Performance and Reliability of AlGaN/GaN HEMT on 100-mm SiC Substrate With Improved Epitaxial Growth Uniformity

Sangmin Lee, Tim Kennedy, Christer Hallin, Helder Antunes, Brian Fetzer, Scott T. Sheppard, Al Burk,
Don A. Gajewski, Rick McFarland, Jim Milligan and John Palmour

Cree Inc., 4600 Silicon Dr., Durham, NC 27703, (919) 407-5030, sangmin_lee@cree.com

Keywords: …GaN, HEMT, SiC, uniformity, reliability

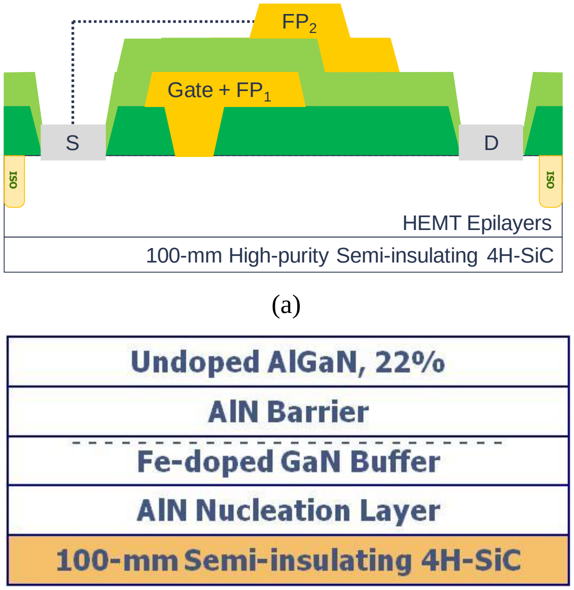
Abstract

Significant improvement was made in AlGaN epi thickness uniformity by improved gas flow in a MOCVD reactor. RF and dc device performance and reliability have been examined for wafers with improved uniformity. A number of wafers were included in 3 production lots, and the data have been compared between the wafers with and without this improvement. The dc/RF device performance was comparable, and the reliability test at 380 °C junction temperature for 500 h shows similar behavior compared to the known reliability of the technology. The threshold voltage (V_T) shows greatly improved radial uniformity across the 100-mm wafers.

INTRODUCTION

GaN/SiC HEMT devices have superior performance for high frequency, high power and high temperature applications compared to other competing technologies based on GaAs and Si [1,2] due to its unique material characteristics such as wide bandgap, high electron mobility and high thermal conductivity. Cree has introduced multiple GaN HEMT technology platforms starting from 0.4-µm gate length (L_g) devices for 28 V application in 2006 [3] and subsequently introduced 0.25-µm L_g devices for up to 40 V [4] application as well as 0.4-µm L_g devices for 50 V [5] use. Since their introduction, over one million discrete transistors and MMIC products have been fielded; originally by military customers and more recently by the commercial sector [6]. The FIT rate has been confirmed to be less than 10 from the fielded products [7]. Recently, the price of GaN HEMT devices has been reduced to the point where commercial segments have started rapidly adopting the technology. As evidence, the introduction of GaN-on-SiC technology has been clearly increasing in commercial systems, including LTE base stations, point-to-point radios, Civil Radar and satellite communications [8, 9]. As the commercial market opens up, the maturity and manufacturability of the process become the most pressing issues for high-volume, low-cost production [10]. The uniformity of the starting material is a vital factor for high yield and tighter device specification. To further evolve the manufacturability of the GaN HEMT process, an improvement in MOCVD reactor geometry has been made to ensure more streamlined gas flow in the chamber. With the same epitaxial structure, the AlGaN thickness uniformity has been improved by ~3x. To adopt this new epitaxial growth format, dc and RF characteristics and reliability performance of devices from 3 different production lots have been examined.

EXPERIMENT AND RESULTS



(a)

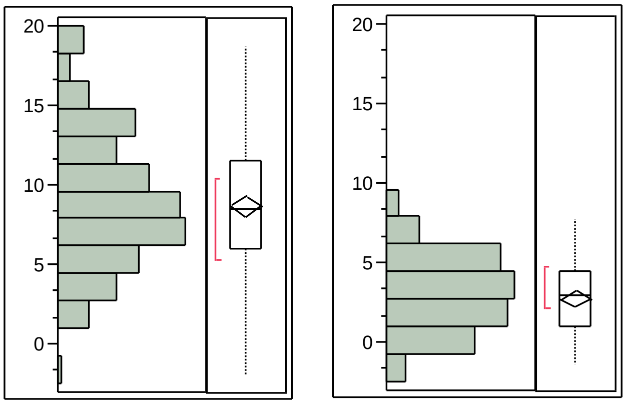
(b)

Figure 1. The schematic diagram of: (a) device structure and (b) epi layer grown on 100-mm semi-insulating 4H-SiC substrate

Figure 1 shows a schematic diagram of Cree's GaN-on-SiC epilayer and devices for all technology platforms. The epilayers are grown on 100-mm diameter high purity semi-insulating SiC substrates using a multi-wafer MOCVD reactor with 8 satellite positions. The epitaxial growth method has been described elsewhere more in detail [11].

