RF Power Performance of Sc(Al,Ga)N/GaN HEMTs at *Ka*-Band

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***Abstract*— We report the RF power results of Sc(Al,Ga)N/GaN high electron mobility transistors (HEMTs). We show dc, small-signal RF and load-pull performance at 30 GHz with two barrier alloys—a ternary of ScAlN and a quaternary of ScAlGaN. The active layers are grown by molecular beam epitaxy on a GaN-on-SiC template. The Sc(Al,Ga)N HEMTs with 120 nm gate length achieve transconductance >700 mS/mm and >70 GHz cutoff frequency. The quaternary ScAlGaN sample shows reduced current collapse during pulsed I-V and load-pull characterization. The ScAlGaN HEMT delivers 5.77 W/mm output power (V_D = 20 V) and 47% power-added efficiency (V_D = 15 V) when tuned for maximum power and efficiency, respectively.**

***Index Terms*—ScAlN, ScAlGaN, GaN, radio frequency, dispersion, small-signal, large-signal, HEMT.**

I. Introduction

NEXT-GENERATION GaN-based amplifiers require low sheet resistance and a thin barrier layer to meet efficient radio frequency (RF) power demands for millimeter-wave applications. Multiple approaches have accomplished this by adjusting the barrier alloy to increase the total polarization charge in the GaN channel with varying levels of piezoelectric charge such as in strained InAlN/GaN [1]–[3], AlN/GaN HEMTs [4]–[6] as well as N-polar variations [7]–[9]. Lattice-matched $In_{0.18}Al_{0.72}N$/GaN HEMTs have been reported with performance in X and Ka-band but with limits on spontaneous induced sheet charge [10]–[12].

Attributed to the spontaneous polarization coefficient ScAlN [13]–[15], ScAlN/GaN can also be lattice-matched with up to 2x sheet charge density compared to $In_{0.18}Al_{0.72}N$/GaN [15], [16]. It has been shown that lattice-mismatch causes defect generation leading to device degradation in Al and In based alloys [17], [18]. A lattice-matched Sc-based barrier enables high sheet charge density without strain and may enhance reliability.

Currently the whitespace for high current/high power applications is being evaluated with respect to these tradeoffs. Sc(Al,Ga)N growths have been reported by molecular beam epitaxy (MBE) [15], [19], and a ScAlN/GaN HEMT was recently reported with impressive dc and small-signal RF performance [20].

Here, we report RF power performance of Sc(Al,Ga)N/GaN HEMTs. Two samples were grown by MBE with a ternary ScAlN and quaternary ScAlGaN barrier to compare the trade-off in sheet charge density with respect to mobility as Ga is introduced. These devices have improved short-channel effects over previously reported ScAlN/GaN HEMTs [20]. State-of-the-art DC performance is reported for each while pulsed *I-V* and 30-GHz power sweeps indicate differences in current collapse between the two samples. Both samples achieve >10 dB transducer gain (G_T) at 30 GHz. The quaternary ScAlGaN/GaN HEMT achieved 5.77 W/mm output power (P_{OUT}) and 47% power-added efficiency (PAE) when tuned for optimal P_{OUT} and PAE, respectively. The early RF power performance nearly matches state-of-the-art Ga-polar devices at our reported frequency and bias conditions [9], [21]–[24].

II. Epitaxial Growth and Device Fabrication

Epitaxial structure design and growth were performed by Qorvo. A nucleation, GaN buffer and GaN channel layer was grown by MOCVD followed by a 1 and 2 nm spacer layer of AlN and $Al_{0.25}Ga_{0.75}N$, respectively. The wafer was then immediately loaded into a gas source MBE reactor, followed by the growth of lattice matched 5.5 nm of $Sc_{0.18}Al_{0.72}N$ or 5.3 nm $Sc_{0.07}Al_{0.38}Ga_{0.55}N$ barrier layers, nominally. The growth of quaternary is achieved by adding Ga flux into ScAlN growth without adjusting other growth parameters. The exact compositions are still subject of research due to the lack of reliable material data such as lattice constants, etc. Finally, 1.2 nm of a GaN capping layer was grown.

