0.15µm GaN MMIC Manufacturing Technology for 2-50 GHz Power Applications

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ABSTRACT

Qorvo has developed high performance and highly reliable 0.15µm GaN HEMT technology on 100 µm thick and 100mm diameter SiC substrates for Ku, Ka and Q-band as well as wide band applications. At 30GHz, 0.15µm GaN transistors have an output power density of 3W/mm, power gain higher than 8dB, and PAE higher than 50%. This technology is very reliable with a median DC lifetime of greater than 1E7 hours at T_{ch} = 200°C. In this paper, we report our fabrication process, device characteristics, reliability, and MMIC RF performance of a standard product at Ka band.

I. INTRODUCTION

GaN HEMT based MMICs are economically viable technology for commercial applications due to the higher power densities per unit chip area and higher efficiency. GaN HEMTs enable microwave designers to pursue market opportunities currently served by GaAs power pHEMT technology [1-10]. Currently, there are number of suppliers for GaN based MMICs at lower frequencies (2 to 20 GHz) for production level quantities of MMICs. Other than Qorvo, there are very few suppliers of production quantity MMICs at Ka-band. Over the years, extensive effort has been made to realize high frequency manufacturable GaN MMICs up to Q-band. High frequencies, Ka- and Q- band MMICs are critical components of many commercial VSAT and advanced military millimeter-wave applications. At Qorvo, we have developed a 0.15µm GaN HEMT process technology, which meets the requirements for mm-wave technology and, which is very suitable for realizing high frequency MMIC power amplifiers, LNA & broadband amplifiers.

Qorvo, has a long history with GaN HEMT technology, and has been manufacturing 0. 25 µm GaN HEMTs at S-band and X/Ku band for more than a decade. Qorvo has achieved manufacturing readiness level (MRL) 9 for 0.25 µm GaN HEMTs. 0.15µm GaN HEMT is an extension of the baseline technology, developed by optimizing device epitaxial structures, transistor geometry and fabrication process to meet the requirements of a millimeter-wave technology. In this paper, we report the DC, RF and reliability of this mature technology.

II. 0.15 µm GAN MMIC TECHNOLOGY

A. FABRICATION PROCESS

AlGaN/GaN HEMT epitaxial structures were grown on 4 inch SIC substrates. Epitaxial structure consists a semi-insulating GaN layer for improved isolation, an undoped GaN channel layer, an AlGaN layer. The transistor fabrication process is summarized as follows. Source drain ohmic contacts are formed by Ti/Al alloyed to GaN HEMT epitaxial layers. Active areas of the device are formed by etching of a mesa in AlGaN/GaN epitaxial structures. 0.15 µm gate in this technology is fabricated using e-beam lithography and plasma etching of silicon nitride. A source connected second field plate is fabricated over the gate channel.

Other GaN MMIC components, fabricated during front-side processing includes, TaN resistor and 3 levels of metal interconnects (3MI) including Au plated airbridge and 3 types of SiN capacitors and SiN protective overcoat. After the front-side processing, the substrates are thinned down to 4 mil, followed by back side via etching and metallization for backside ground plane of MMIC.

B. DEVICE CHARACTERISTICS

Typical device characteristics are summarized in Table 1. DC Id_{max} = 1.15A/mm, $g_{m,\ max}$ = 425mS/mm and pinch off voltage = -3.1V at V_{ds} = 10V. Figure 1 shows the normalized Gm transfer curve of the 4x100 um transistor with gmmax at 406 mS/mm. Gate-to-drain device breakdown voltages measured at I_d = 1mA/mm and V_{gs} = -6.0V exceeds 75V. Most of transistors in MMICs are on-wafer DC tested for functionality.

Loadpull characterization of the transistor was done at 30 GHz. Figure 2 shows the typical power density of 3W/mm from a pre-matched 8x50 µm biased at V_d = 20V, I_{dq} = 100mA/mm in a PAE tuned condition. Power gain and PAE of the transistors at the PAE tuned conditions are greater than 8dB and 50% respectively. Power density of 0.15µm GaN transistor is four times higher than the Qorvo's 0.15µm GaAs power pHEMT. PAE is comparable to that of 0.15µm GaAs pHEMT.

Table 1 Key Performance parameter of Qorvo's 0.15µm GaN HEMT Technology.

