Unpassivated AlGaN–GaN HEMTs With Minimal RF Dispersion Grown by Plasma-Assisted MBE on Semi-Insulating 6H–SiC Substrates

Nils G. Weimann, *Member, IEEE*, Michael J. Manfra, *Member, IEEE*, and Thomas Wächtler, *Student Member, IEEE*

***Abstract*—High electron mobility transistors (HEMTs) are fabricated from AlGaN–GaN heterostructures grown by plasma-assisted molecular beam epitaxy (MBE) on semi-insulating 6H–SiC substrates. At a sheet charge density of 1.3 × 10^{13} cm^{-2}, we have repeatedly obtained electron mobilities in excess of 1350 cm^2/Vs. HEMT devices with a gate length of 1 μm, a gate width of 200 μm, and a source–drain spacing of 5 μm show a maximum drain current of 1.1 A/mm and a peak transconductance of 125 mS/mm. For *unpassivated* HEMTs, we measured a saturated power output of 8.2-W/mm continuous wave (cw) at 2 GHz with an associated gain of 11.2 dB and a power-added efficiency of 41%. The achievement of high-power operation without a surface passivation layer suggests that free surface may not be the dominant source of radio—frequency (RF) dispersion in these MBE-grown structures. This data may help discriminate between possible physical mechanisms of RF dispersion in AlGaN–GaN HEMTs grown by different techniques.**

***Index Terms*—Gallium nitride, high electron mobility transistor (HEMT), heterojunctions, molecular beam epitaxy (MBE), RF dispersion.**

I. INTRODUCTION

RECENT progress in high electron mobility transistors (HEMTs) fabricated from AlGaN–GaN heterostructures has highlighted the potential of this promising semiconductor material system for microwave power transistor applications. Record radio-frequency (RF) power densities for small-periphery devices of more than 11 W/mm have been reported for metal-organic chemical vapor deposition (MOCVD)-grown layers on semi-insulating (SI) 4H–SiC substrates [1], [2]. One group has reported 8.2 W/mm from MBE-grown material on 4H–SiC substrates [3]. While improvements in power density have been swift, RF current collapse, or drain dispersion, represents a major challenge to the commercialization of the AlGaN–GaN HEMT technology. For MOCVD-grown layers, it has been found that the addition of a SiN$_X$ surface passivation layer greatly reduces the RF dispersion [1], [2]. These results strongly suggest that dispersion is related to the termination of surface electronic states. MBE offers excellent uniformity, reproducibility, and scalability, the ability to grow atomically sharp interfaces, along with very low background impurity concentrations, making it the technology of choice for GaAs-based pseudomorphic and metamorphic HEMTs. Given that only one other group has reported high-power operation of AlGaN–GaN HEMTs grown by MBE [3], little information is available concerning RF dispersion in MBE-grown layers. In addition, little work has been published on AlGaN–GaN HEMTs grown on SI 6H–SiC substrates. We have chosen to explore SI 6H–SiC for two reasons. First, the cost of SI SiC remains high. Currently, the cost of SI 6H–SiC is approximately one half the cost of the more commonly used 4H polytype. Second, the SI 6H–SiC obtained from Sterling Semiconductor Inc. has not been compensated with Vanadium in order to suppress background n-type conduction. Deep level trapping in compensated SI 4H–SiC substrates has been proposed as a possible source of drain dispersion in SiC MESFETs [4]. Moving to high-purity SI SiC substrates for GaN epitaxy should eliminate this possible source of dispersion in AlGaN–GaN HEMTs. In this letter, we report on the plasma-assisted MBE growth of AlGaN–GaN heterostructures on SI 6H–SiC substrates, and the fabrication of the first 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 drain dispersion, which is commonly found to date in unpassivated AlGaN–GaN HEMTs. All results in this letter are given for *unpassivated* structures.

