

Fig. 2 shows the output $I_{DS}(V_{DS})$ characteristics for a device featuring 2 fingers of 50 µm each, with a gate-to-drain spacing L_{DG} = 730 nm, and a source-to-gate spacing L_{GS} = 500 nm. From these measurements, a maximum DC current density $I_{DS\,Max}$ of 950 mA.mm^{-1} is reached at V_{GS} = 1 V, associated with an ON-resistance of 3 Ω.mm.

As shown in Fig. 3, for different V_{GS} ranging from -6 V to 0 V, an extrinsic transconductance $g_{m,ext}$ peak of 300 mS.mm^{-1} at V_{GS} = - 2.5 V and V_{DS} = 6 V is obtained. A threshold voltage V_{th} of -3.5 V is deduced from the transfer characteristic. The gate leakage current is as low as 3.10^{-7} A/mm. The I_{ON}/I_{OFF} ratio of drain current I_{DS} is above 10^6.

3.2 RF Characteristics

The scattering Sij parameters are measured in the 250 MHz to 67 GHz frequency range, using a Vector Network Analyzer (VNA). The calibration procedure is performed on wafer, using a Line-Reflect-Reflect-Match (LRRM) procedure. The current gain modulus ($|H_{21}|$) and Mason's unilateral gain (U) are extracted from S-parameters versus frequency measurement. Using Open-Short patterns, the inductive and capacitive pad contributions are de-embedded. The current transition frequency (f_T) and the maximum oscillation frequency (f_{Max}) are directly extracted from the first order linear frequency regression (- 20 dB/decade) plots of $|H_{21}|$ and U respectively. These figures of merit are depicted in Fig. 4 for a biasing at V_{GS} = -2.5 V and V_{DS} = 6 V, corresponding to the extrinsic transconductance peak.

An intrinsic current gain cut-off frequency f_T of 100 GHz associated with a maximum oscillation frequency f_{Max} of 125 GHz are achieved. These values are obtained thanks to an optimized device processing (T-shaped gate), and also to the high material quality, by using thin barrier (11 nm) and thick GaN buffer on the Free-Standing GaN substrate. Optimization of thickness and carbon doping level of the C-doped GaN layer may further improve these results. It must be a trade-off between crystal quality and buffer isolation [18], [19].

3.3 Microwave power measurements

Large-signal microwave power measurement was performed at 40 GHz. It is based on an active load pull setup under CW conditions with a large-signal network analyser (LSNA) working up to 50 GHz. At V_{DS} = 10 V and I_{DS} = 300 mA.mm^{-1} corresponding to class AB operation, the optimal load impedance is $\Gamma_{load} = 0.75 \angle 85°$. At this condition, the device exhibits an output power density (P_{out}) of 1.2 W.mm^{-1} associated with a maximum power-added efficiency (PAE) of 26.2 % and a linear gain of 5 dB. Measurement was also carried out at V_{DS} = 15 V and I_{DS} = 300 mA.mm^{-1} (Fig. 5). For $\Gamma_{load} = 0.7 \angle 80°$, an output power density of 2 W.mm^{-1} associated with a maximum power-added efficiency (PAE) of 20.5 %, and a linear gain of 4.2 dB are achieved.

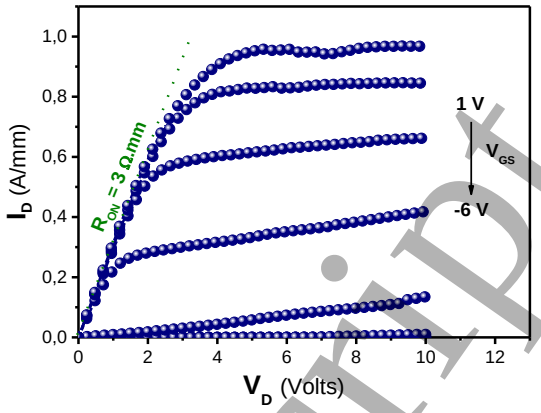

Fig. 2. I_{DS} (V_{DS}) characteristics for a 2 × 50 × 0.07 µm^2 AlGaN/GaN HEMT on Free-Standing GaN substrate.

