Optically-Defined 150-nm, 28-V GaN HEMT Process for Ka-Band

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Abstract – We report the fabrication process, device characteristics, MMIC RF performance and reliability of a high-performance GaN-on-Silicon Carbide HEMT featuring a 150-nm gate length for millimeter wave applications. The transistor exhibits output power density greater than 3 W/mm and peak power added efficiency (PAE) above 35% at 30 GHz. Small signal measurements at 28 V indicate a cut off frequency beyond 30 GHz and a 10 GHz small signal gain larger than 20 dB. We demonstrate high voltage robustness under high-temperature reverse bias (HTRB) at 84 V / 150 °C with zero failures and negligible performance change after 1000 hours. Accelerated reliability testing of this technology demonstrates a comparable lifetime to Wolfspeed's earlier generation HEMT devices.

INTRODUCTION

GaN-on-SiC MMICs have consistently increased the performance capability for operating frequency, output power and drain efficiency compared to other semiconductors materials. The latest high frequency Ka-band designs are critical for commercial communications, military and aerospace mm-wave applications [1]. These designs require improved RF performance beyond currently available 0.25-µm GaN technology, but will require the same scale and cost. Wolfspeed has leveraged 10+ years of GaN HEMT manufacturing experience to develop a leading 150-nm, GaN-on-SiC HEMT technology. This paper will cover the salient process development, performance and reliability of our 150-nm GaN HEMT technology for millimeter-wave applications.

FABRICATION

The fabrication techniques of the 150-nm GaN HEMT were leveraged from Wolfspeed's 0.25-µm HEMT technology. The substrate and epitaxy were optimized for 30 GHz RF performance while maintaining the robustness and high reliability. The typical epitaxial structure comprises an AlN nucleation layer, an Fe-doped insulating GaN layer, an AlN barrier layer, and a 15-nm cap layer of undoped $Al_{0.24}Ga_{0.76}N$. The source/drain ohmic contacts were optimized to provide very smooth morphology, enabling consistent fine-line lithography, and a well-controlled distribution centered at 0.2 Ω-mm for the contact resistance (see Figure1a). This is an 0.2 Ω-mm reduction compared to the 0.25-µm process which improved the peak current density, on-state resistance and knee voltage. The 150-nm gate dimensions shown in Figure 1b (measured by AFM) were fabricated with an i-line lithography spacer method [2]. A gate reduction technique produced gate lengths below the optical lithography limits while maintaining cross wafer repeatability. The control capability of the gate length with i-line lithography makes this process economically scalable beyond 100-mm-diameter GaN-on-SiC substrates. In addition to the 150-nm GaN HEMT, the associated process design kit also includes the standard Wolfspeed passive components for MMIC design.

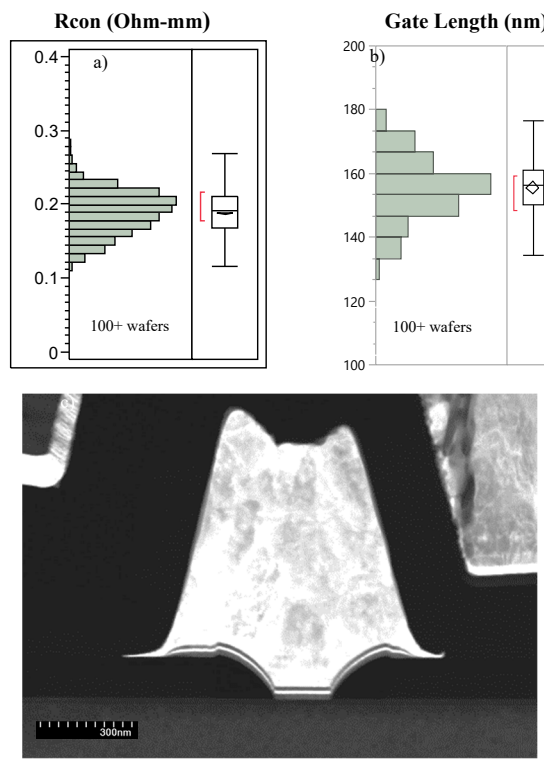

Fig. 1. (a) In-line electrical characterization of contact resistance from the last year. (b) AFM gate length distribution from the past year. (c) STEM cross-section of the 150-nm gate.