	Unit	Nominal
Idss (Vgs=0,Vds=5V)	mA/mm	800
Imax (Vgs=1, Vds=5)	mA/mm	1150
Gmmax	mS/mm	425
Vp	V	-3.1
BVGD@ Id=1mA/mm, Vgs= -6V	V	75
Ft@20V, 100 mA/mm	GHz	32.5
Fmax@ 20V, 100 mA/mm	GHz	160
Pout@ 30 GHz, 20V, Id=100 mA/mm	W/mm	3
PAE@30 GHz, 20V, 100 mA/mm	%	50%

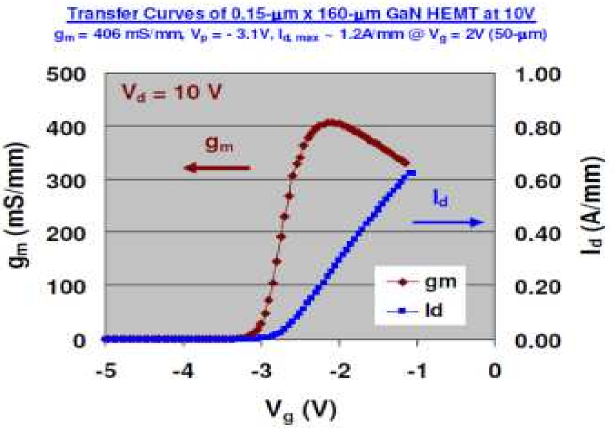

Figure 1: Gm Transfer curve of 0.15µm GaN HEMT.

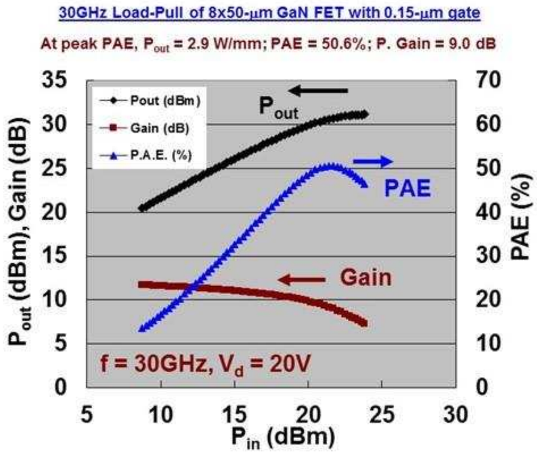

Figure 2: 30 GHz Loadpull data of pre-matched 8X50 µm FET cell biased at Vd=20V and Idq=100 mA/mm.

C. IN-LINE PROCESS CONTROL MONITOR

Several critical process parameters, including Ohmic S/D spacing size, e-beam critical dimensions of trunk and cap of the 0.15µm gate fabrication step, size of the source connected field plates and nitride thickness are monitored using statistical process control (SPC) charts. Automated electrical measurements are performed on process control monitor (PCM) test structures at various stages of the fabrication steps. Critical DC parameters such as, Idss, Imax, Vp, Gmmax, BV, Rd, Rs, Rg, contact resistance, resistance of gate metal stack, capacitance of capacitors are monitored using trend charts.

In addition to critical process and DC parameters, RF performance of the transistors were monitored by performing small-signal and power measurements of at least 15 or more standard FET cells (SFC, 4X100 µm finger) on every wafer. Equivalent circuit parameters (ECP) such as, transconductance (Gmm), gate to source capacitance (Cgs), gate to drain capacitance (Cgd) etc. are extracted in an automated algorithms from S-parameters data taken over a range of frequencies of 0.5-26 GHz. Details of extraction algorithm are discussed by Campbell and Brown [6]. Cut-off frequency (Ft = [Gmm/ (2*π.(Cgs+cgd))]) at the bias condition, Vd=20V, Id=100 mA/mm is calculated from extracted ECPs. Figure 3 shows the trend of the cut-off frequency, f_T, of 200 wafers with mean value at 32.5 GHz.

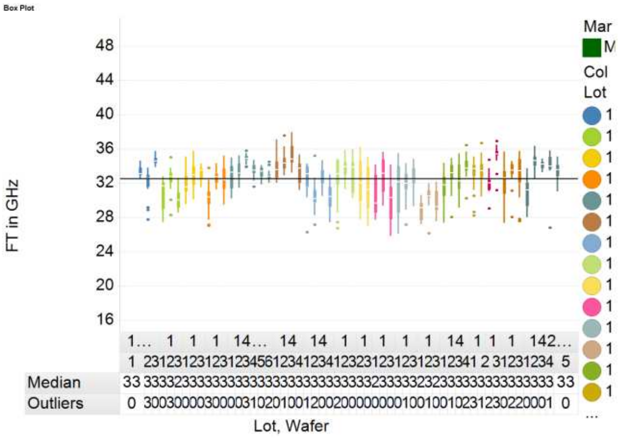

Figure 3: Cut-off frequency trend 0.15µm GaN HEMT.

