

Very-High Power Density AlGaIn/GaN HEMTs

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Abstract—Research work focusing on the enhancement of large-signal current-voltage (I - V) capabilities has resulted in significant performance improvement for AlGaIn/GaN HEMT's. 100–150 μm wide devices grown on SiC substrates demonstrated a record power density of 9.8 W/mm at 8 GHz, which is about ten times higher than GaAs-based FETs; similar devices grown on sapphire substrates showed 6.5 W/mm, which was thermally limited. 2-mm-wide devices flip-chip mounted on to AlN substrates produced 9.2–9.8 W output power at 8 GHz with 44–47% PAE. A flip-chip amplifier IC using a 4-mm device generated 14 W at 8 GHz, representing the highest CW power obtained from GaN-based integrated circuits to date.

Index Terms—AlGaIn, FET, flip-chip, GaN, HEMT, microwave power.

I. INTRODUCTION

WIDE-BANDGAP AlGaIn/GaN high electron mobility transistors (HEMTs) have great promise in power generation at high frequencies, due to the high breakdown field and excellent electron transport properties. These devices are typically grown on either SiC or sapphire substrates. The former provides an excellent thermal conductivity of 3.5 to 4.5 W/cm $^{\circ}\text{C}$, while the latter is available at a lower cost and in larger wafer sizes. For a specific device technology, output power density is a major performance benchmark. This is usually evaluated using small devices with minimum thermal complications. For practical applications, however, the device periphery needs to be scaled up to obtain high total output power. Earlier demonstrations include devices grown on sapphire substrates with power density of 4.6 W/mm and a total power of 7.6 W [1], as well as devices on SiC with power density of 6.9 W/mm and a total power of 9.1 W [2]. In this paper, we present further improvement of the AlGaIn/GaN HEMT technology focusing on enhancement of large-signal current-voltage (I - V) capabilities under rf operations.

II. DEVICE TECHNOLOGY

The devices in our laboratories were grown by metal organic chemical vapor deposition on either semi-insulating SiC substrates or sapphire substrates. The epi-layers consisted of a semi-insulating GaN buffer and a modulation-doped AlGaIn layer

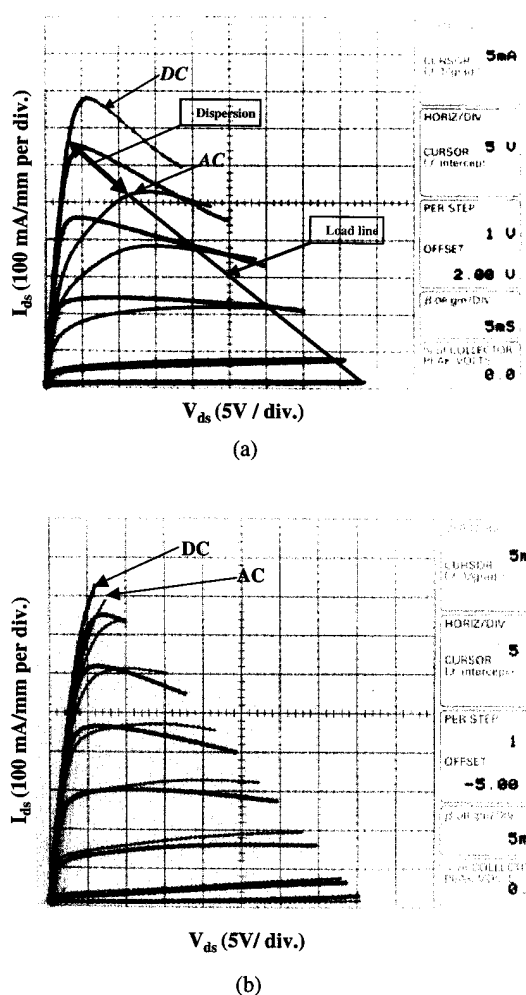


Fig. 1. I - V characteristics under dc and ac gate drives for (a) an AlGaIn/GaN HEMT with severe trapping effect or dispersion, and (b) an AlGaIn/GaN HEMT with minimum trapping effect.

to supply charge for the two-dimensional (2-D) gas as well as to offer a Schottky-gate barrier. The basic device fabrication process included ohmic contacts by Ti/Al/Ni/Au [3], mesa isolation by Cl_2 reactive ion etching and gate formation by Ni/Au. Important issues in device development are addressed below.

