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High power GaN/AlGaN/GaN HEMTs operating at 2 to 25 GHz grown by plasma-assisted MBE

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We report on the growth and power performance of GaN/AlGaN/GaN high electron mobility transistors (HEMTs) grown by plasma-assisted molecular beam epitaxy (MBE) on semi-insulating SiC substrates. We detail the MBE growth conditions that consistently produce high mobility two-dimensional electron gases (2DEGs) with room temperature mobility of ~1400 cm^2/Vs at a sheet density of 1.2×10^{13} cm^{-2}. Transistors fabricated from these layers have demonstrated power densities in excess of 8 W/mm at 2 GHz, 6 W/mm at 7 GHz, and 3 W/mm at 25 GHz. All power data is achieved without the use of a SiN surface passivation layer. Central to the achievement of high power operation is the reduction of RF dispersion. Our growth studies have focused on the suppression of RF dispersion and maximizing RF output power. Pulsed $I-V$ and gate lag measurements are used to quantify the amount of dispersion in different heterostructure designs.

1 Introduction Recent progress in high electron mobility transistors fabricated from AlGaN/GaN heterostructures has highlighted the potential of this promising semiconductor material system for microwave power applications. Record RF power densities for small-periphery devices of more than 11 W/mm have been reported for MOCVD grown layers on semi-insulating SiC substrates [1, 2]. Improvements in power density have come swiftly. Nevertheless, RF dispersion still represents a major challenge to the commercialization of the AlGaN/GaN HEMT technology. For MOCVD grown layers, it is found that the addition of a SiN surface passivation layer greatly reduces the RF dispersion [1, 2]. While MOCVD grown structures have been thoroughly studied, less data is available from epilayers grown by MBE [3, 4]. Micovic et al have reported an excellent power density of 8.2 W/mm from MBE grown material on SiC substrates [3]. In this paper, we report on the plasma-assisted MBE growth of GaN/AlGaN/GaN heterostructures on semi-insulating 6H–SiC substrates, and the fabrication of HEMTs from these layers yielding RF power densities in excess of 8 W/mm. The optimization of the layer structure, the MBE growth, and the device fabrication process were focused on the maximization of RF output power, and the suppression of RF dispersion. All results in this paper are given for *unpassivated* structures. Our results suggest that RF dispersion can be reduced in MBE grown layers through heterostructure design and careful control of MBE growth conditions.

2 Growth and fabrication GaN/AlGaN/GaN heterostructures were grown by plasma-assisted MBE on semi-insulating 6H–SiC substrates. Prior to growth, the SiC substrates receive an addition chemical-mechanical polish treatment from NovaSiC Inc. to remove polishing scratches on the as-received wafers. In our experience, this step is has proven necessary for the reproducible growth of high quality epilayers. The growth is initiated with the deposition of an approximately 60 nm AlN nucleation layer at a substrate

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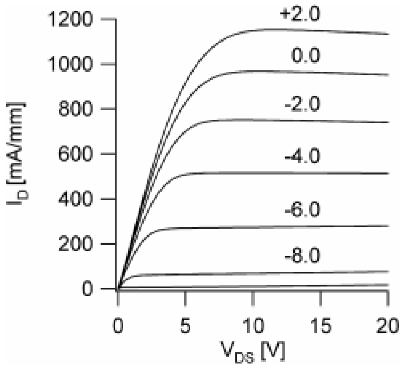

Fig. 1 I–V curve of a HEMT with a 1 µm long and 25 µm wide gate. The source–drain spacing is 5 µm.

temperature of 800 °C. The utility of the AlN nucleation layer is governed by the aluminum to nitrogen ratio and substrate temperature. We have found that growth under Al-rich growth conditions such that a streaky 1 × 1 rheed pattern is observed during the entire 60 nm layer is crucial to epilayer quality. The AlN nucleation layer is followed by 2 µm undoped GaN buffer grown at 745 °C under Ga-rich conditions, but below the transition to Ga droplet formation. The GaN buffer layer is grown at a rate of 0.5 µm/hr. The structure is completed with a 35 nm $Al_{0.34}Ga_{0.66}N$ barrier and a 5 nm GaN capping layer. The top half of the AlGaN barrier and the GaN capping layer are doped with Si to a level of ~1×10^{18} cm^{-3}. This MBE growth recipe consistently produces 2DEGs with a room temperature mobility of 1400 cm^2/Vs at a sheet density of ~1.2×10^{13} cm^{-2} as determined by low field Hall measurements. Typical sheet resistances are between 350 and 380 Ω/sq.