II. EPITAXIAL STRUCTURE AND HEMT DEVICE PROCESS

Careful study of MBE growth conditions has lead to dramatic improvements in the mobility of the two-dimensional electron gas (2DEG) in AlGaN–GaN heterostructures. We have previously reported that close monitoring of the III/V ratio used during growth and the reduced background impurity incorporation due to cleaner systems and sources have lead to a record low-temperature mobility of 75 000 cm^2/Vs at $T = 4.2$ K [5]. Building on our experience with growing high-mobility structures on GaN templates, we have grown high-mobility AlGaN–GaN heterostructures by plasma-assisted MBE directly on commercially available 50-mm-diameter SI 6H–SiC substrates. Prior to MBE growth, the substrates receive a chemical–mechanical polish at Nova SiC Inc. We have found this additional surface treatment crucial to the reproducible production of high-mobility 2DEGs. The HEMT epilayer structure consists of a 30-nm AlN nucleation layer, an undoped

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N. G. Weimann and M. J. Manfra are with Bell Laboratories, Lucent Technologies, Murray Hill, NJ 07974 USA (e-mail: weimann@lucent.com).

T. Wächtler is with the Chemnitz University of Technology, 09107 Chemnitz, Germany.

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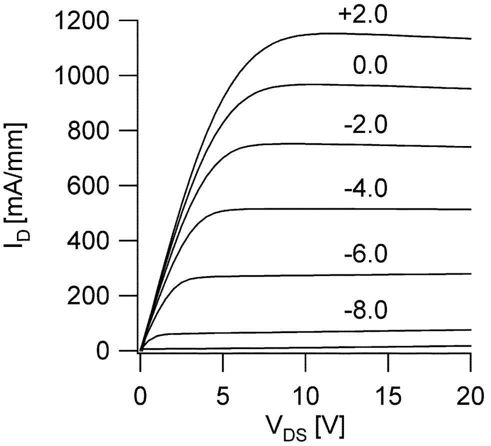

Fig. 1. I–V curve of a HEMT with a 1-μm-long and 25-μm-wide gate. The source–drain spacing is 5 μm.

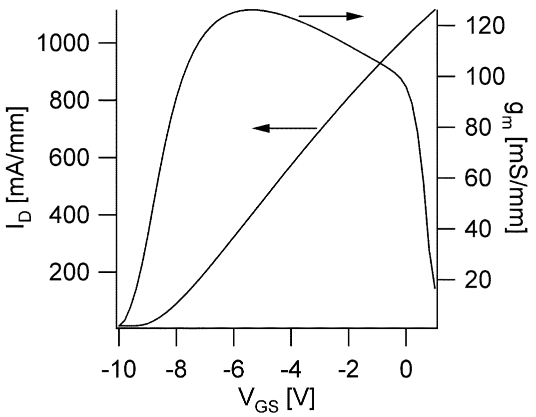

Fig. 2. Transconductance and drain current of same device as shown in Fig. 1 at 15 V_{DS}.

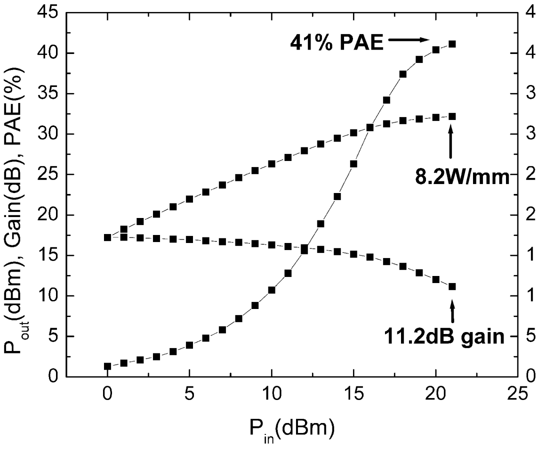

Fig. 3. Load-Pull data of a 1 μm gate length and 200 μm gate width device with a source–drain spacing of 5 μm biased at 45 V_{DS} and -4.7 V_{GS} and measured at 2 GHz. This device is located on the same wafer and die as the transistor shown in Figs. 1 and 2.

GaN layer of 2-μm thickness, followed by a 30-nm-thick $\mathrm{Al_{0.34}Ga_{0.66}N}$ barrier, and a GaN cap of 5-nm thickness. The top half of the barrier is doped with Si at 1×10^{18} cm^{-3} in order to improve the ohmic contacts. At an electron sheet concentration of approximately 1.3×10^{13} cm^{-2}, the low field electron mobility was 1370 cm^2/Vs.