A. Maximizing Channel Current and Breakdown Voltages

The output power density of a field-effect-transistor (FET) is directly related to its current density and breakdown voltage. For an AlGaIn/GaN HEMT, the maximum channel current is set by the conduction band discontinuity between the AlGaIn donor/barrier layer and the GaN channel layer. Device optimization has to do with increasing this discontinuity by increasing

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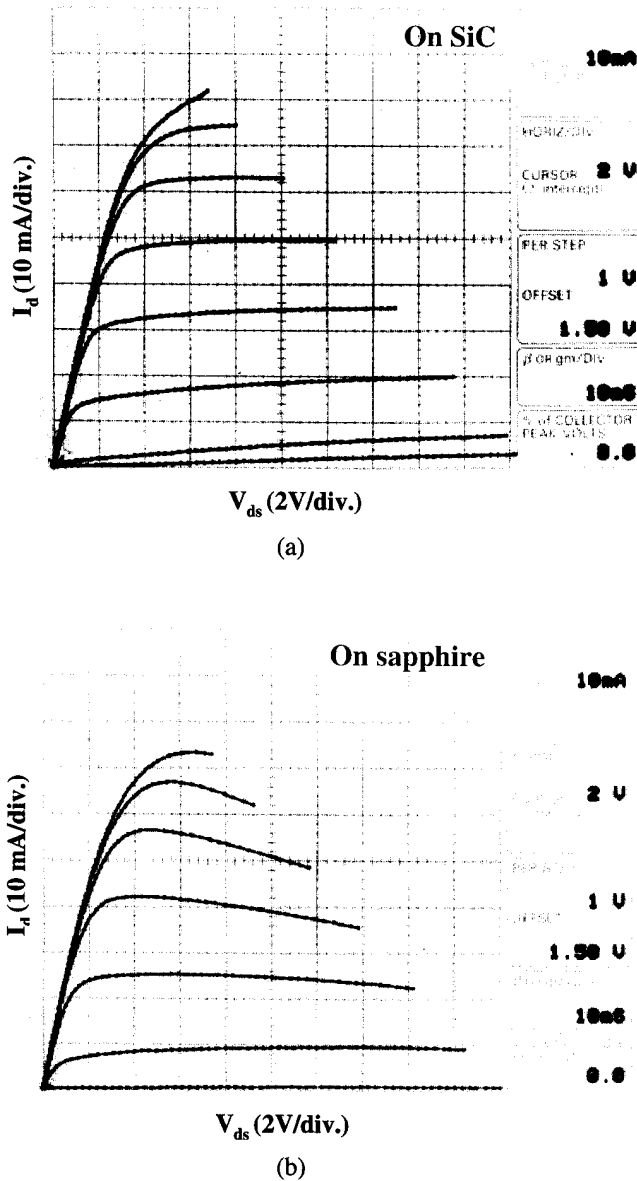


Fig. 2. I - V characteristics of AlGaN/GaN HEMTs (a) grown on SiC substrates, and (b) grown on sapphire substrates. Device dimension: $0.5 \times 75 \mu\text{m}^2$. V_{gs} start: +1.5 V, step: -1 V.

the Al content of the AlGaN layer. Additional advantages of adopting a high Al-content include a higher breakdown field in the AlGaN and a higher Schottky barrier of the gate diode. These enhance both the voltage handling capability and temperature tolerance of the devices. However, the high Al content should be realized without unwanted compromises such as introduction of deep levels and reduction in the crystal quality of the epi-layers. Although not yet conclusive, research work to date has shown that high-current AlGaN/GaN HEMTs can be grown with Al-contents up to 50% [4]. However, achieving high crystal quality for high Al-content AlGaN layers is still a challenge. Also, difficulty in forming a low-resistance ohmic contact was observed when Al content exceeded 40–45%. Devices covered in this work used an Al-content of 38–40% for optimum overall performance with the present material and device technologies.