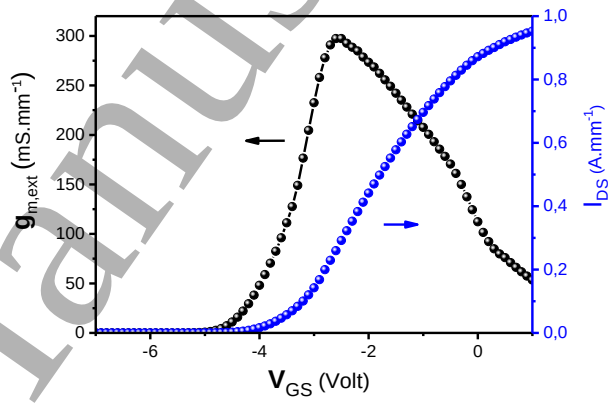

Fig. 3. Transfer characteristics at V_{DS} = 6 V for a 2 × 50 × 0.07 µm^2 AlGaN/GaN HEMT on Free-Standing GaN substrate.

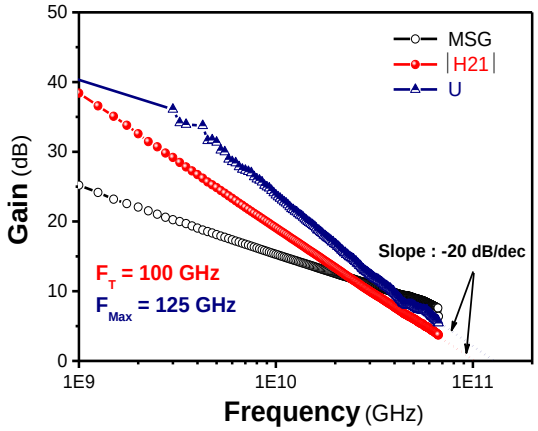

Fig. 4. Current gain modulus $|H_{21}|$, Mason's unilateral gain (U) and maximum Stable Gain (MSG) versus frequency for a 2 × 50 × 0.07 µm^2 AlGaN/GaN HEMT on Free-Standing GaN substrate at V_{GS} = -2.5 V, V_{DS} = 6 V

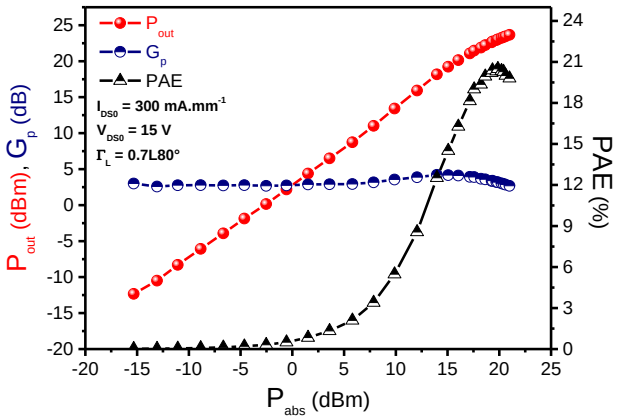

Fig. 5. Output power, power gain and power added efficiency versus absorbed power at 40 GHz for a 2 x 50 x 0.07 µm^2 AlGaN/GaN HEMT on Free-Standing GaN substrate.

Up to now, this result constitutes the state-of-the-art large signal at 40 GHz for AlGaN/GaN HEMTs on Free-Standing GaN substrate.

4. Conclusion

AlGaN/GaN HEMT grown on Free-Standing GaN substrate are fabricated. Attractive small-signal and RF power performances are demonstrated for a 2 x 50 x 0.07 µm^2 device. A record output power density for HEMT on Free-Standing GaN substrate, as high as 2 W.mm^{-1} is obtained at 40 GHz associated with a PAE of 20.5 % and a linear power gain of 4.2 dB. The transistor exhibits intrinsic cut-off frequencies f_T = 100 GHz and f_{Max} = 125 GHz at V_{GS} = - 2.5 V and V_{DS} = 6 V. These results show the capability of AlGaN/GaN HEMT based on Free-Standing GaN substrate for high millimeter-wave power applications.

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