Large Signal Properties of AlGaN/GaN HEMTs on High Resistivity Silicon Substrates Grown by MBE

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Abstract — **The large signal characteristics of *1 µm* long π-gate AlGaN/GaN HEMTs on resistive silicon substrates have been measured and analyzed. The HEMTs demonstrated maximum transconductance and current density values of 350 mS/mm and 1,200 mA/mm respectively. High current gain and maximum power gain frequencies f_t and f_{max} were measured at 25 *GHz* and *43 GHz*. Large signal gain and power density values of *16 dB* and *1.7 W/mm* for a two-finger *1x75 µm²* HEMT respectively were observed at 5 GHz. The device also exhibited *PAE* values as high as *40%* with P_{1dB} around *+2.0 dBm* for Class AB operation.**

I. INTRODUCTION

Due to the recent advancements in epitaxial layer quality and device processing techniques, GaN-based High Electron Mobility Transistors (HEMTs) have become prime candidates for high power and high frequency applications. The large breakdown field ($F_B > 2MV/cm$) and carrier saturation velocity ($v_s \sim 2.0x10^7$ *m/s*) of this material system allows for a definite improvement over current Si or GaAs based devices. State-of–the-art power density and high frequency performances have been observed for nitride-based HEMT devices and circuits [1], but there are still important problems to overcome. The significant strides made recently in growth of high crystalline quality III-V nitride layers on larger area Si(111) substrates by Metalorganic Chemical Vapor Deposition (MOCVD) [2,3,4], and most recently by Molecular beam Epitaxy (MBE) [5,6] presents unique opportunities for a cost effective microwave device technology.

While the best power performance reported for GaN-based HEMTs are from device layers grown on SiC, the use of Si(111) substrates allows for greater ease of backside processing and thermal management. Preliminary results for GaN-on-Si HEMTs grown by MOCVD did show promising DC results with improved growth techniques and material quality, but had limited RF and large signal performance due to capacitive loading effects from conductive substrates [6]. With the use of high resistivity substrates and optimization of MBE growth parameters, many of those challenges can be resolved, as the authors have observed. In this work, the fabrication and measurement of HEMTs will be reported using AlGaN/GaN layers grown on high resistivity silicon substrate by MBE with extremely promising microwave power performance.

II. FABRICATION AND DC MEASUREMENTS OF ALGAN/GAN HEMTS

The HEMT device layers were grown on Si(111) substrates with $R_s > 5,000$ Ω/sq using MBE by the Picogiga Corporation. The device layers used had an undoped GaN cap layer and AlGaN barrier layer and manifested measured Hall mobility and sheet carrier density values of $\mu = 1,640$ cm²/V-s and $n_s = 7.8 \times 10^{12}$ cm⁻² respectively. The device mesas were defined using reactive-ion etching (RIE) and CCl_2F_2:*Ar* etching chemistry. Source and drain ohmic contacts were defined using optical lithography, and Ti/Al/Au metallization layers were deposited by electron-beam evaporation. Successive annealing steps between 800°C and 850°C were employed to improve the contact resistance R_c and specific contact resistivity R_{sc} to ~ *0.3 Ω/mm* and $3.6x10^{-6}$ *Ω-cm²* respectively. The gate Schottky contacts consisted of a Ni/Ti/Au metallization,

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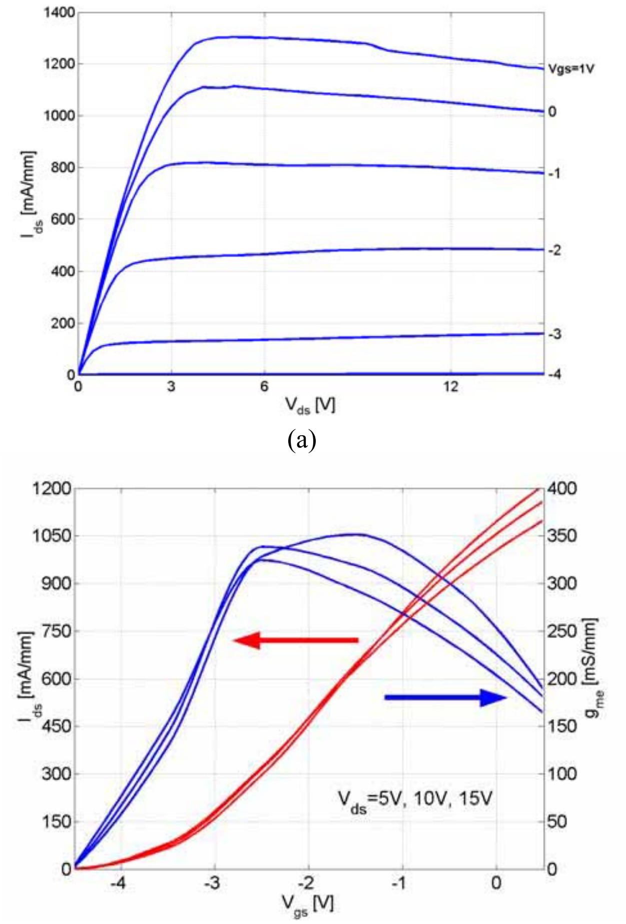


