

The Effect of Surface Passivation on the Microwave Characteristics of Undoped AlGaIn/GaN HEMT's

Bruce M. Green, *Student Member, IEEE*, Kenneth K. Chu, E. Martin Chumbes, *Student Member, IEEE*, Joseph A. Smart, James R. Shealy, *Member, IEEE*, and Lester F. Eastman, *Life Fellow, IEEE*

Abstract—Surface passivation of undoped AlGaIn/GaN HEMT's reduces or eliminates the surface effects responsible for limiting both the RF current and breakdown voltages of the devices. Power measurements on a $2 \times 125 \times 0.5 \mu\text{m}$ AlGaIn/GaN sapphire-based HEMT demonstrate an increase in 4 GHz saturated output power from 1.0 W/mm [36% peak power-added efficiency (PAE)] to 2.0 W/mm (46% peak PAE) with 15 V applied to the drain in each case. Breakdown measurement data show a 25% average increase in breakdown voltage for $0.5 \mu\text{m}$ gate length HEMT's on the same wafer. Finally, 4 GHz power sweep data for a $2 \times 75 \times 0.4 \mu\text{m}$ AlGaIn/GaN HEMT on sapphire processed using the Si_3N_4 passivation layer produced 4.0 W/mm saturated output power at 41% PAE (25 V drain bias). This result represents the highest reported microwave power density for undoped sapphire substrated AlGaIn/GaN HEMT's.

Index Terms—Breakdown, FET's, GaN, HEMT's, microwave power.

I. INTRODUCTION

THERE is an ever-increasing need for high power, high efficiency microwave transistor amplifiers and switching devices in a variety of military and commercial wireless communications applications. This demand, coupled with advances in the growth of the group III nitrides, has spurred the development of high power AlGaIn/GaN high electron mobility transistors (HEMT's). To date, the state-of-the-art reported power performance for AlGaIn/GaN HEMT's grown on SiC substrates is 9.1 W/mm at 8.2 GHz with the total power extracted from a single device of 9.8 W (8.2 GHz) [1]. State of the art power added efficiency of 77% (1.7 W/mm) at 4 GHz was reported for a 0.5-mm periphery HEMT grown on a sapphire substrate [2].

A significant frequency-dependent slump or even collapse in drain current has plagued the saturated output power and efficiency realized by AlGaIn/GaN HEMT technology [4]. Efforts have been underway in several laboratories to understand this effect [4], [5]. However to date, no solutions to the problem have been reported in the literature. We attribute this frequency dependent current degradation in AlGaIn/GaN HEMT's to the presence of slow-acting trapping states between the gate and drain of the device. These trapping states are assumed to be associated with surface states created by dangling bonds, threading dislocations accessible at the surface, and ions absorbed from

the ambient environment. These states trap electrons injected by the gate and create a layer of charge at or near the surface that depletes the channel in the high field region between the gate and drain. Since the time constants of the trapping states in this surface layer range from seconds to microseconds, it is not possible for electrons contained in the surface layer to fully modulate the channel charge during large signal RF operation. The result is reduced RF current swing and output power. In addition, conduction and ionization along this surface layer limits the breakdown voltages of the devices. This communication demonstrates the use of Si_3N_4 passivation layers as a means of controlling the undesirable frequency-dependent current and reduced breakdown voltage associated with the layer of trapped electrons near the surface. These results resulted in the achievement of 4 W/mm saturated output power at 4 GHz for a $2 \times 75 \times 0.4 \mu\text{m}^2$ device on a sapphire substrate.

II. PRELIMINARY DEVICE CHARACTERIZATION AND DIELECTRIC DEPOSITION

Undoped AlGaIn/GaN HEMT's were grown using organo-metallic vapor phase epitaxy. A 220 nm ECR etch was used to isolate the active regions. Ohmic contact formation consisted of a Ti/Al/Ti/Au metal stack followed by a 800°C anneal for 30 s. A Ni/Au metal stack patterned using a three-layer resist scheme formed the mushroom gates. Further details concerning the materials growth and processing may be found in the literature [2], [6].