III. RELIABILITY

Reliability of the process technology is monitored by characterizing transistors from each wafer at an accelerated dc life test condition. At the early stage of process development, a complete three-temperature reliability study (T_{ch} = 370°C, 389°C, 405°C), using 6x50µm GaN HEMT unit cells was performed starting with a sample population size of 72 devices. An extensive thermal modeling based on device geometry was done to calculate the rise in channel temperature from a given base plate temperature and DC power density. For the accelerated life test, devices are biased up at Vd=22V and Id= 350mA/mm. During the test, gate bias was adjusted to keep the Id constant so that the channel temperature remains constant during the test. Periodically, Idmax (Vd=5.0V, Vg=1.0V) current was recorded to assess the degradation of the device. A 10% degradation of Idmax is considered as failure of the transistor. This test is repeated 2 times from 2 different lots to capture the variation of activation energy. Arrhenius plot of median lifetimes versus the three channel temperatures (°C) was used to extract the activation energy (Ea @ $t_{50\%}$) of 2.6eV with a single-sided 90% lower confidence bound (Ea@ $t_{90\%}$) of 2.2 eV. Based on the activation energy of 2.2ev, lifetime of the transistor is calculated to be greater than 1E7 hours at channel temperature of 200°C.

IV. 0.15µm GaN MMIC Performance

Using this 0.15µm GaN HEMT technology, Qorvo has developed standard products such as, TGA2594, 4W-30 GHz PA, TGA2595 8W-30GHz PA, TGA2239 13-15.5 GHz PA, TGA2214 2-18 GHz 5W PA, TGA2958 13-18 GHz 2W driver amp and many other products from X-band to Ka-band. These products are designed using Qorvo's released process design kit (PDK) with small-signal and large signal models. Small-signal models are developed using broadband s-parameter measurements up to 50 GHz. Large signal models are developed from loadpull measurements at specific frequencies at number of bias conditions using power tune as well as efficiency tune conditions. In this paper, we will discuss the MMIC performance of TGA2595 from wafers over a period of times. Details of the TGA2595 design is published elsewhere [2]. MMICs are 100% on-wafer DC and RF tested with parametric yields greater than 90%.

Figure 4 shows the distribution of small-signal gain of 8W HPA from 5000 MMICs from several lots. The measured small-signal gain is typically 27 dB from 29, 30 & 31 GHz. The maximum in-band input and output return losses are 15dB. Based on the data from 5000 MMICs, the spread small-signal is around 3 to 4 dB, exhibiting the robustness and reproducibility of the technology.

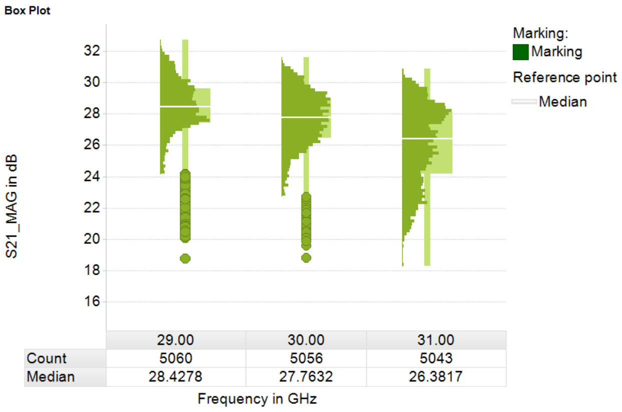

Figure 4: On-wafer small-signal S-parameter (dB) data of TGA2595 MMIC from 29-31 GHz.

On-wafer MMIC power probe was performed in a pulsed environment in order to minimize the thermal impact during test. Drain supply voltage, Vd=20V, is pulsed at 10% duty cycle with 10 µsec pulse. Figure 5 shows the the distribution of saturated output power at 29, 30 & 31 GHz. Nominal output power of the MMICs are at 10W (40 dBm) with a typical spread of 1.5 to 2 dB. Input power for this test was Pin =22 dBm. Output power was relatively flat across the band. Figure 6.0 shows distribution of PAE from 29, 30 & 31 GHz with a nominal value at 25%.

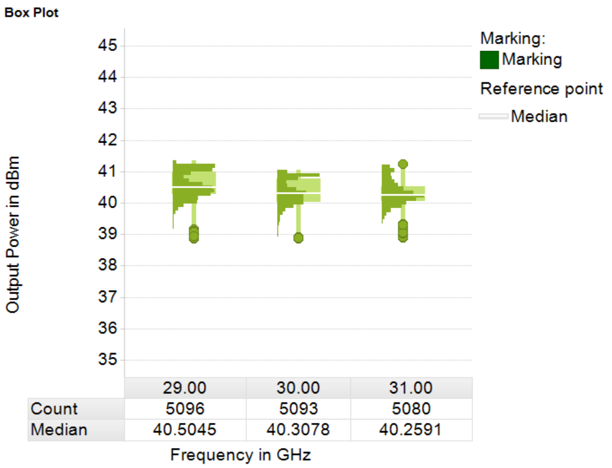

Figure 5: On-wafer saturated output power data of TGA2595 MMIC from 29-31 GHz.