The AlGaN layers were modulation doped to $\sim 2 \times 10^{18} \text{ cm}^{-3}$ by Si. Typical room temperature charge density and mobility are $1200 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ and $1.3 \times 10^{13} \text{ cm}^{-2}$, respectively.

B. Reducing the Large-Signal Trapping Effect

It has been observed that most previous AlGaN/GaN HEMTs were plagued with a discrepancy, or dispersion, between the I - V characteristics under dc gate drives and ac (or pulsed) gate drives as illustrated in Fig. 1(a) [1]. When measured at dc conditions, the device shows a high channel current and a low knee voltage. Under fast gate drives, however, the available drain current is significantly reduced along with a much higher knee voltage. This directly reduces the output power and efficiency under ac operation.

The above phenomenon is caused by traps in the device structure. A power device operates along the load line as indicated in Fig. 1(a). In the off state the device supports a large drain voltage, which leads to a high gate-drain electric field. Electrons can then be excited and captured in the traps between the gate-drain region. The time constant for detrapping is too long for these trapped electrons to follow the ac signal and hence they are not available for conduction in the on state. This results in a lack of free electrons at the drain side of the device and forms a current choke, which both limits the channel current and increases the knee voltage. Potentially, all traps on the AlGaN surface, in the AlGaN layer, at the AlGaN/GaN interface or even in the GaN buffer can cause the above problem. A multitude of efforts have to be made to ensure high-quality epi-growth and low-damage device processing. A well-engineered device shows well-behaved I - V characteristics under ac gate drive as in Fig. 1(b). Reduction of this trapping effect is key to the improvement of device performance.

III. DEVICE PERFORMANCE

Fig. 2(a) shows the I - V characteristics of a $75\text{-}\mu\text{m}$ wide $\text{Al}_{0.38}\text{Ga}_{0.62}\text{N}$ HEMT grown on SiC substrates. The maximum current is greater than 1 A/mm. This compares favorably with the 0.68 A/mm value for the lower-Al-content $\text{Al}_{0.14}\text{Ga}_{0.86}\text{N}$ /GaN HEMTs grown on the same substrates [2]. The ohmic contact resistance was measured to be 0.5–0.6 $\Omega\text{-mm}$, substantially lower than the 0.9–1.0 $\Omega\text{-mm}$ value for the higher-Al-content $\text{Al}_{0.5}\text{Ga}_{0.5}\text{N}$ HEMTs reported earlier [4]. This resulted in a low device on-resistance of 3 $\Omega\text{-mm}$. The Schottky gate turn-on is about 1.8 V and gate-drain breakdown voltage is typically 60 ~ 80 V. The channel pinch-off is about -5 V and the transconductance is as high as 230 mS/mm. I - V curves of a device grown on sapphire substrate are shown in Fig. 2(b) for comparison. The characteristics are quite similar except for the apparent negative output resistance at high dc power levels, which is attributed to the poor thermal conductivity of sapphire. Both devices exhibited minimal large-signal trapping effect similar to what is shown in Fig. 1(b). Small-signal current-gain and power-gain cutoff frequencies were measured as 25–30 GHz and 60–100 GHz, respectively, for these 0.5–0.6 μm gate devices. The superior gain properties were maintained at high bias voltages well