TABLE I
TYPICAL DEVICE PERFORMANCE FOR WOLFSPEED 150 NM GAN HEMT

GaN 150-nm Device Performance		
Peak Drain Current	1.2 A/mm	Vd = 10 V Vg = 2 V
Max Transconductance	470 mS/mm	Vd = 10 V
Pinch-off Voltage	-2 V	Vd = 10 V Id = 1 mA/mm
Breakdown Voltage	> 84 V	Vg = -8 V Id = 1 mA/mm
f_{T_28V}	> 30 GHz	Vd = 28 V Idq = 100 mA/mm
f_{T_10V}	40 GHz	Vd = 10 V Idq = 100 mA/mm
Max. Available Gain (10 GHz)	> 20 dB	Vd = 28 V Idq = 100 mA/mm
Output Power (10 GHz)	5 W/mm	Vd = 28 V Idq = 100 mA/mm
Output Power (30 GHz)	3.5 W/mm	Vd = 28 V Idq = 100 mA/mm
PAE (30 GHz)	> 30%	Vd = 28 V Idq = 100 mA/mm

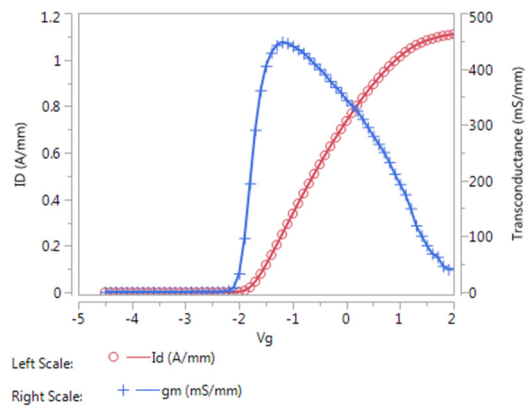

Fig. 2. Transfer curve for a large periphery (3.6 mm) discrete device.

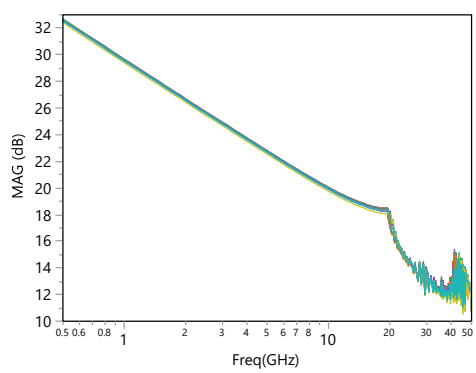

Fig. 3. On-wafer variation of the small signal MAG.

DEVICE PERFORMANCE

Standard electrical dc and RF characteristics shown in Table I were obtained on wafer. The small signal cut-off frequency and small signal gain were extracted from the s-parameters at 2 GHz. The transfer curves measured on devices with a 3.6 mm total gate periphery are shown in Figure 2. They exhibit a maximum current density above 1.2 A/mm and peak transconductance 470 mS/mm. The HEMT off-state properties are characterized by pinch-off voltage of -2 V, measured at 10 V and 1 mA/mm on the drain. The minimum breakdown voltage rating is 84 V at a gate voltage of -8V and a maximum drain current of 1 mA/mm.

Multi-fingered devices (6x75 µm) were used to characterize the performance of the 150-nm technology. The devices were biased at room temperature with a quiescent current and drain voltage of Id = 100 mA/mm and Vd = 28 V, respectively. The variability of on-wafer small signal gain, shown in Figure 3, was a direct result of the ability to maintain a consistent gate length. Continuous wave (CW) power sweeps were performed at 10 GHz and 30 GHz to determine the maximum output power and peak added efficiency, shown in Figure 4. This technology demonstrated power densities > 5W/mm @ 10 GHZ and > 3.5W/mm @ 30GHz with PAE = 45% and 39%, respectively. Furthermore, when biased at 10V, the devices demonstrate cut-off frequencies of 40 GHz.