Typically, we fabricate devices with 1 µm and 2 µm gate lengths defined by optical lithography. After MBE growth, the substrates are cut into quarters for device processing. After dry etch mesa isolation, ohmic contacts were defined with a drain-source opening of 5 µm. The Ti/Al/Ni/Au ohmic metal stack was alloyed at 850 °C in N_2 atmosphere. Lastly, 1 µm and 2 µm long Schottky gates were deposited by e-beam evaporation of Ni (300 Å) followed by Au (3000 Å). The chips were not passivated before measurement. The devices are laid out in coplanar test frames in common-source configuration for on-wafer testing. Each HEMT consists of two opposed gate fingers, with total gate peripheries between 50 µm and 200 µm.

TLM data and DC device characteristics were measured on-wafer with an HP4145B parameter analyzer using needle probes. Small-signal *S*-parameters were measured on-wafer with an HP8510C network analyzer and an HP8516A test set up to 8 GHz. Large-signal device characterization was performed with an ATN LP1 automated load-pull setup at 2 GHz. Figure 1 displays the DC I–V characteristics of a typical device with a 1 µm gate length, 5 µm source–drain separation, and 25 µm periphery. This wafer exhibited a room temperature mobility of 1370 cm^2/Vs at a sheet density of 1.3×10^{13} cm^{-2}.

3 Results and discussion In order to quantify the degree of RF dispersion, we have examined the pulsed IV characteristics of our devices. For transient characterization, the gate potential was controlled with a pulse generator. The gate voltage is pulsed from pinch off to $V_{GS} = 0$ V. The pulse rise and fall time is 150 ns. The transient drain current is measured using a low insertion impedance current probe and displayed on a digitizing oscilloscope. The temporal response of a device that displays minimal dispersion is shown in Fig. 2. The pulsed I–V characteristics using a 10 µs pulse are compared to the steady-state I–V characteristics. The inset displays the drain current response to a 10 µs gate pulse from $V_{GS} = -10$ V to $V_{GS} = 0$ V with a duty cycle of 0.1%. During most of the measurement, the device is stressed in the off state (–10 V). The transistor switches to the full dc current value within 100–200 ns (limited by the temporal resolution of the measurement setup). Large signal load pull measurements of devices that display similar characteristics have yielded power densities over 8 W/mm at 2 GHz [5]. The measured saturated power density in these devices agrees with the value predicted from a simple load-line analysis of the dc I–V characteristics.

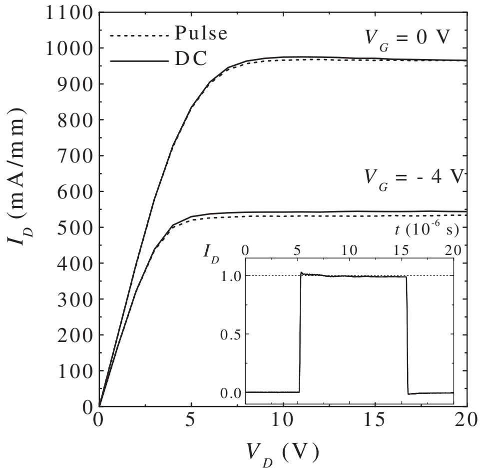

Fig. 2 Pulsed and steady-state $I-V$ characteristics of a device that displays minimal dispersion. The inset shows the response of the drain current to a 10 μs gate pulse. The gate is pulsed from pinch off $V_{GS} = -10$ V to $V_{GS} = 0$ V with duty cycle of 0.1%; the drain is biased in saturation at $V_{DS} = 10$ V.

