FABRICATION AND CHARACTERIZATION OF SUBMICRON AlGaN/GaN HEMTS

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ABSTRACT

Using our in-house 0.3 µm mushroom gate process, AlGaN/GaN high electron mobility transistors (HEMTs) with total gate periphery up to 0.6 mm were fabricated and characterized. The transistors were processed on an AlGaN/GaN heterostructure grown by MBE on sapphire. Output current densities up to 1 A/mm and extrinsic DC-transconductances (g_m) of 240 mS/mm were measured. Extrinsic cut-off frequencies (f_t) of 35 GHz, maximum frequencies of oscillation (f_{max}) of 75 GHz, were calculated from S-parameters measurements. On wafer Load-Pull measurements were performed without any active cooling on HEMTs of different sizes. Continuous wave (CW) output power densities up to 3.2 W/mm at 6 dB compression and 1.9 W/mm at 3 dB compression at 6 GHz were achieved.

INTRODUCTION

AlGaN/GaN high electron mobility transistors (HEMTs) have demonstrated excellent performance for high-power, high speed and high temperature applications [1,2,3] because of their high breakdown voltage, high carrier velocities and very high two-dimensional electron concentrations ($>10^{13}$ cm^{-2}) generated without delta doping at the AlGaN/GaN heterojunction owing to the combination of strong polarization fields [4].

Because of the large power output density of these HEMTs, a large amount of heat is generated and thermal management of the devices becomes significantly important [5]. Since almost all the AlGaN/GaN structures are grown heteroepitaxially due to the scarcity of large, high quality semi-insulating substrate, the substrate on which the heterojunction is grown plays an essential role. The thermal conductivity of sapphire (0.5 $W \cdot cm^{-1} \cdot K^{-1}$) is a limiting factor in the ultimate performances of power amplifiers based on HEMTs grown on sapphire. SiC, however, has a higher thermal conductivity (4.9 $W \cdot cm^{-1} \cdot K^{-1}$) and presents a smaller lattice mismatch to GaN, therefore it is a more appropriate choice of substrate for high power applications. In fact, output power densities of 6.4 W/mm and above 10 W/mm in the X-band have been measured on AlGaN/GaN HEMTs grown on sapphire and SiC respectively [6,7].

In this paper, we report on the DC and high frequency performances of high power non-recessed air-bridged multi-finger AlGaN/GaN HEMTs, with a total gate periphery up to 0.6 mm, fabricated using our in-house 0.3 µm mushroom gate process on an AlGaN/GaN heterostructure grown by MBE on sapphire.

EXPERIMENTAL

The AlGaN/GaN heterostructure was grown by MBE on sapphire substrate by SVT Associates. The modulation doped structure consists of a 200 Å undoped ($N_D<10^{16}$ cm^{-3}) $Al_{0.25}Ga_{0.75}N$ layer grown on a 2 µm undoped ($N_D<10^{16}$ cm^{-3}) GaN buffer, caped under an undoped GaN ($N_D<10^{16}$ cm^{-3}) layer of 20 Å. Hall measurement showed a room temperature low field mobility of 1150 $cm^2 \cdot V^{-1} \cdot s^{-1}$ and a sheet carrier density of $1.4 \cdot 10^{13}$ cm^{-2} in the 2DEG formed at the AlGaN/GaN interface.

HEMTs with a total gate periphery up to 0.6 mm were successfully fabricated (Fig. 1). The mesas were formed by inductively coupled plasma reactive ion etching (ICP-RIE). Ohmic contacts for the source and drain were obtained by e-beam evaporation of a Ti/Al/Ni/Au multilayer followed by a rapid thermal anneal (RTA) in a nitrogen environment. A typical contact resistance of 0.42 Ω·mm was measured on-chip using TLM patterns. The 0.3 µm mushroom gates (Fig. 2) were defined by electron beam lithography and centered in the 3 µm source-drain spacing. The Ni/Au gate metallization was deposited by e-beam evaporation. The transistors were passivated by SiN_x prior the formation of the gold airbridges for the multifinger devices.

