

# AlGaIn/GaN HEMTs on (111) Silicon Substrates

P. Javorka, A. Alam, M. Wolter, A. Fox, M. Marso, M. Heuken, H. Lüth, and P. Kordoš

**Abstract**—AlGaIn/GaN HEMTs on silicon substrates have been fabricated and their static and small-signal RF characteristics investigated. The AlGaIn/GaN material structures were grown on (111) p-Si by LP-MOVPE. Devices exhibit a saturation current of 0.91 A/mm, a good pinchoff and a peak extrinsic transconductance of 122 mS/mm. A unity current gain frequency of 12.5 GHz and  $f_{\max}/f_T = 0.83$  were obtained. The highest saturation current reported so far, static output characteristics of up to 20 V and breakdown voltage at pinchoff higher than 40 V demonstrate that the devices are capable of handling  $\sim 16$  W/mm static heat dissipation.

**Index Terms**—GaN, MODFETs, semiconductor device fabrication, silicon.

## I. INTRODUCTION

AlGaIn/GaN HEMTs have recently been attracting much attention due to their promising characteristics for high-frequency, -power, and -temperature applications. Sapphire and recently SiC are commonly used as substrates because of their lack of large-area GaN bulk crystals. However silicon can be a useful alternative because of its low cost, large area availability, good thermal conductivity as well as potential integration of GaN power devices with advanced Si electronics. Much effort has been done on the growth of GaN on Si (about 100 references were found for the period of the last three years [1]). Growth of GaN on Si is more difficult than on sapphire due to the higher lattice and thermal expansion coefficient mismatches, which produce a higher dislocation density and the possible generation of cracks. This might be the reason for the few reports on GaN/Si transistors. Static measurements on MESFETs with a saturation current of  $\sim 0.1$  A/mm and a transconductance of 25–30 mS/mm have been presented recently [2], [3]. AlGaIn/GaN HEMTs on Si have also only recently been realized for the first time [4], [5]. Saturation currents of 0.1 and 0.5 A/mm and peak transconductances of 20 and  $\sim 100$  mS/mm were obtained on samples with different buffer layers [4]. Static output characteristics of up to 20 V, a saturation currents of 0.66 A/mm, an extrinsic transconductance of 140 mS/mm and current gain cutoff frequencies of up to 15 GHz (with  $f_{\max}/f_T < 1$ ) have been achieved on undoped AlGaIn/GaN HEMTs on (111) p-Si substrates [5]. Recently, we have reported on AlGaIn/GaN/Si round-HEMTs with a saturation current of 0.82 A/mm, a peak extrinsic transconductance of 110 mS/mm, a breakdown voltage at pinchoff of 40 V on devices with 0.3  $\mu\text{m}$  gate length [6]. The round-HEMT technology allows simple and fast processing of HEMTs [7]

and thus it is a useful tool for fast feedback between material structure growth and static device properties. We successfully used this procedure for the evaluation of AlGaIn/GaN/sapphire HEMT structures for which different device performances were resolved in spite of the nearly identical 2-DEG properties [8], [10].

In this work, we report on the fabrication and performance of linear i.e., RF-optimized AlGaIn/GaN HEMTs grown on (111) silicon substrates. The fabricated devices show a saturation current density of 0.91 A/mm, which is higher than reported before for AlGaIn/GaN HEMTs on Si and comparable to similar devices prepared on SiC substrates. A good pinchoff and a peak extrinsic transconductance of 122 mS/mm were obtained. An improvement in heat dissipation is observed for HEMTs on Si compared to those on sapphire due to its better thermal conductivity. The small signal characterization of the devices with 0.5  $\mu\text{m}$  gate length yielded  $f_T$  and  $f_{\max}$  of 12.5 and 10.4 GHz, respectively.

## II. DEVICE FABRICATION

Low-pressure MOVPE technique is used to grow AlGaIn/GaN heterostructures on 2-in (111)-oriented p-type Si substrates. For wurtzitic group III-nitride based heterostructures, a high 2-DEG channel conductivity can be obtained without doping due to large spontaneous and piezoelectric polarization. However, here we used a conventionally doped heterostructure to enhance the 2-DEG channel conductivity. A low-temperature AlN nucleation layer was grown first, followed by a special layer series on which a 2.5  $\mu\text{m}$  thick GaN buffer was deposited. Finally, a 6-nm undoped AlGaIn spacer, a 20-nm Si doped AlGaIn carrier-supply, and a 6-nm undoped AlGaIn barrier layer were grown, all with the mole fraction of AlN  $x = 0.23$  as determined by RBS. Crack-free structures with reduced tensile strain and very good surface roughness determined by atomic force microscopy (rms of 0.64 nm) were obtained [6].