(a)

(b)

Figure 1. I_{ds}-V_{ds} curves (a) and DC transfer characteristic (b) for a two finger π-gate HEMT

defined through optical lithography, with a minimum gate length of 1 µm. A thick Ti/Al/Ti/Au interconnect metallization was finally deposited to complete the process.

The DC I-V transfer characteristic of a two-finger *1x75 µm*^{2} AlGaN/GaN π-gate HEMT is shown, in Figure 1. The devices show good current capability with a maximum current density of *~ 1200 mA/mm*, a threshold voltage V_{th} of *-4.0 V* and a low knee voltage V_{knee} of *~ 3.25 V*. The maximum extrinsic transconductance (g_m^{ext}) of *350 mS/mm* occurs at a gate to source voltage V_{gs} of *–2.0 V*. This represents a significant improvement over previously published DC characteristics of GaN-based HEMTs grown on silicon [7,8,9]. The gate diode characteristics were also exceptionally good with gate turn on voltages V_{to} ranging from *+1.3V* to *+1.6V* and reverse leakage values as low as *-5µA* at V_{gs} = *-5.0V*. The drain-to-source breakdown voltage, V_{DS}^{BD}, was measured using a special technique based on current injection, which is described elsewhere [10]. V_{DS}^{BD} values of *~ 35 V - 45V* were observed consistently among devices of different gate peripheries and across the wafer.

III. HIGH FREQUENCY CHARACTERIZATION OF ALGAN/GAN ON Si(111) HEMTS

Small signal, on wafer S-parameter measurements of the fabricated microwave HEMTs were performed using a HP 8510 S-parameter network analyzer in an automated setup. The current gain (f_t) and maximum power gain cutoff frequencies (f_{max}) were extracted from the S-parameter data for several DC bias points. The maximum f_t value obtained was *25 GHz (see Figure 2)*. The peak value for f_{max} *(U)* was *43 GHz* and occurred at a gate to source voltage V_{gs}, of *–2.0V* and a drain to source voltage V_{ds} of *+9 V*.

Under fixed gate bias conditions f_{max} values show a steady increase for V_{ds} from *+3.0 V* to *+9.0 V*, but level off and show gradual improvement for V_{ds} > *+10 V*. Conversely, f_t values decrease slightly for V_{ds} > *+9.0 V*, but level out at *18 GHz* for V_{ds} > *+18.0* V. Under fixed drain bias conditions, f_t and f_{max} values have a broad peak centered at V_{gs} = *-2.0 V*, but decrease more quickly closer to channel pinch off. The effective carrier velocity was also extracted to further study the device and material quality. An intrinsic transit time *τ* of *5.2 ps* was obtained from small signal equivalent modeling. The effective carrier velocity is given in equation (1),

$$v_{eff} = (L_g + 2t)/\tau \qquad (1)$$

where L_g is the gate length, *t* is the AlGaN barrier thickness, and *τ* is the intrinsic channel transit time [11].