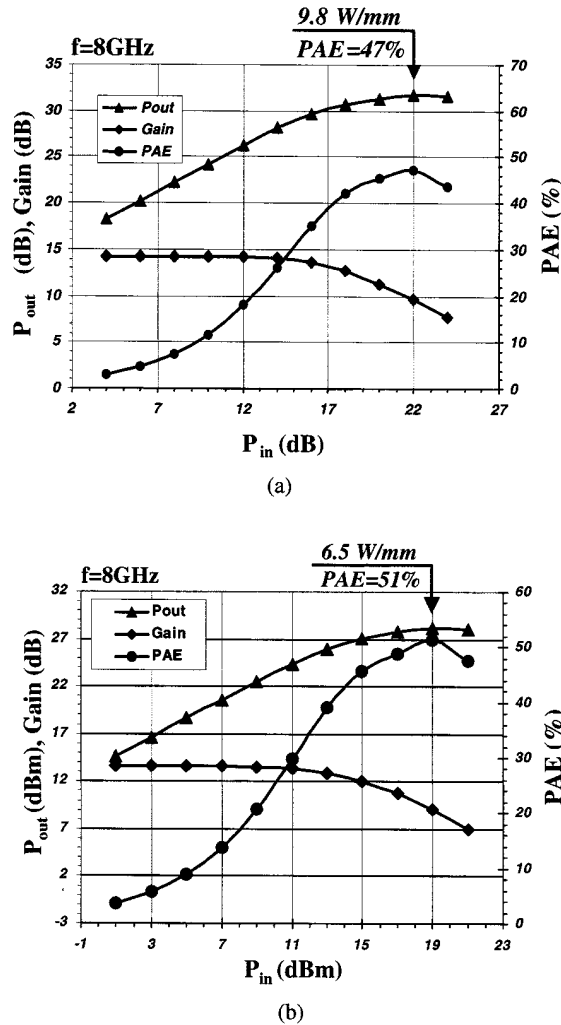


Fig. 3. Power performance of the AlGaIn/GaN HEMTs for (a) a 150- μ m-wide devices grown on SiC substrate and (b) a 100- μ m-wide device grown on sapphire substrate.

above 30 V for the devices on SiC without thermal complications, which is in agreement with the high electron velocity predicted for this material system [5].

An ATN load-pull system was used for large-signal continuous-wave (CW) characterization at 8 GHz. Fig. 3(a) shows the on-wafer measurement result of a 150- μ m-wide device on SiC substrate. The device was biased at 38 V and 487 mA/mm and tuned for maximum power. The saturation power is 31.7 dBm, translating into a power density of 9.8 W/mm. The associated power gain and power added efficiency (PAE) are 9.6 dB and 47%, respectively. The power density level is the highest for a field effect transistor (FET) to date and is about ten times greater than GaAs-based FETs in the same frequency band. The devices were also tested in class-AB mode for high efficiency with single-harmonic turning. The bias voltage was 24 V with a quiescent current of 120 mA/mm, which was self-adjusted with increasing input drive to 436 mA/mm. At an input power of 0.63 W/mm, an excellent PAE and power density combination of 60% and 6.5 W/mm was achieved.

The same measurements were also performed on devices grown on sapphire substrates for comparison. Fig. 3(b) shows

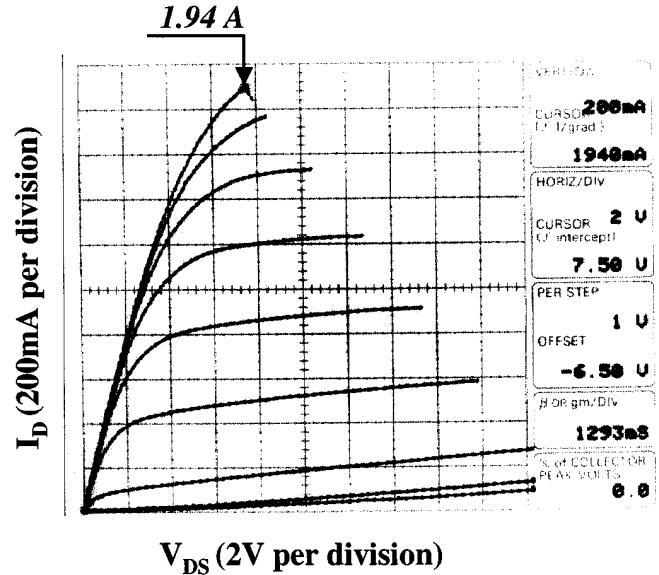
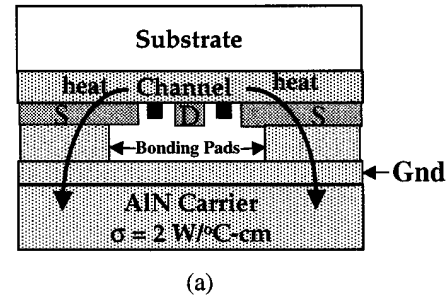