Nominal layer thicknesses and material properties area shown in Table I. The Hall data was obtained from separate calibration samples grown on sapphire substrates without

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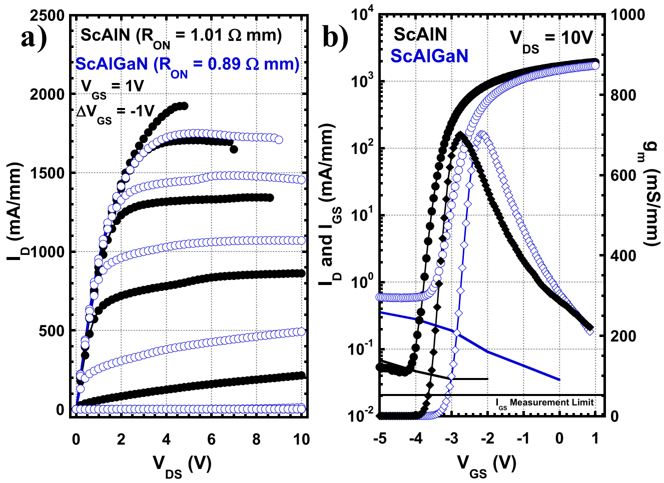

Fig. 1. Representative a) output IDS vs. VDS family of curves and b) transfer characteristics for a 4 × 65 μm HEMT from each sample.

surface passivation. An expected decrease in the sheet charge density is observed as Sc is replaced with Ga.

Sc(Al,Ga)N/GaN HEMTs were fabricated with regrown ohmic contacts using the same process from reference [20]. Devices reported in this manuscript have a 4×65 μm total gate periphery with source connected electroplated air bridges. The HEMT channels were protected by SiO_2 deposited by plasma-enhanced chemical vapor deposition (PECVD) during ohmic contact regrowth. The devices have a 200 nm PECVD silicon-rich SiN surface passivation which has suppressed current collapse in multiple barrier designs [3], [11], [12], [25]. Ni/Au T-shaped gates with 120 $\pm$ 20 nm gate length (L_G) were defined by electron beam lithography with an offset of 0.5 μm towards the source electrode from the center of the channel. The source-to-drain distance (L_{SD}) is 3 μm. Contact resistance (R_C) for the devices was extracted from transmission line measurement (TLM) test structures as <0.1 Ωmm for both samples.

III. DC and Pulsed Performance

Representative dc *I-V* performance is shown in Fig. 1 for each sample with the device dimensions described in Sec II. Fig. 1(a) shows the family of output curves for the ScAlN/GaN (black) and ScAlGaN/GaN (blue) HEMTs. The ScAlN/GaN (ScAlGaN/GaN) devices have low on-resistance (R_{ON}) and high maximum current density ($I_{DS,max}$) of 1.01 (0.89) $\Omega \cdot$ mm, and 1.92 (1.73) A/mm, respectively. Fig. 1(b) shows the log(I_{DS}) and transconductance (G_m) transfer characteristics with a peak $G_m = 700$ (701) mS/mm measured at $V_{DS} = 10$ V. The on/off current ratio is $\sim 10^4$ (10^3) and is mainly limited by high Schottky gate off-state leakage which remains under investigation.

The negative threshold voltage (V_{TH}) shift for the ScAlN/GaN sample can be attributed to the higher sheet charge density according to Table I. While not shown, a soft breakdown voltage (V_{BK}) limited by gate leakage is recorded at 15.8 (16.0) V defined by current compliance at 2 mA/mm in the off-state. Hard V_{BK} is expected to be >40V due to successful repeated power sweeps at $V_D = 20$V. Improved device performance is expected by eliminating gate leakage and optimizing the gate-to-drain distance without affecting the breakdown voltage [26].

TABLE I
Sample Material Properties

	Gate-to-channel distance (nm)	Ra (nm)	R_{SH} (Ω/□)	n_s (cm^{-2})	Mobility (cm^2/V·s)
ScAlN/GaN	~9.7	0.21	233	2.4e13	1110
ScAlGaN/GaN	~9.5	0.32	259	1.76e13	1370

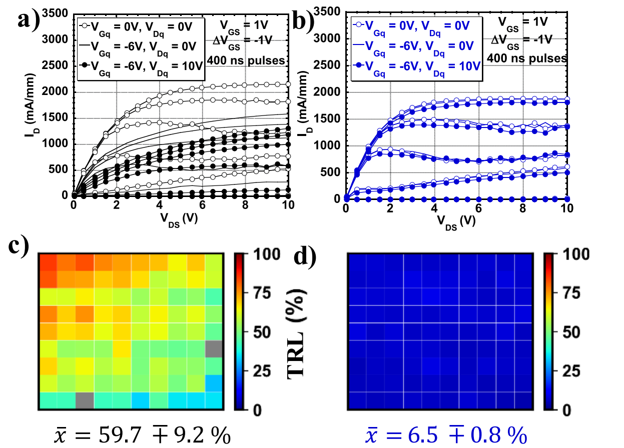

Fig. 2. 400-ns (5 ms period) pulsed *I-V* performance with three quiescent points for the (a) ScAlN/GaN and (b) ScAlGaN/GaN HEMTs. A 9 row x 10 column heat map (~900 mm^2) of the total gate and drain lag (TLR%) is shown for the (c) ScAlN/GaN and (d) ScAlGaN/GaN HEMT wafers.