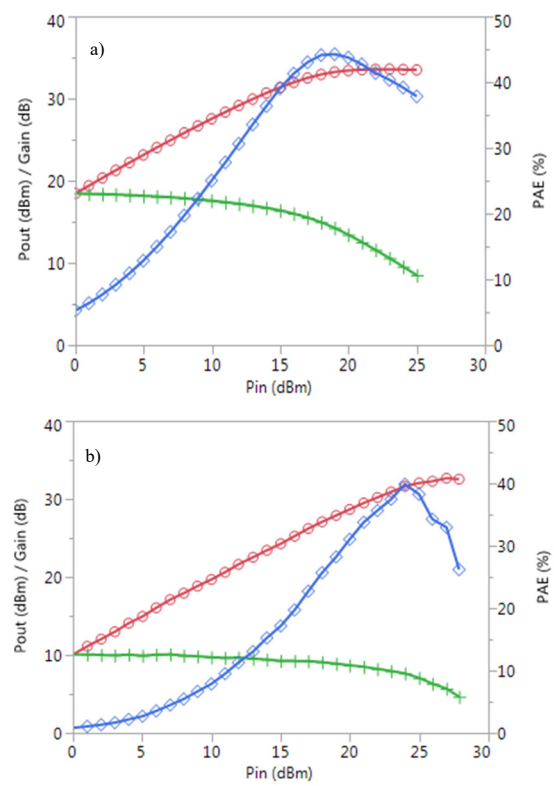

Fig. 4. (a) 10 GHz and (b) 30 GHz power sweep for a 6x75 um FET biased at 28 V and 100 mA/mm.

Early results from foundry collaborations have been favorable, and the versatility of this technology has shown promising potential to be used in a wide range of RF applications [3].

150-NM GAN MMIC PERFORMANCE

A 28 V Ka-band MMIC was designed and fabricated with Wolfspeed's 150-nm GaN HEMT technology. The GaN MMICs utilize microstrip lines on 3-mil SiC with standard passive components such as dielectrically-supported bridge metal, 180 pF/mm^2 MIM capacitors, 12 Ω/sq. thin film resistors and compact through-wafer source slot vias. This MMIC design was used to demonstrate the capability of the technology to meet the requirements for 5G telecom mm-wave and aerospace-defense applications. The Wolfspeed 150-nm GaN process design kit (PDK), was created from small signal and large signal models. The large signal model was created from multiple device periphery, frequencies, bias conditions and tuner settings. The 3-stage, Ka-band MMIC, shown in Figure 5, was designed for 26.5-30.5 GHz operation.

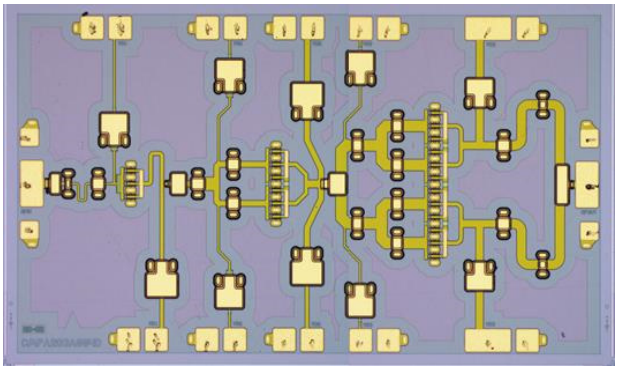

Fig. 5. Wolfspeed's 5G mm-wave power amplifier.

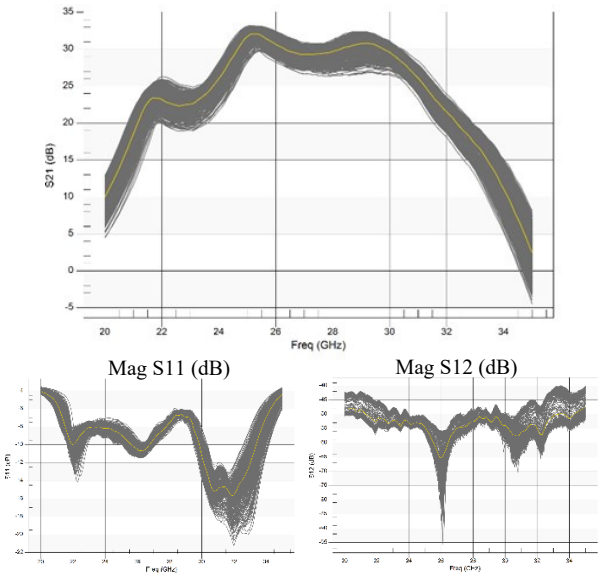

Fig. 6. On-wafer small-signal S-parameters (dB) from 1000 Ka-band MMICs were measured from 20-34.5 GHz.