The device processing consisted of conventional HEMT fabrication steps. After mesa etching, ohmic contacts were prepared by evaporating layered Ti/Al/Ni/Au followed by annealing at 900 °C for 30 s in a N<sub>2</sub> ambient. The ohmic contact resistance of 0.8–1.1  $\Omega$  mm with a channel sheet resistivity of  $\sim 1$  k $\Omega$ /sq. were measured using the transmission-line-method. The sheet carrier density of  $\sim 6 \times 10^{12}$  cm<sup>-2</sup> and the carrier mobility of  $\sim 700$  cm<sup>2</sup>/Vs is obtained from Hall effect measurements on 5  $\times$  5 mm<sup>2</sup> van der Pauw samples. The Schottky gate metallization consisted of a Ni/Au layers patterned by e-beam lithography. Unpassivated two-finger devices with source-drain separations of 3 and 5  $\mu\text{m}$ , gate lengths of 0.3, 0.5, and 0.7  $\mu\text{m}$  and a gate width of 0.1 mm (2  $\times$  50  $\mu\text{m}$ ) were prepared.

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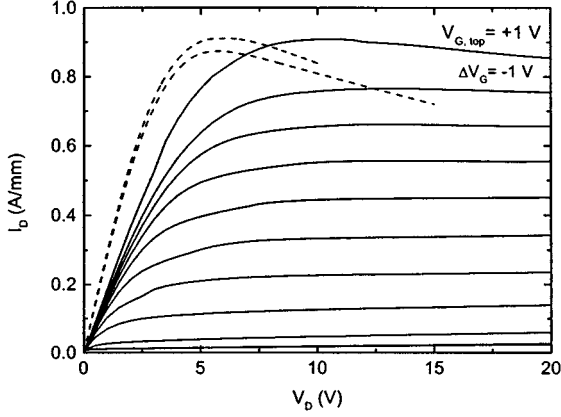


Fig. 1. Static  $I$ - $V$  characteristics of AlGaIn/GaN HEMT grown on a silicon substrate (full lines,  $V_{G,top} = +1$  V,  $\Delta V_G = -1$  V). For comparison, two typical characteristics of devices using the similar layer structure grown on sapphire are shown (dotted lines,  $V_G = +1$  V).

### III. EXPERIMENTAL RESULTS

Typical static output characteristics at different gate voltages from +1 V up to  $-10$  V ( $\Delta V_G = -1$  V) measured up to drain voltage of 20 V on devices with  $0.3 \mu\text{m}$  gate length are shown in Fig. 1 (solid lines). Low output conductance and minimal thermal effects are observed. A drain saturation current of  $0.91$  A/mm ( $0.72$  A/mm for devices with  $0.5 \mu\text{m}$  gate length, not shown here) is obtained at +1 V on the gate. This is higher than so far reported for AlGaIn/GaN HEMTs on Si [4] and comparable to values on high-performance microwave power HEMTs on SiC substrates [9]. Also presented in Fig. 1 are typical output characteristics at  $V_G = +1$  V for two devices with a similar layer structure however grown on sapphire substrates (dotted lines). The HEMTs on Si substrates can sustain significantly higher dc power in comparison to similar devices grown on sapphire. The drain current decreases only slightly ( $V_G = 1$  V) or is almost constant ( $V_G \leq 0$  V) with increasing drain voltage for devices on Si (Fig. 1). An improvement in heat dissipation because of the higher thermal conductivity of Si compared to sapphire ( $k_{\text{Si}}/k_{\text{sapphire}} \cong 5$ ) is evident. Thus, channel heating effects are significantly reduced and the devices can handle static heat dissipation of up to about  $16$  W/mm without remarkable degradation of their performance.

The transfer characteristics of the AlGaIn/GaN HEMT on Si are shown in Fig. 2. The peak extrinsic transconductance of  $122$  mS/mm was measured at  $V_G = -5$  V. This is only slightly lower than reported for high-performance microwave power GaN-based HEMTs on SiC [9]. However, further enhancement may be achieved by optimizing the HEMT dimensions, especially the gate length and the gate drain spacing. The threshold voltage of these devices is close to  $-9$  V opposed to  $-6$  V observed on similar devices on sapphire. The breakdown voltage at pinchoff is found to be slightly above  $40$  V.