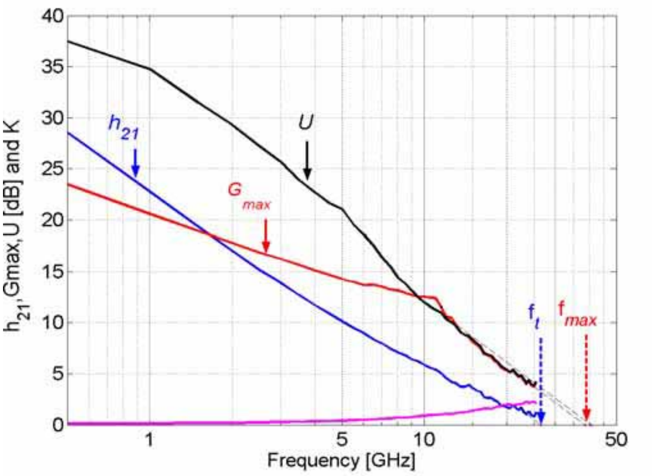


Figure 2. Extraction of f_t and f_{max} values for two-finger *1x75µm*^{2} AlGaN/GaN Picogiga HEMT

This intrinsic channel transit time is calculated from the extracted intrinsic g_{mi} and C_{gsi} values as shown in equation (2),

$$\tau = f_{ti}^{-1} = (g_{mi}/C_{gsi})^{-1} \qquad (2)$$

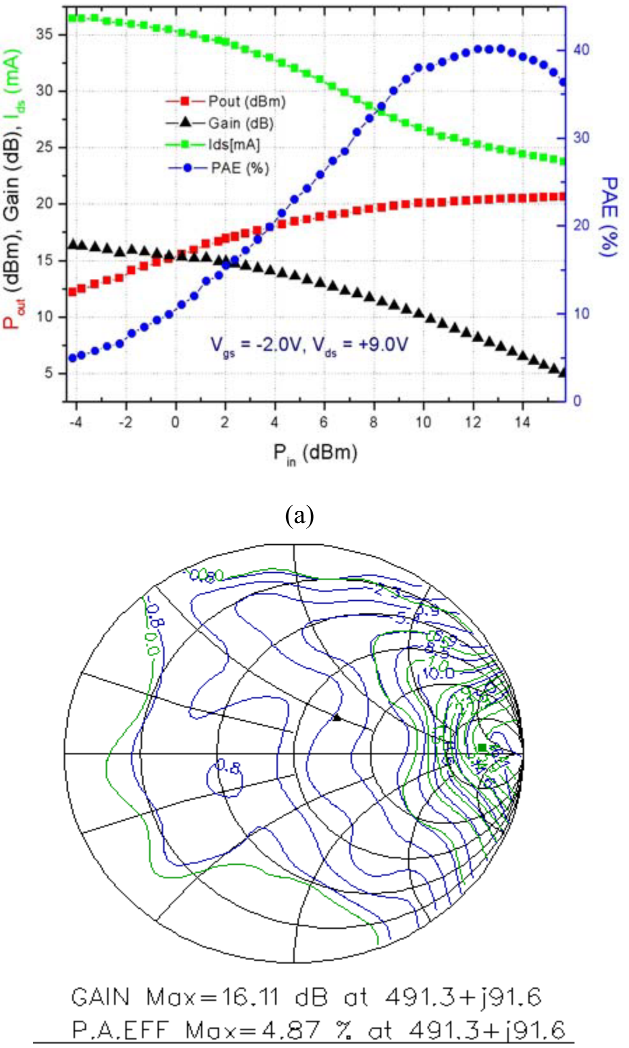
Using the appropriate values for the device and material structure an effective carrier velocity of $v_{eff} = 2.02x10^7$ *cm/s* is obtained. This is very close to the theoretical value of $2.50x10^7$ *cm/s* for GaN.

These exceptional high frequency results for an optical lithography *1-μm* gate process are very promising for the use of GaN-based device layers on silicon substrates. Due to the high I_{ds}, g_m, and excellent ohmic contact quality of these devices, the reported f_t and f_{max} values compare even to reported *0.3 μm* gate length devices also fabricated on MBE grown AlGaN/GaN HEMTs on resistive Si(111) substrates ($f_t \sim 28$ *GHz*, $f_{max} \sim 50$ *GHz*) [12].