Fig. 4. (a) Schematics of the flip-chip bonded AlGaIn/GaN HEMT; (b) I - V characteristics of the 2-mm-wide AlGaIn/GaN HEMT showing a maximum current of 1.94 A.

the power sweep of a 100- μ m-wide device when biased at 26 V, 427 mA/mm and tuned for maximum power. The saturation power density is 6.5 W/mm along with associated gain of 9.1 dB and PAE of 51%. Due to the poor substrate thermal conductivity, the device was not able to withstand higher bias, which limited its output power. Nonetheless, it demonstrated significant improvement over previous devices on sapphire [1]. When operated in class-AB mode at 20 V, the device achieved 60% PAE with 4.4 W/mm power density. The performance improvement for both AlGaIn/GaN HEMTs on SiC and sapphire substrates is attributed to adoption of a high Al content and reduction of the trapping effect, which greatly enhance large-signal current-voltage capabilities under rf operations.

Large-periphery devices were also fabricated and flip-chip bonded on to AlN carriers as shown in Fig. 4(a). The Au source bonds serve as low-inductance ground connection as well as paths for heat dissipation. A 2-mm-wide device exhibited a high current level of 1.94 A as seen in Fig. 4(b). The corresponding current density is 0.97 A/mm, indicating excellent current scaling. Due to both the thermal cross talk inherent in a multifinger device and the lower thermal conductivity of AlN (1.8 W/cm $^\circ$ C) compared with SiC, a relatively low bias of 22 V was used during the power measurement. Nonetheless, it

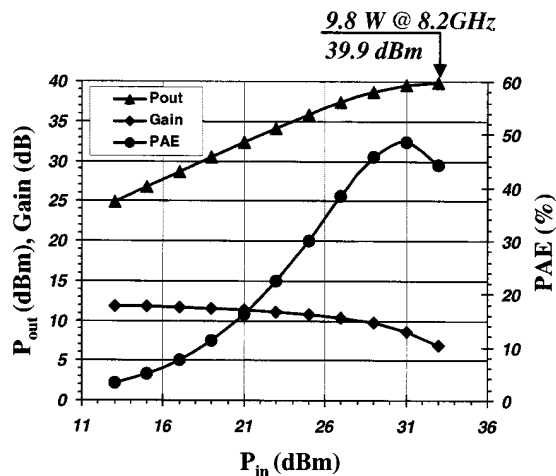


Fig. 5. Power performance of the 2-mm-wide AlGaIn/GaN HEMTs when biased at 22 V, showing an output power level of 9.2–9.8 W with PAE 44–47% at 8 GHz.

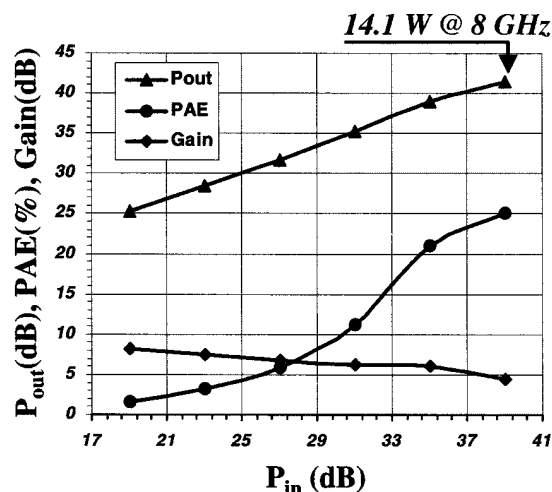


Fig. 7. Power performance of the AlGaIn/GaN amplifier IC showing a CW output power of 14 W at 8 GHz.