The small signal characterization of the devices was carried out by on-wafer S-parameter measurements using an HP 8510C network analyzer. Fig. 3 shows the short circuit current gain ( $h_{21}$ ) and the unilateral power gain (GU) as a function of frequency measured for  $0.5 \mu\text{m}$  gate length devices. Typically, the best performance was achieved at a gate bias close to the

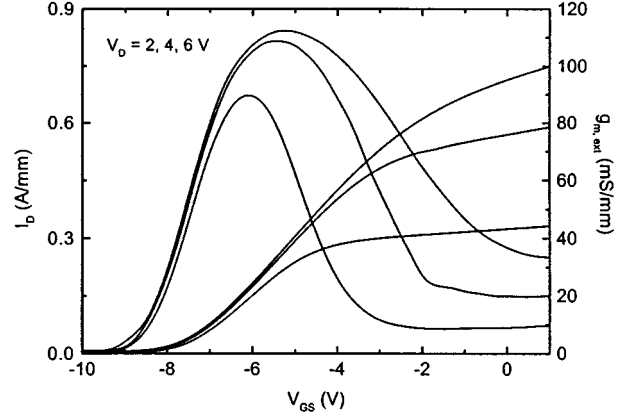


Fig. 2. Transfer characteristics and transconductance of AlGaIn/GaN HEMT grown on a silicon substrate.

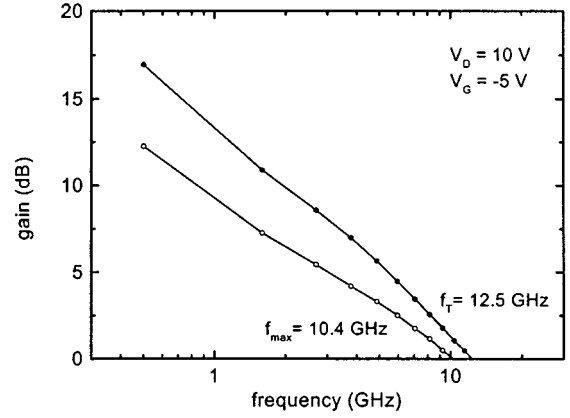


Fig. 3. Small signal performance of AlGaIn/GaN HEMT on silicon substrate ( $L_g = 0.5 \mu\text{m}$ ,  $W_g = 2 \times 50 \mu\text{m}$ ).

transconductance maximum. An extrinsic current-gain cutoff frequency ( $f_T$ ) of  $12.5$  GHz and a maximum frequency of oscillation ( $f_{\text{max}}$ ) of  $10.4$  GHz are evaluated at  $V_{DS} = 10$  V and  $V_G = -5$  V biases. These are slightly higher values than the  $10.3$  GHz and  $9.3$  GHz for the  $f_T$  and  $f_{\text{max}}$  respectively, reported previously for AlGaIn/GaN/Si HEMTs with a gate length of  $0.5 \mu\text{m}$  [5]. A  $f_{\text{max}}$  to  $f_T$  ratio of  $0.83$  is achieved, nearly the same as found before for the similar gate length [5]. On the other hand, devices we prepared on similar layer structure grown on sapphire show  $f_T$  of  $50$ – $54$  GHz and  $f_{\text{max}}/f_T$  of  $1.2$ – $1.5$ . This indicates an influence of parasitic conduction through the Si substrate under small signal conditions. Thus, Si substrates with higher resistivity need to be used in order to improve RF performance of AlGaIn/GaN/Si HEMTs. Another question is the device degradation under high dc power stress. We observed a partial current reduction after biasing the devices with  $V_{DS} = 10$  V and  $V_G = -5$  V, i.e., at conditions used for RF characterization—these results will be reported elsewhere.

### IV. CONCLUSION

AlGaIn/GaN HEMTs on (111) Si substrates were prepared and their static and RF characteristics investigated. The devices exhibit a saturation current of  $0.91$  A/mm, good pinchoff, a peak extrinsic transconductance of  $122$  mS/mm and a break-

down voltage of  $\geq 40$  V at pinchoff. A unity current gain frequency of 11.5 GHz and  $f_{\max}$  to  $f_T$  ratio of 0.83 were achieved. The highest saturation current reported so far and static output characteristics measured up to 20 V demonstrate that the devices prepared are capable of handling  $\sim 16$  W/mm of static heat dissipation without significant degradation of their performance. Further improvement might be achieved by optimizing the layer structure (mainly by using a higher Al content) and the HEMT dimensions (the gate length and the gate drain spacing) as well as by using Si substrates with higher resistivity. Power measurements of our AlGaIn/GaN/Si devices are in progress and results obtained will be reported elsewhere.

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