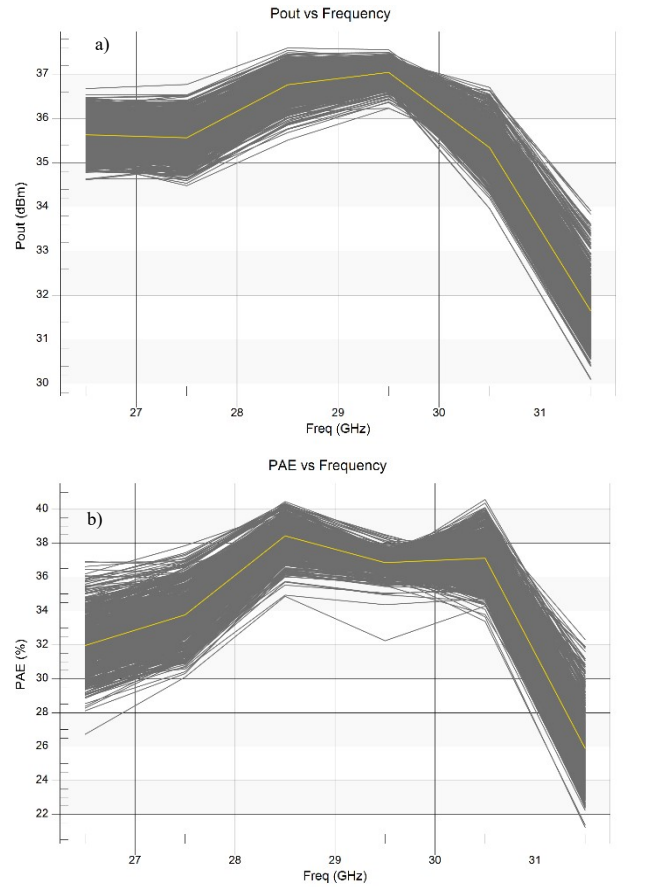

Fig. 7. Power Testing for between 26.5 and 30.5 GHz with an input power of 6dBm. The (a) output power (Pout) and (b) Power added efficiency (PAE) of a 1000 MMICs.

Conventional dc and RF electrical measurements were conducted on each MMIC to determine performance and yield. The s-parameters, shown in Figure 6, were obtained from 1000 MMICs. The small signal gain (S21) was nominally 27 dB between 26.5 - 30.5 GHz with a distribution of < 5 dB. This is indicative to the robustness and repeatability of the Wolfspeed's 150-nm GaN HEMT fabrication process. Frequency-power sweeps were conducted on-wafer to obtain the output power and power added efficiency. The power amplifier produced a typical output power of 37 dBm and a PAE above 30%, shown in Figure 7. Wolfspeed's 150-nm GaN technology fabricated with an i-line photolithography technique has enabled a manufacturing friendly processing without degrading the performance requirements for Ka-band applications.

RELIABILITY

The reliability and lifetime of the technology was evaluated with 3.6-mm periphery devices to demonstrate the maturity of the technology. We ran 20 devices for 1000 hours