Prior to passivation, dc, small signal, and large signal characterization of a $2 \times 125 \times 0.5 \mu\text{m}^2$ AlGaIn/GaN HEMT took place. In addition, breakdown voltage data on $2 \times 75 \times 0.5 \mu\text{m}^2$ in-line gate finger devices with gate-drain spacings of $1.5 \mu\text{m}$, $2 \mu\text{m}$ and $2.5 \mu\text{m}$ were taken. The maximum static current of the $2 \times 125 \times 0.5 \mu\text{m}^2$ devices with 0 V on the gate (I_{DSS}) was found to be 520 mA/mm. The f_T and f_{max} were 25.3 GHz and 40.3 GHz, respectively.

Loadpull data taken on the $2 \times 125 \times 0.5 \mu\text{m}^2$ HEMT at 4 GHz using Focus Microwaves™ computer controlled microwave tuners showed the maximum saturated output power to be 0.5 W/mm at $V_D = 10$ V and 1.0 W/mm at $V_D = 15$ V with associated maximum PAE's of 31% and 36%, respectively. The gate-source bias for both of these measurements was held constant at -4 V (120 mA/mm). The knee voltage, V_{knee} , was 4 V. A simple estimate of the maximum saturated output power based on the $I - V$ characteristics of the device is given by

$$P_{\text{sat}} = \Delta I \Delta V / 8 \quad (1)$$

Manuscript received February 29, 2000. This work was supported by the Office of Naval Research MURI under Contract N00014-96-1-1223, monitored by Dr. John Zolper. The review of this letter was arranged by Editor D. Ueda.

The authors are with the School of Electrical and Computer Engineering, Cornell University, Ithaca, NY 14853 USA (e-mail: green@iiiiv.tn.cornell.edu).

Publisher Item Identifier S 0741-3106(00)04701-7.

where $\Delta V = 2(V_D - V_{knee})$ and $\Delta I = I_{D,max}$ (in mA/mm) and should be approximately 1.7 W/mm at $V_D = 15$ V and 0.8 W/mm at $V_D = 10$ V. Although this method of calculating the maximum power is approximate in nature, the disparity between the expected and measured output powers are too large to be ascribed to the calculation procedure or any small experimental errors (typical power measurement errors are $< \pm 0.5$ dB). It is assumed that the lack of available RF current limits the saturated power and efficiency.

The device wafers were then cleaned using acetone, methanol, isopropanol, and DI water (in this order) and then dipped in 30:1 buffered oxide etch for 30 s. No significant changes in device characteristics were seen after these cleaning and etch steps. An IPETM plasma-enhanced chemical vapor deposition (PECVD) system using Silane (SiH_4) and ammonia (NH_3) sources was used to deposit 350 nm of Si_3N_4 on the device wafers at a baseplate temperature of 300 °C.

III. RESULTS AND DISCUSSION

After the passivation, the dc, small signal, large signal, and breakdown characteristics of the HEMT's were remeasured. The value of I_{DSS} (at low drain-source bias) of the $2 \times 125 \times 0.5 \mu\text{m}^2$ device increased from 520 mA/mm to 640 mA/mm. Since the thermal conductivity of Si_3N_4 (0.37 W/cm²K) is approximately the same as that of sapphire (0.42 W/cm²K) and is very thin compared to the device dimensions (350 nm compared to microns), it is improbable that the passivation alters the thermal resistance of the device enough to increase the current. More likely, the rise in current is due to an increase in positive charge at the $\text{Si}_3\text{N}_4/\text{AlGaIn}$ interface, resulting in a higher sheet carrier concentration in the channel. Similar increases in sheet carrier concentration have been observed in other AlGaIn/GaN surface passivation studies [6]. A minor change in threshold voltage of the device from -4.5 V to -4.75 V after the passivation suggests that the maximum current is limited by the ungated regions of the device. Correspondingly, the small-signal transconductance increased from 195 mS/mm to 210 mS/mm, consistent with the rise in current and small change in threshold voltage.

Small signal measurements also showed that the value of f_T decreased from 25 GHz to 22.7 GHz. The value of C_{gd} increased from 0.12 pF/mm to 0.17 pF/mm which in conjunction with the decrease in f_T reduced f_{max} from 40.7 GHz to 34.0 GHz. The increase in C_{gd} is due, in part, to the increase in surface dielectric constant caused by the Si_3N_4 . In addition, the inability of the gate to charge the passivated surface layer confines the gate-drain depletion region to a smaller area near the gate edge, further increasing C_{gd} .