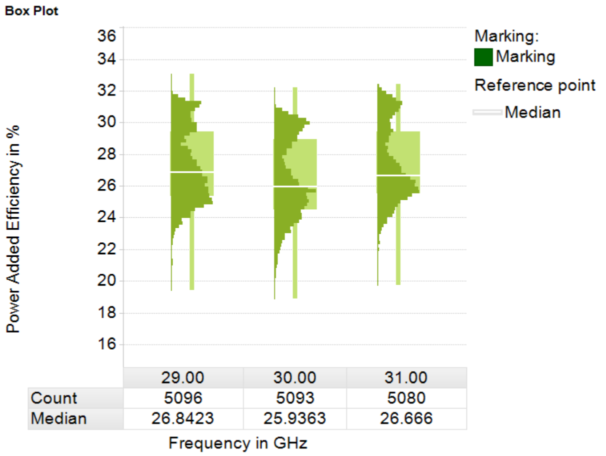

Figure 6: On-wafer Power Added Efficiency (PAE, %) data of TGA2595 MMIC from 29-31 GHz.

Several TGA2595 MMIC amplifier die were soldered to 40 mil thick Cu-Mo carrier plates to perform in-fixture measurements in a continuous wave (CW) environment. Details of the fixture tests are published elsewhere [2].

Measured fixtured results are shown on Figures 7 and 8. All the fixture measurements were done at Vd=20V and Id=100 mA/mm. Ouput power is measured at the input power level of 22 dBm. Figure 7 shows that measured fixture result of output power is close to 10W across the band with a PAE of 25%. In- fixture CW measurement results confirms the median on-wafer RF probe data in a pulsed environment. Small-signal frequency response is shown on Figure 8. Linear gain is above 27 dB in the band of 28 to 31 GHz, which is in agreement with the on-wafer RF probe measurements discussed earlier.

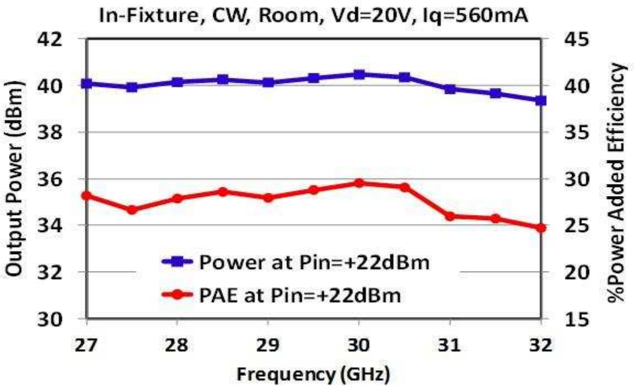

Figure 7: In-fixture power and PAE data of TGA2595.

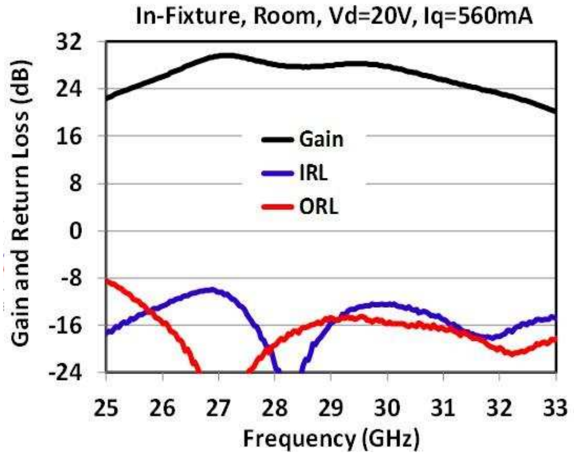

Figure 8: In-fixture small-signal S-parameter data of TGA2595

TGA2595 0.15μm GaN MMICs is compared to the TGA4046 and other published results in term power, PAE and die size. In term of die size reduction, these MMICs are one quarter of the area of the comparable GaAs based pHEMT. Qorvo, Spatium PA KA150W-2730 is based on TGA2595. In addition to these results, Kris Kong et al [5] have published results using Qorvo's 0.15μm GaN HEMT with similar die size reduction in comparison to GaAs pHEMTs. The published results and products in this technology is the state-of-art in term of performance at Ka-band.

V. CONCLUSION

In this paper, we have demonstrated a 0.15μm GaN HEMT MMIC technology with excellent Ku- and Ka-band performance, proven manufacturing reproducibility and high reliability for microwave and millimeter-wave applications. Using this technology, several standard products at Ka-band, Ku-band and 2-18 GHz have been released with excellent power and PAE. The state-of-the-art performance of this technology has been attributed to the combination of design optimization of epitaxial structure, gate channel geometry, and Qorvo's manufacturing techniques with excellent process control. In addition to manufacturing, Qorvo's design team has excellent design capability at millimeter-wave circuits. There are number of standard products with frequency ranging from 2 to 40 GHz in various stages of production using this technology.

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