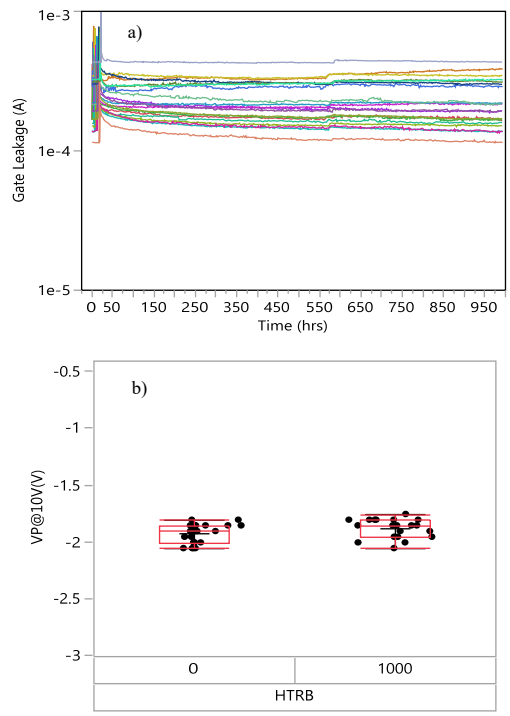

Fig. 8. (a) In-situ gate leakage of the 84V 1000 hour HTRB. (b) Parametric change of pinch-off voltage.

on our HTRB system with a plate temperature of 150 °C. The standard off-state bias conditions were Vg= -8 V and Vd=84 V. In-situ gate leakage was monitored throughout the test. The devices demonstrated negligible performance degradation and zero device fails, shown in Figure 8. To our knowledge, this is the first 150-nm Ka-band GaN HEMT that is capable of enduring 84V HTRB for the standard 1000 hour test.

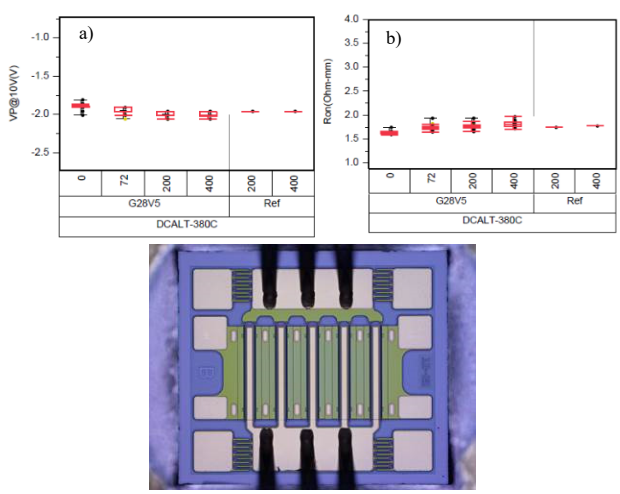

Fig. 9. Parametric changes of the (a) pinch-off voltage and (b) on-resistance during 380 °C ALT. (c) Typical 3.6 mm device after 400hours ALT.

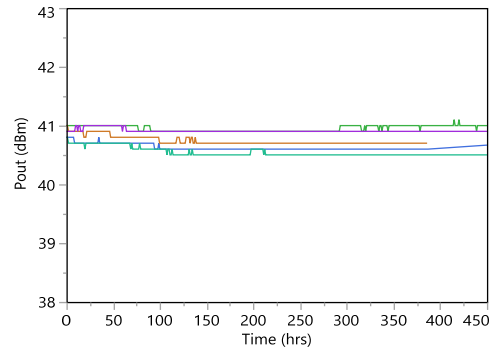

Fig. 10. In-situ monitoring of output power for 3.5 GHz RF ALT at 325 °C.

Preliminary reliability testing was conducted for 380 °C junction temperature on large periphery devices (3.6 mm). The dc-ALT bias conditions were Vd=28 V and 6 W/mm dissipation. Figure 9 shows the 380 °C dc ALT reliability test and shift analysis of the contract resistance and pinch-off voltage. All devices demonstrated device stability throughout test. The RF accelerated lifetime testing (3.5 GHz) was conducted at 325 °C on large periphery devices (3.6 mm). The monitored output power, shown in Figure 10, demonstrated minimal degradation and zero failures after 400 hours.

CONCLUSIONS

Wolfspeed has demonstrated a manufacturable 28-V, 150-nm GaN HEMT technology for MMIC foundry design, and the pre-production material has provided competitive performance up through 30 GHz. The optically-defined, i-line 150-nm gate can provide outstanding power and PAE for many Ka-band and Ku-band applications. The high voltage off-state HTRB reliability testing confirmed the robustness of the technology with negligible performance degradation. Multiple temperature accelerated life testing was used to evaluate the potential life time of the technology. This on-state testing confirmed the lifetime is equivalent to other GaN technology products released by Wolfspeed.

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