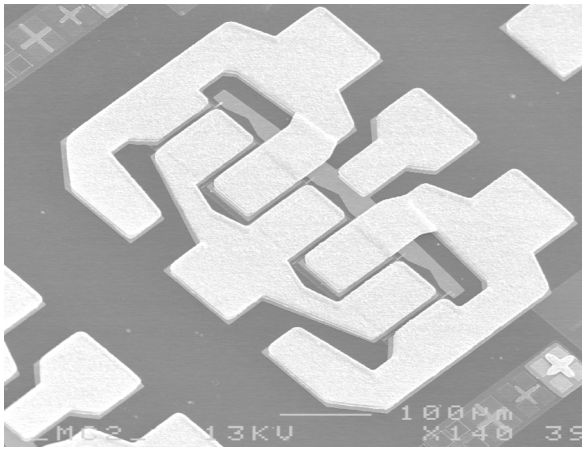

Fig. 1. SEM picture of a 0.6 mm HEMT

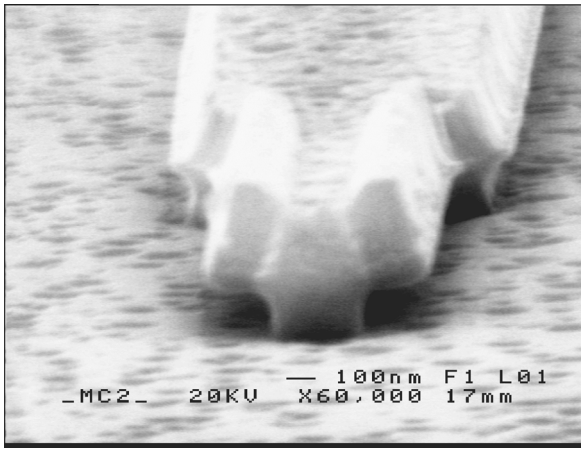

Fig. 2. 0.3 µm mushroom gate on GaN

RESULTS AND DISCUSSION

The DC-current-voltage characteristics and transfer characteristics were measured with a semiconductor parameter analyzer and demonstrated output current densities over 1 A/mm and extrinsic transconductances (g_m) of 240 mS/mm. The threshold voltage was typically –5 V.

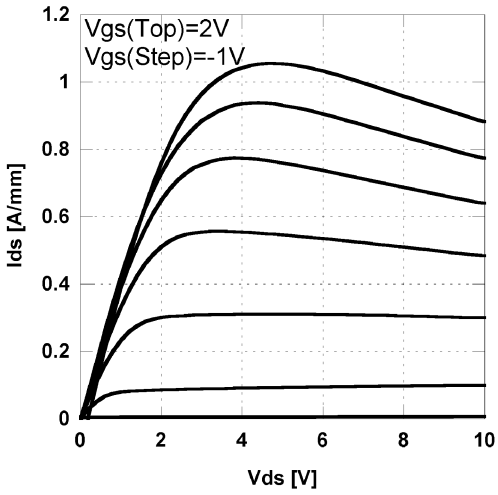

Fig. 3. DC-IV of a 0.2 mm HEMT

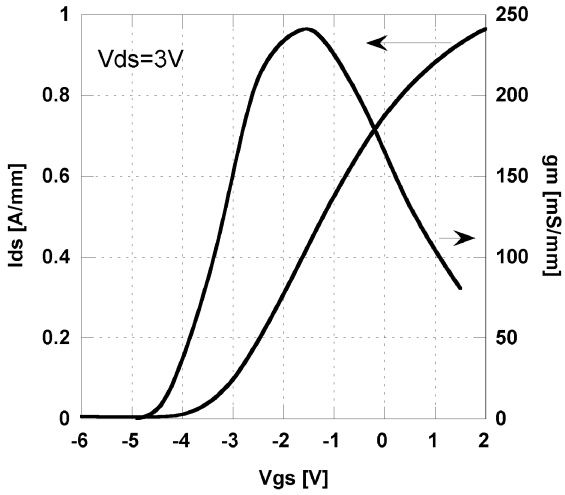

Fig. 4. DC transfer characteristics of a 0.2 mm HEMT

The transistor's I-V characteristics reveal the presence of a self-heating effect, which significantly limits the performance of the transistor. In order to determine the actual impact of self-heating, pulsed I-V measurements were compared to the DC-characteristics of the HEMTs (Fig. 5). It was clearly showed that even for small gate periphery devices, self-heating was observed due to the poor thermal conductivity of the sapphire substrate. Furthermore, the saturation output current density was drastically reduced as the gate periphery increased (Fig. 6), showing the critical importance of a lower thermal resistance and a careful transistor design for the realization of very large periphery devices.