Unlike the small signal case, a tremendous difference in large signal performance before and after passivation was observed. Fig. 1 shows the difference in saturated power and PAE characteristics before and after passivation. As the figure indicates, an increase in saturated output power of 100% to 2.0 W/mm was measured at the same bias point ($V_D = 15$ V, $V_G = -4$ V) and frequency (4 GHz) which previously yielded only 1.0 W/mm. Using the simple calculation of (1) and accounting for the increase in maximum current, a value of 2.1 W/mm was expected.

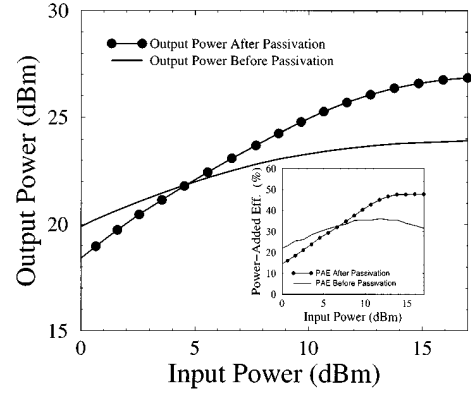


Fig. 1. Output power and power-added efficiency (inset) as a function of drive for a $2 \times 125 \times 0.5 \mu\text{m}$ HEMT before and after passivation at bias point of $V_D = 15$ V, $V_G = -4$ V and frequency of 4 GHz ($Z_L = 131 + j120$, $Z_S = 22 + j90$ before passivation and $Z_L = 122 + j51$, $Z_S = 32 + j85$ after passivation).

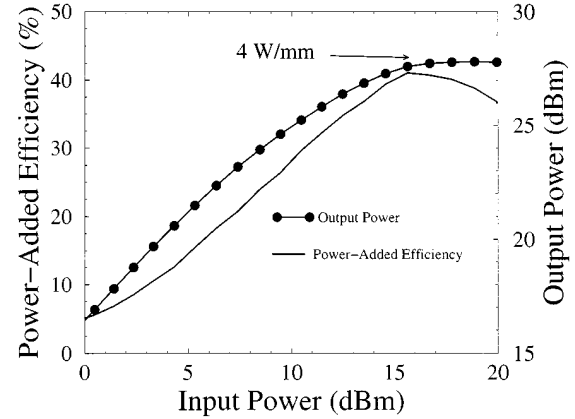


Fig. 2. Output power and power-added efficiency as a function of drive for a passivated $2 \times 75 \times 0.4 \mu\text{m}$ AlGaIn/GaN HEMT at a bias point of $V_D = 25$ V, $V_G = -4$ V demonstrating 4 W/mm saturated output power ($Z_L = 187 + j66$, $Z_S = 106 + j108$).

An increase in PAE from 36% to 46% was also noted as shown in the figure. The power sweep characteristics of the passivated device also show 1.5 dB lower small signal gain as expected because of the increased C_{gd} of the device. However in the case of the passivated device, the power saturation characteristics show less gain compression at higher drive which is consistent with the higher saturated output power achieved. The passivation appears to prevent steady-state depletion of the channel by the surface layer of extra trapped charge, and the gate can now completely modulate the channel. Hence, the full RF current swing (≈ 640 mA/mm) is preserved.

Breakdown measurements were performed on $2 \times 75 \times 0.5 \mu\text{m}^2$ devices with gate-drain spacings of 1.5 μm , 2.0 μm and 2.5 μm . The determination of the breakdown voltage was performed by pinching the channel off ($V_{GS} = -8$ V) and then raising V_{DS} until an appreciable amount of current ($I_D = 1$ mA/mm) began to flow. The data shown in Fig. 2 demonstrate a 25% average increase in drain-source breakdown voltage with a maximum of $V_D = 95$ V for a 2.5 μm gate-drain spacing. Both before and after passivation, there was a sharp turn-on of drain current with a relatively unchanged gate current indicative of either surface conduction or avalanche breakdown. However, since the