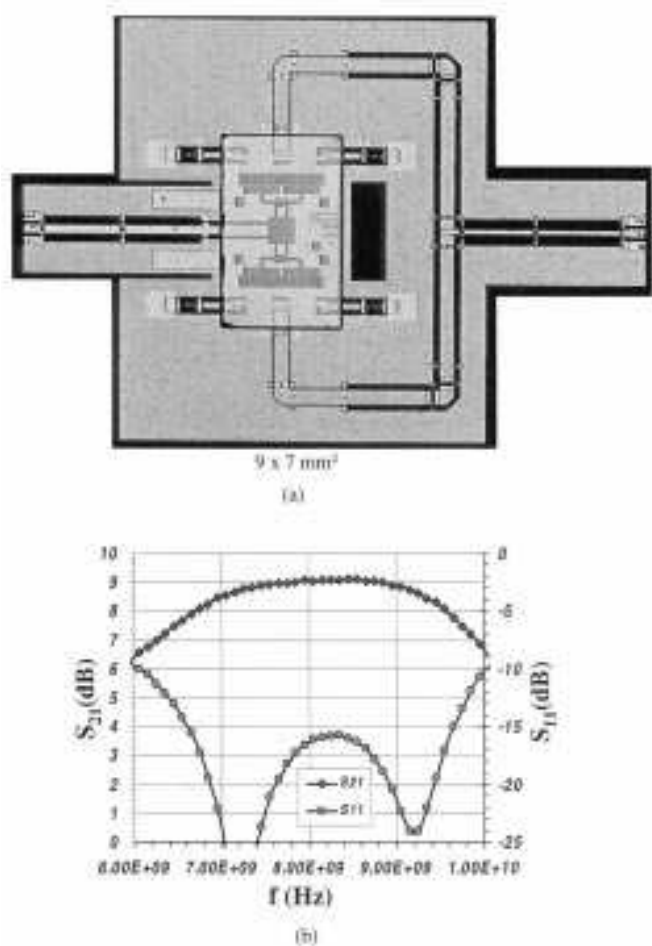


Fig. 6. (a) Photograph and (b) small-signal characteristics of the flip-chip power amplifier IC using a 4-mm-wide AlGaIn/GaN HEMT.

generated an output power of 9.8 W at 8 GHz with 44% PAE as seen in Fig. 5. The peak PAE is 47% at an output power level of 9.2 W. This 2-mm gate periphery device outperforms previous

3-mm-wide $\text{Al}_{0.14}\text{Ga}_{0.86}\text{N}/\text{GaN}$ HEMTs [2] in all aspects including shear output power, PAE and operation frequency. At higher biases than 22 V, the output power exceeded 10 W. However, both the gain and PAE were significantly reduced, which is attributed to the limited thermal conductivity of the AlN circuit substrate mentioned earlier.

Owing to the low input impedance for devices larger than 2-mm wide, it is difficult to realize optimum input matching at X band using passive turners. For this reason, a flip-chip amplifier IC employing a 4-mm device was designed and constructed, where all matching elements were fabricated on the AlN circuit substrate as seen in Fig. 6(a). Small-signal characteristics of the amplifier are shown in Fig. 6(b). The bandwidth is 6–10 GHz with better than -10 dB input return loss. The mid-band linear gain is greater than 9 dB. When biased at 25 V, the amplifier generated 14 W at 8 GHz, as seen in Fig. 7, which sets the highest CW power generation using a GaN-based FET to date. Optimization of both the circuit design and thermal management is needed for improving both the power density and efficiency of large-periphery devices. Reliability studies are also yet to be done before a viable product is introduced.

IV. CONCLUSION

Development of AlGaIn/GaN HEMTs focusing on adopting high Al-content AlGaIn layers and reduction of large-signal trapping effect has resulted in significant performance improvement. Devices grown on SiC substrates showed a very-high power density of 9.8 W/mm at 8 GHz, which is the highest for a FET to date and is ten times higher than GaAs-based FETs at the same frequency band. Devices on sapphire also generated 6.5 W/mm in spite of the poor substrate thermal conductivity. Initial large periphery devices were fabricated. A 2-mm-wide device produced 9.2 to 9.8 W at 8 GHz with 44 to 47% PAE. Initial high-power amplifier ICs were also demonstrated with a flip-chip IC scheme. The amplifier using a 4-mm-wide device generated 14 W at 8 GHz. This is the highest CW power level obtained using a GaN-based integrated circuit to date.

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