Device operation beyond S-band requires the realization of submicron gate lengths. We have adapted a manufacturable bilayer resist scheme [6] for GaN/AlGaN/GaN HEMT structures resulting in *T*-gates with a foot length of 200 nm. Our submicron process routinely yields HEMT devices with drain current densities in excess of 1.6 A/mm. To evaluate the power performance of our 0.2 μm devices, we measured large-signal data using an automated ATN LP1 load-pull setup at 7 GHz. Figure 3 displays load-pull data at 7 GHz for a 0.2 μm × 200 μm device. The source–drain bias is 25 V and the gate bias is –5 V, corresponding to class A operation. This device displays a saturated output power density of 6.1 W/mm with 40% power-added-efficiency (PAE) and 10.9 dB of gain. We note that this high power density was achieved without driving the device into deep gain compression.

Presently there is great interest in exploring the use of AlGaN/GaN transistors for power amplification beyond *X* band. To date there are only a few reports in the literature of AlGaN/GaN HEMTs operating above 25 GHz. A continuous wave power density of 6.4 W/mm at 30 GHz for a 0.36 mm wide device grown by MOCVD has been reported [7]. We have recently evaluated the power performance of our devices at 25 GHz. On-wafer CW load-pull measurements were performed without substrate cooling at 25 GHz. From *S*-parameter data, we have calculated a maximum stable gain of 12 dB at 25 GHz. Figure 4 displays the measurement of a 100 μm device under class AB bias conditions. The drain–source bias is 20 V and the quiescent current is 36 mA. The device exhibited a linear gain of 6.4 dB, limited by the source tuning range of our load-pull setup. At an input power of 20.5 dBm, an output power of 25.1 dBm

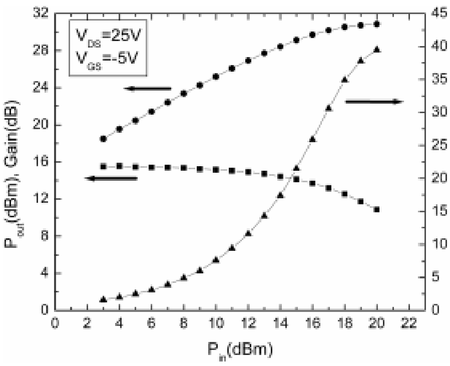

Fig. 3 Load-pull data at 7 GHz for a 0.2 μm × 200 μm HEMT at $V_{DS} = 25$ V and $V_{GS} = -5$ V. The peak output power density is 6.1 W/mm with 40% PAE and 10.9 dB gain.

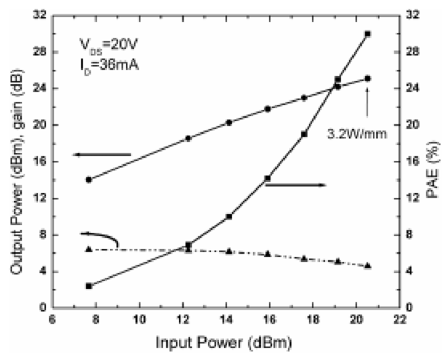

Fig. 4 Load-pull data at 25 GHz. The device is bias at $V_{DS} = 20$ V and $V_{GS} = -7.5$ V. The quiescent drain current is 36 mA. The device geometry is 0.2 μm × 100 μm.

is recorded, corresponding to a power density of 3.2 W/mm. The power added efficiency is 30% and the drain efficiency is 44% with 1.8 dB gain compression. Our data suggests that higher power densities may be obtained from these devices under more optimal load tuning conditions. Nevertheless, the measured power density of 3.2 W/mm at 25 GHz demonstrates the potential for MBE grown GaN/AlGaN/GaN HEMT operating at 25 GHz and higher.

4 Conclusions We have grown high quality GaN/AlGaN/GaN HEMT layers by plasma-assisted MBE on semi-insulating 6H-SiC wafers. HEMTs fabricated from these layers yielded a saturated output power of 8.2 W/mm at 2 GHz, 6.1 W/mm at 7 GHz, and 3.2 W/mm at 25 GHz. RF dispersion is evaluated with pulsed IV and gate lag measurements. The RF dispersion is found to be remarkably low given the absence of a surface-passivating layer. While the origins of RF dispersion are not fully understood, the power performance of these unpassivated devices grown by MBE should provide a useful comparison to MOCVD grown material.

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