After MBE growth, we cut the substrates further into quarters for device processing. After dry-etch mesa isolation, ohmic contacts were defined using optical contact lithography. The Ti–Al–Ni–Au ohmic metal stack was alloyed at 850 °C in N_2 atmosphere, yielding ohmic contacts with a transfer resistance of 1.1 Ω·mm as measured by TLM, along with a sheet resistance of 350 $\Omega/\Box$.

Finally, Schottky gates were deposited by electron-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 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.

III. RESULTS AND DISCUSSION

The HEMTs pinch off with -9 V applied between the gate and source, as shown in Fig. 1 for a device with 1 μm gate length and 25 μm gate periphery. A maximum extrinsic transconductance of 125 mS/mm was obtained with a drain–source voltage of 15 V, as shown in Fig. 2.

Device RF power testing was performed on 200-μm-wide devices with gate lengths of 1 and 2 μm. Here, we detail the performance of the 1-μm-long device with the highest saturated output power density. At $V_{\mathrm{DS}} = 45$ V, a quiescent drain current of 437 mA/mm was set by adjusting the gate bias to -4.7 V. Under large-signal operation, 3-dB gain compression occurs at an input power of 17 dBm with an output power of 31.3 dBm, as shown in Fig. 3. This corresponds to a scaled output power of 6.7 W/mm. The output power saturates at 32.2 dBm, corresponding to a power density of 8.2 W/mm with an associated gain of 11.2 dB and a power-added efficiency of 41%.

Drain dispersion, also known as RF current collapse or premature gain compression, is a phenomenon commonly observed in unpassivated AlGaN–GaN HEMTs to date. Drain dispersion has been attributed to charged surface states [6], [7], traps in the AlGaN barrier [8] or in the GaN buffer [7], [9], trapping in SI SiC substrates [4], and insufficient confinement of the channel charge [10]. As a measurement of drain dispersion, we recorded the dc drain current as a function of RF input power during the load-pull power sweep, while keeping the drain and gate voltages constant [11]. Fig. 4 displays the large-signal characteristics of a device with a 2-μm gate that produced a saturated power density of 7.6 W/mm with only 4.3-dB gain compression. This device was biased at $V_{\mathrm{DS}} = 53$ V and $V_{\mathrm{GS}} = -5$ V. The dc current density is constant at 363 mA/mm over the entire power sweep up to 21-dBm input power. It is clear that the channel current is not significantly degraded by trapping effects. Given

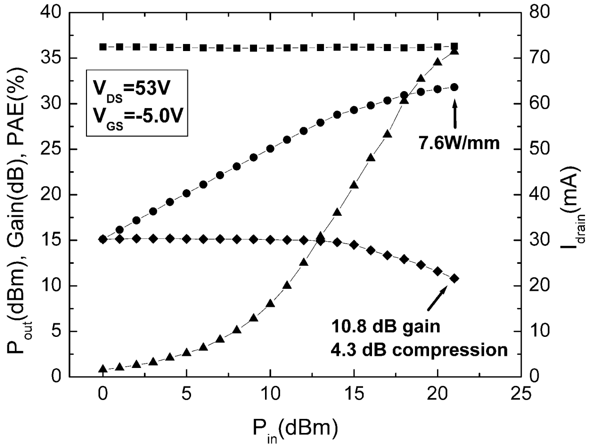

Fig. 4. Large-signal operation of a device with 2-μm gate length, 200-μm periphery, and a source–drain spacing of 6 μm. A saturated output power density of 7.6 W/mm is obtained with only 4.3-dB gain compression. The dc drain current is constant over the entire power sweep.

the observed high power densities and the lack of a surface passivation layer, our data suggests that surface effects are not the dominant source of dispersion in these MBE-grown layers.

IV. CONCLUSION

We have grown high-quality AlGaN–GaN HEMT layers by plasma-assisted MBE on SI 6H–SiC wafers. HEMTs fabricated from these layers with 1-μm-long and 200-μm-wide gates yielded a saturated output power of 8.2 W/mm at 2 GHz, with an associated gain of 11.2 dB and a power-added efficiency of 41%. SI 6H–SiC is shown to be a viable and cost-effective alternative to Vanadium-doped 4H–SiC. The drain dispersion, defined as the drop in dc drain current with large-signal RF input power, is found to be minimal. The drain dispersion is remarkably low given the absence of a surface-passivating layer. While the origins of drain 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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