Fig. 2 shows pulsed *I-V* performance for each sample type. In Figs. 2(a-b), pulses with 400 ns width and 5 ms period were applied to the gate and drain quiescent voltage (V_{Gq}, V_{Dq}) points (0V,0V), (−6V,0V) and (−6V,10V). The filled data points show the effect of both gate and drain lag. The magnitude of current collapse is defined as the ratio of I_{DS} at the (0V,0V) and (−6V,10V) conditions taken at the knee voltage (V_K) for the (0V,0V) curve. Significant dispersion is observed on the ScAlN/GaN sample compared to the ScAlGaN/GaN, but the origin of this current collapse is not yet understood. Figs. 2(c-d) show wafer scale heat maps (9 row x 10 columns, ~900 mm^2) of the total lag ratio (*TLR*) indicating uniform 59.7% $\pm$ 9.2% and just 6.5% $\pm$ 0.8% on the ScAlN/GaN and ScAlGaN/GaN samples, respectively. We note that the GaN cap likely does not play a strong role in suppressing charge trapping since a third ScAlGaN wafer without a GaN cap was fabricated and showed total current collapse of 5% $\pm$ 3%.

Current collapse can be caused by many factors such as the alloy composition, growth condition, chamber history, and passivation. It originates from the depletion of 2DEG in the channel by trapped electrons located at the epitaxial surface or in the layers above the channel. It has been reported previously that current collapse may increase with reduced distance between the 2DEG location and the surface per the charge/distance relationship in Columbic force equation [27].

To understand the difference of the current collapse in HEMTs with ternary and quaternary barriers, we applied the Fang-Howard model [28] to calculate the 2DEG centroid position by $< z > \int_0^\infty z|\varphi|^2 dz$, where the AlN/GaN interface is defined at z=0 and the wave function $\varphi(z)$ is given by $\varphi(z) = \sqrt{\frac{b^3}{2}} z e^{-bz/2}$ where $b = (33m * q^2 n_s / 8\hbar^2 \varepsilon_0 \varepsilon_{GaN})$, m* is the

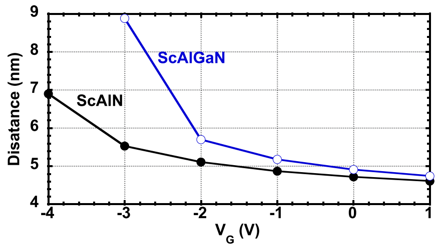

Fig. 3. Distance between the 2DEG centroid and AlGaN/ScAl(Ga)N regrown interface as a function of V_G.

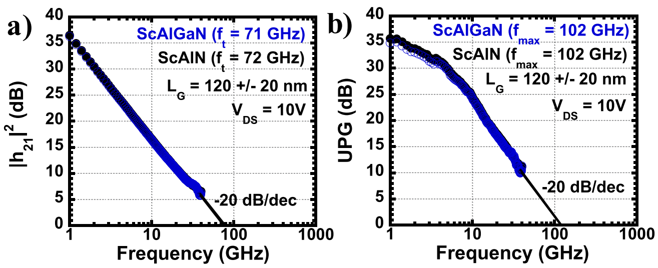

Fig. 4. a) Current gain and b) unilateral power gain versus frequency for each sample with the extrapolated f_T and f_{MAX} indicated at $V_{DS} = 10$V and V_{GS} corresponding to 39.5 (37.0) mA.

effective mass of electron in GaN, q is the electron charge, $\hbar$ is the reduced Planck's constant, ε_0 is the permittivity of vacuum and ε_{GaN} is the dielectric constant of GaN. Assuming all gate voltage drops across the Sc(Al,Ga)N/AlGaN/AlN layers, we calculate the charge density change in the channel as a function of gate bias.

As expected, the centroid position moves farther away from the AlGaN/Sc(Al,Ga)N regrown interface with increasingly negative gate bias. The distance between the gate and centroid position is shown in Fig. 3. This indicates under the same V_G, the 2DEG in the ScAlGaN HEMT is less depleted from the trapped charges located above the interlayer—those either at the epitaxial surface or AlGaN/Sc(Al,Ga)N regrown interface resulting in less current collapse.