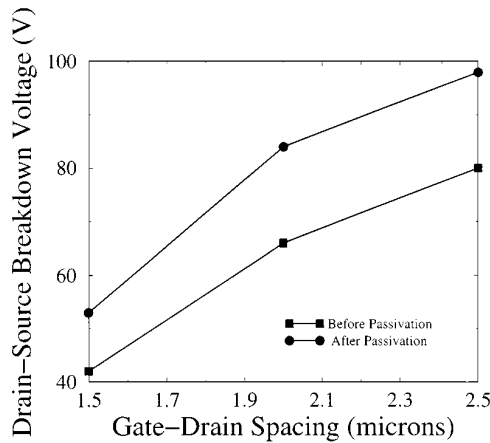


Fig. 3. Breakdown voltage as a function of gate width before and after device passivation for $0.5\ \mu\text{m}$ gate length AlGaIn/GaN HEMT's showing an increase in breakdown voltage of $\approx 25\%$ with the addition of Si_3N_4 passivating layer.

breakdown voltage increased after passivation, this would suggest that prior to passivation the conduction and ionization of states in the surface layer dominates device breakdown while after passivation, avalanche breakdown near the gate edge dominates.

A second wafer was passivated using the same process. Again, the saturated power at 4 GHz was measured on a $2 \times 125 \times 0.5\ \mu\text{m}^2$ device and an improvement from 1.67 W/mm (36% PAE) at $V_D = 15\ \text{V}$ to 2.3 W/mm (41% PAE) at the same bias point of $V_D = 15\ \text{V}$, $V_G = -4\ \text{V}$ (40% improvement in power) was observed. As seen in Fig. 3, a $2 \times 75 \times 0.4\ \mu\text{m}^2$ in-line finger device from this wafer yielded 4.0 W/mm (41% PAE) of 4 GHz power at $V_D = 25\ \text{V}$, $V_G = -4\ \text{V}$. This power density is the highest reported for undoped AlGaIn/GaN HEMT structures with sapphire substrates.

IV. CONCLUSION

This communication demonstrates Si_3N_4 as a means of reducing the surface layer mechanisms that limit the maximum

RF current and breakdown voltage in AlGaIn/GaN HEMT's. The experimental data presented show that the addition of a Si_3N_4 passivation layer to undoped AlGaIn/GaN HEMT's increases the saturated power density by up to 100% at 4 GHz and increases the breakdown voltage by an average value of 25%. Furthermore, the passivation process achieved a state-of-the-art power density (4 W/mm at 4 GHz) for undoped AlGaIn/GaN HEMT's on sapphire substrates. While it is presumed that the passivation eliminates the surface trapping effects that produce the frequency-dependent current, presumably by altering the properties of the surface states, a detailed description of the mechanism(s) responsible for the dispersion is admittedly lacking. Future studies will address in detail these mechanisms and the physical effect of surface passivation in eliminating the frequency-dependent current slump and the related reduction of breakdown voltage. Nevertheless, these promising initial results offer a simple means of reducing or eliminating large-signal slump in undoped AlGaIn/GaN HEMT's and merit further study of the physical mechanisms responsible for the improvements.

REFERENCES

- [1] Y.-F. Wu *et al.*, "High Al-content AlGaIn/GaN HEMT's on SiC substrates with very high power performance," in *IEDM Tech. Dig.*, Dec. 1999, pp. 925-927.
- [2] K. K. Chu, J. A. Smart, J. R. Shealy, and L. F. Eastman, "AlGaIn/GaN piezoelectric HEMT's with submicron gates on sapphire," in *Proc. State-of-the-Art Program on Compound Semiconductors (SOTAPOCS) XXIX*, 1998.
- [3] E. Kohn, I. Daumiller, P. Schmid, N. X. Nguyen, and C. N. Nguyen, "Large signal frequency dispersion of AlGaIn/GaN heterostructure field effect transistors," *Electron. Lett.*, vol. 353, pp. 1022-1024, Dec. 1999.
- [4] S. C. Binari *et al.*, "Fabrication and characterization of GaN FETs," *Solid-State Electron.*, vol. 41, pp. 1549-1554, 1997.
- [5] J. A. Smart *et al.*, "AlGaIn/GaN heterostructures on insulating AlGaIn nucleation layers," *Appl. Phys. Lett.*, vol. 75, pp. 388-390, July 1999.
- [6] T. Prunty *et al.*, "Passivation of AlGaIn/GaN heterostructures with silicon nitride," submitted for publication.