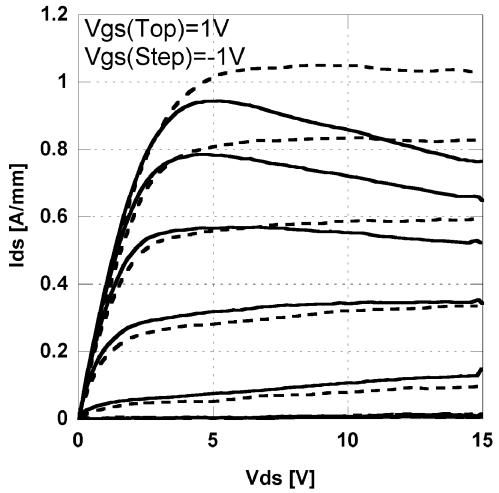

Fig. 5. Pulsed (dashed lines) and DC (solid lines) I-V characteristics of a 0.1 mm device

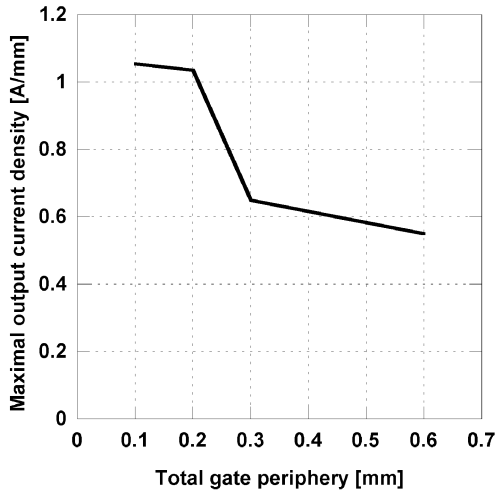

Fig. 6. Saturation output current density as a function of the HEMTs total gate periphery

Extrinsic cut-off frequencies (f_t) up to 35 GHz and maximum frequencies of oscillation (f_{max}) up to 75 GHz were calculated (Fig. 7) from S-parameters measurements performed between 500 MHz and 50 GHz. Furthermore, on-wafer Load-Pull measurements were performed without any active cooling on HEMTs of different sizes at 6 GHz. Continuous wave (CW) output power densities up to 3.2 W/mm at 6 dB compression and 1.9 W/mm at 3 dB compression for a 0.1 mm device were achieved (Fig. 8). We believe that the output power density is thermally limited, as suggested by the pulsed measurements. By active cooling or a lower thermal resistance, the output power density of these devices is likely to increase. Nevertheless, this output power density is among the highest reported under such experimental conditions for a 0.3 µm gate-length AlGaN/GaN HEMT grown on sapphire [8].

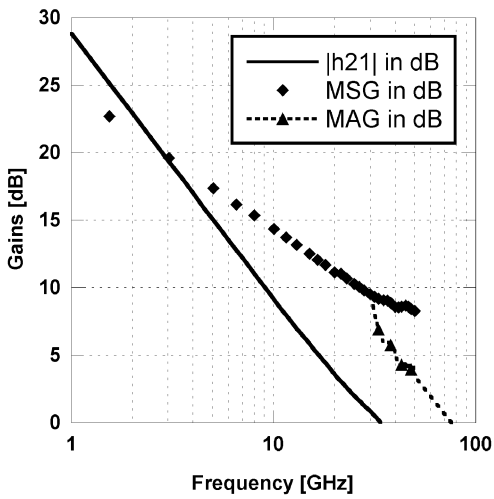

Fig. 7. Measured current gain and power gains versus frequency of a 0.1 mm HEMT

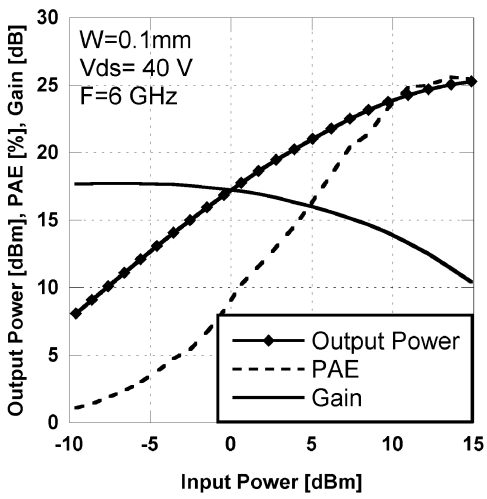

Fig. 8. Load-Pull measurement of 0.1 mm HEMT

CONCLUSION

AlGaN/GaN HEMTs, with total gate periphery of 0.6 mm were successfully fabricated with our in-house 0.3 µm process flow on commercial wafers. Output drain current densities over 1 A/mm were measured. A short circuit current gain cut-off frequency (f_t) and a maximum frequency of oscillation (f_{max}) of 35 GHz, respectively 75 GHz, were obtained. The devices exhibited thermally limited CW output power densities as high as 3.2 W/mm at 6 GHz with no active cooling.

ACKNOWLEDGMENTS

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