Since the pinch-off voltage does not change in both HEMTs in the pulsed I-V measurements, the traps most likely remain in the access region between the gate and drain/source instead of under the gate. This can be observed from the larger dispersion measured at the (−6V,0V) Q point. Further investigation is required to determine if these traps are located at the Sc(Al,Ga)N/AlGaN interface or in the Sc(Al,Ga)N layer. Higher current collapse in ScAlN could also be attributed to more trapping states in the ternary alloy compared to the quaternary.

IV. Small and Large Signal RF Performance

Small signal RF performance of the devices is shown for both wafers in Fig. 4. S-paramaters were measured from 0.1 – 40 GHz at $V_{DS} = 10$V and V_{GS} corresponding to 10% I_{DSS} (I_{DS} measured at $V_{GS} = 0$V) which is relevant for class-AB power conditions. The devices from each sample performed nearly identically with a current gain cutoff frquency (f_T) and maximum oscillating frequency (f_{MAX}) of about $f_T/f_{MAX} = 72/102$ GHz using a −20 dB/dec extrapolation.

Ka-band power performance of the Sc(Al,Ga)N/GaN HEMTs was evaluated using class-AB power sweeps at

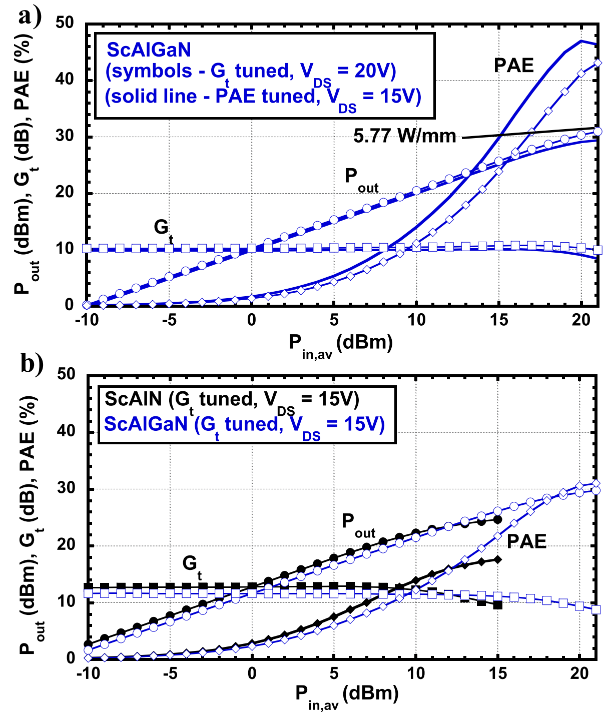

Fig. 5. Load Pull at 30 GHz for the devices in Figure 1 at (top) $V_{DS} = 15$ V with optimal G_t tuning and (bottom) the best RF performance reported for each sample up to $V_{DS} = 20$ V with tuning conditions indicated.

30 GHz configured. In Fig. 5(a) each device was driven with input power ($P_{IN,AV}$) until G_T compresses by 3 dB at $V_{DS} = 15$V while tuned for maximum G_T. The G_T compresses at ∼7 dB higher $P_{IN,AV}$ for the ScAlGaN/GaN sample which is attributed to differences in current collapse shown in Fig. 2. The ternary (quaternary) measures a maximum P_{OUT} of 0.89 (3.55) W/mm and a PAE of 16.0 (31.0)% at $V_G = -2.94$ (−2.65) V. Fig. 5(b) shows the highest performance achieved during the power sweep. When impedance matched for efficiency, the quaternary device was able to achieve 47% PAE with the drain biased at $V_D = 15$V with a P_{OUT} of 3.54 W/mm. The same device was then tested at $V_D = 20$V while tuned for G_T and reached a maximum P_{OUT} of 5.77 W/mm with a PAE of 43%. The reported RF power performance is near state-of-the-art when benchmarked with Ga-polar 30-GHz RF power performance reviewed in ref [9].

V. Conclusion

RF power performance was compared between a ScAlN/GaN and ScAlGaN/GaN sample with varying sheet charge density and mobility characteristics. Both samples achieve high G_M and f_{MAX} around 700 mS/mm and 102 GHz, respectively. The ScAlN sample had higher current collapse which is theorized to originate from the difference in the 2DEG centroid position with respect to the barrier layer. The ScAlGaN/GaN wafer delivered 5.77 W/mm P_{OUT} ($V_D = 20$V) and 47.0% efficiency ($V_D = 15$V) with optimal tuning. Both sample types are expected to significantly improve with materials maturation and device research to suppress gate leakage and traps that limit the power performance presented in this manuscript.

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