IV. LARGE SIGNAL MEASUREMENTS

Large signal measurements of a two-finger 1×75 μm^2 wide HEMT were made at *5.0 GHz* using an automated load-pull station with computer controlled mechanical tuners from Focus Microwaves. In addition, a programmable harmonic tuner was used at the output to minimize power loss to the second (*10.0 GHz*) or third (*15.0 GHz*) harmonics. An optimum drain bias V_{ds} of *+9.0 V* was chosen based on the peak value of small signal gain for the device. The gate bias V_{gs} was varied from *0.0 V* (Class A) to *–3.5 V* (Class B). In order to investigate device behavior on various classes of operation, Load pull contours were measured for each bias point at a power *–4.0 dBm* where the optimum load and source impedance points (Z_L and Z_s) for gain and *PAE* were investigated. Using power sweep measurements, the P_{1dB} point, maximum P_{out}, and peak *PAE* values were observed for each bias point.

The peak gain value observed for the two-finger $1x75\mu m^2$ HEMT was about 16 dB at 5.0 GHz for both Class A and A/B operation, which was for $V_{gs} = 0.0V$ to *-2.0V*. A peak PAE value of 42% was observed for P_{in} = *+13.0 dBm* (see Figure 3). No discernable current collapse effects were observed for this device as the DC value for $I_{ds} \sim 37$ *mA* was identical to the value at low P_{in} values for the large signal measurement. The maximum saturated output power of *21 dBm* for this device corresponds to an output power density of *1.7 W/mm*, with a P_{1dB} point of *1.0 dBm*. These P_{out} and power density values are comparable with those of devices made on Sapphire and SiC substrates [13]. The peak PAE value is around *25%* even for Class A operation and the associated gain is *16 dB*. This is due to the large current density and transconductance values for this device along with the highly resistive substrate. It is also noted that the peak large signal gain and efficiency values occur at the same bias for optimum DC and RF performance. Such a resistive substrate reduces RF power loss, which can arise from capacitive loading effects from a conductive substrate



(a)

(b)

Figure 3. Large signal power sweep (a) and load pull contour graphs (b) for a two-finger $1x75\mu m^2$ HEMT

The source and load impedance values for optimum gain, PAE, and Pout were also examined. For standard III-V devices significant design tradeoffs are sometimes encountered due to large differences in matching points for gain, *PAE*, or P_{out}. For each individual class of operation, the source and load impedances for gain, PAE and Pout were identical (see

Figure 3). Even across different classes of operation, the optimum Z_L and Z_s values were very similar. Such a similarity of optimum matching conditions allows great latitude in circuit design without the need of significant trade offs for gain, *PAE* or P_{out}.

V. CONCLUSIONS

A *1-μm* gate process was demonstrated for AlGaN/GaN HEMTs grown by MBE on high resistivity silicon substrates. The maximum current density and extrinsic transconductance values observed are *1,200 mA/mm* and *350 mS/mm* respectively. DC I-V characteristics exhibit well defined linear and saturation regions, with low threshold and knee voltage of $V_{th} = -4.0\ V$ and $V_{knee} = +3.25V$ respectively. The gate diode characteristics also show low gate leakage values of $-5.0\mu A$ at $V_{gs} = -5.0V$ and high turn-on voltage V_{to} values of $+1.3V$ to $+1.6V$ across the wafer. Drain-to-source breakdown voltages, V_{DS}^{BD} of $35V - 45V$, using the current injection technique, were also observed for the measured devices.

Maximum values of the current and power gain cutoff frequencies of $f_t = 25\ GHz$, and $f_{max} = 43\ GHz$, were observed at $V_{gs} = -2.0V$ and $V_{ds} = +15\ V$. An effective carrier velocity of $v_{eff} = 2.02x10^7\ cm/s$ was extracted from device and material parameters. Peak large signal gain and *PAE* values of *16.0 dB* and *41%* were observed at *5.0 GHz* for a two-finger $1x75\mu m^2$ HEMT operating in Class AB. These values are comparable to nitride devices made on SiC and sapphire substrates. P_{1dB} values of *+1.0 dBm* to *7.0 dBm* for Class A/AB to Class B operation were measured. No effects of current collapse were observed between the DC and RF I_{ds} values for the device under test. Optimum Z_L and Z_s values were nearly identical for *gain*, *PAE*, and P_{out} values for each individual class of operation. These optimum Z_L and Z_s values were also very similar across different classes of device operation. Significant improvements in large signal performance are expected with the use of submicron gates, larger multi-finger device geometries, and further improved ohmic contacts.

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