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 μm\(^2\) 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 (\( F_B > 2\) MV/cm) and carrier saturation velocity (\( v_s \approx 2.0 \times 10^7 \) 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 \( \mu = 1.640 \) cm\(^2\)/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 \( 3.6 \times 10^{-6} \) Ω-cm\(^2\) respectively. The gate Schottky contacts consisted of a Ni/Ti/Au metallization,

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Figure 1. Id-Vds 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 μm² 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 Vth of -4.0 V and a low knee voltage V_knee of ~3.25 V. The maximum extrinsic transconductance (g_m extr) of 350 mS/mm occurs at a gate to source voltage Vgs 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 Vto ranging from +1.3V to +1.6V and reverse leakage values as low as ~5μA at Vgs = -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) and maximum power gain cutoff frequencies (f_max) were extracted from the S-parameter data for several DC bias points. The maximum f value obtained was 43 GHz (see Figure 2). The peak value for f_max (U) was 43 GHz and occurred at a gate to source voltage Vgs of -2.0V and a drain to source voltage Vds of +9 V.

Under fixed gate bias conditions f_max values show a steady increase for Vds from +3.0 V to +9.0 V, but level off and show gradual improvement for Vds > +10 V. Conversely, f values decrease slightly for Vds > +9.0 V, but level out at 18 GHz for Vds > +18.0 V. Under fixed drain bias conditions, f and f_max values have a broad peak centered at Vgs = -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),

\[ v_{eff} = \frac{(L_g + 2t)/\tau}{(L_g + 2t)/\tau} \]

where L_g is the gate length, τ is the AlGaN barrier thickness, and τ is the intrinsic channel transit time [11].
This intrinsic channel transit time is calculated from the extracted intrinsic $g_{mi}$ and $C_{gsi}$ values as shown in equation (2),

$$\tau = f_t^{-1} = (g_{mi}/C_{gsi})^{-1}$$  \hspace{1cm} (2)

Using the appropriate values for the device and material structure an effective carrier velocity of $v_{eff} = 2.02 \times 10^7$ cm/s is obtained. This is very close to the theoretical value of $2.50 \times 10^7$ 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 ($f_t \approx 28$ GHz, $f_{max} \approx 50$ GHz) [12].

IV. LARGE SIGNAL MEASUREMENTS

Large signal measurements of a two-finger $1 \times 75 \mu m^2$ 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 $1 \times 75 \mu m^2$ HEMT was about 16 dB at 5.0 GHz for both Class A and A/B operation, which was for $V_{gs} = 0.0$V 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.

Figure 3. Large signal power sweep (a) and load pull contour graphs (b) for a two-finger $1 \times 75 \mu m^2$ 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 Pout. 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 $Z_i$ and $Z_o$ 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, $\text{PAE}$ or $P_{\text{out}}$.

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 $\text{mA/mm}$ and 350 $\text{mS/mm}$ respectively. DC I-V characteristics exhibit well defined linear and saturation regions, with low threshold and knee voltage of $V_{th} = -4.0 \text{ V}$ and $V_{knee} = +3.25 \text{ V}$ respectively. The gate diode characteristics also show low gate leakage values of $-5.0 \mu \text{A}$ at $V_{gs} = -5.0 \text{ V}$ and high turn-on voltage $V_{to}$ values of $+1.5 \text{ V}$ to $+1.6 \text{ V}$ across the wafer. Drain-to-source breakdown voltages, $V_{BD}$ of $35 \text{ V} - 45 \text{ V}$, using the current injection technique, were also observed for the measured devices.

Maximum values of the current and power gain cutoff frequencies of $f_t = 25 \text{ GHz}$, and $f_{max} = 43 \text{ GHz}$, were observed at $V_{gs} = -2.0 \text{ V}$ and $V_{bd} = +15 \text{ V}$. An effective carrier velocity of $v_{eff} = 2.02 \times 10^7 \text{ cm/s}$ was extracted from device and material parameters. Peak large signal gain and $\text{PAE}$ values of $16.0 \text{ dB}$ and $41\%$ were observed at $5.0 \text{ GHz}$ for a two-finger $1x75 \mu\text{m}^2$ HEMT operating in Class AB. These values are comparable to nitride devices made on SiC and sapphire substrates. $P_{1dB}$ values of $+1.0 \text{ dBm}$ to $7.0 \text{ dBm}$ for Class A/AB to Class B operation were measured. No effects of current collapse were observed for the DC and RF $I_{ds}$ values for the device under test. Optimum $Z_i$ and $Z_o$ values were nearly identical for gain, $\text{PAE}$, and $P_{\text{out}}$ values for each individual class of operation. These optimum $Z_i$ and $Z_o$ 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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REFERENCES