Continuous improvement initiatives in our fabrication facility required that we focus on reduction of 1-mA/mm threshold voltage standard deviations across all device platforms. In AlGaN/GaN HEMT structures such as these, it is recognized that device parameters like threshold voltage

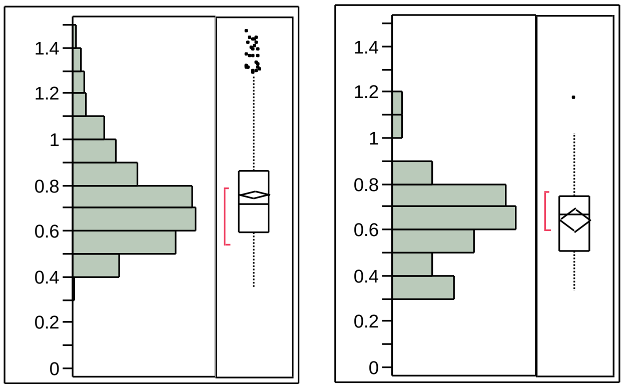
(V_T) are proportional to AlGaN thickness and channel charge density. The uniformity of the epilayers depends on many sensitive factors, including temperature, gas flow, substrate bowing, strain characteristics of the buffer layer and substrate crystal orientation, to name a few [12,13]. In this study, the reactor geometry has been modified to improve reagent depletion profiles and AlGaN growth uniformity. Figure 2 shows the distribution of the AlGaN thickness range before and after the improvement. The thickness range was defined as the AlGaN thickness difference between the center and 40-mm toward the edge of a wafer. With the reactor improvement, the mean AlGaN thickness range was improved from 8.74 Å to 2.77 Å.



(a) (b)

Figure 2. The distribution of the AlGaN thickness range (a) before ($\overline{Range}$ = 8.74 Å) and (b) after ($\overline{Range}$ = 2.77 Å) an MOCVD reactor improvement was made.

In addition, the Al concentration and GaN buffer thickness uniformity was measured to be comparable or slightly improved. The sheet resistivity (R_{SH}), measured by Lehighton 1600, has also been improved. Figure 3 shows the uniformity distribution of R_{SH} data before and after the improvement, demonstrating a ~16% improvement.



(a) (b)

Figure 3. R_{SH} distribution (a) before and (b) after the improvement. The uniformity has been improved from 0.76 Ω/sq to 0.64 Ω/sq in average.

To qualify this new epitaxial growth configuration, wafers were introduced into 3 different production lots to compare yield, dc/RF device performances and reliability. One third of each lot was comprised of the wafers with the improved growth condition. 2 lots (Lot1 and Lot2) were CGH40120 product [14] and 1 lot (Lot3) was CGH40010 product [15]. Figure 4 shows measured dc yield at the end of the fabrication process that was normalized to the maximum yield of each product group. The final yield from the wafers with improved epitaxial growth are comparable or slightly better than before the improvement.

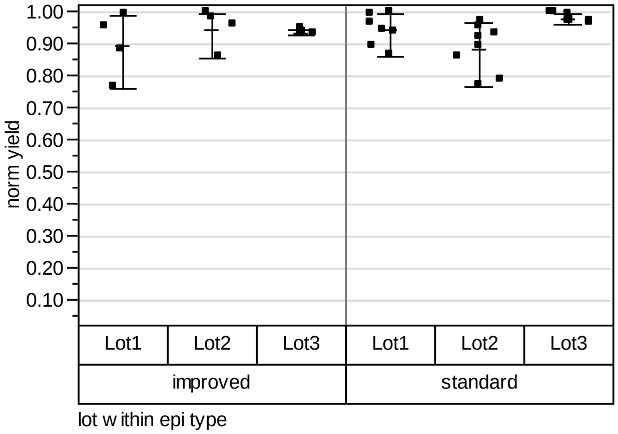
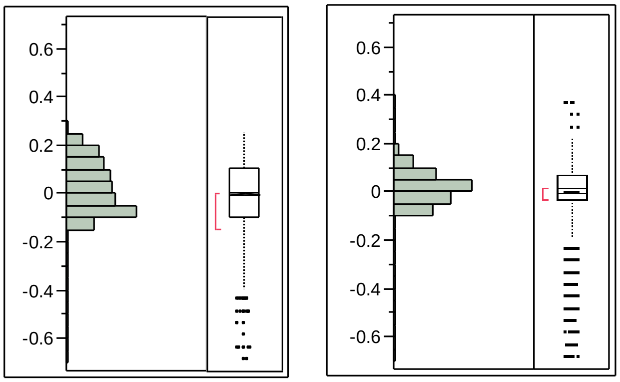


Figure 4. Normalized dc yield at the end of backside process from 3 different GaN-on-SiC HEMT lots. In each lot, one third of the wafers were grown with the improved gas flow.

The CGH40010 product lot was used for further analysis of device performance and validation of reliability because the CGH40010 has been the standard vehicle for technology qualification at Cree [16]. Figure 5 shows the distribution of the deviation of V_T from the average of each group tested at 10 V drain voltage. The devices from the improved uniformity epi wafers show ~25 % lower standard deviation.



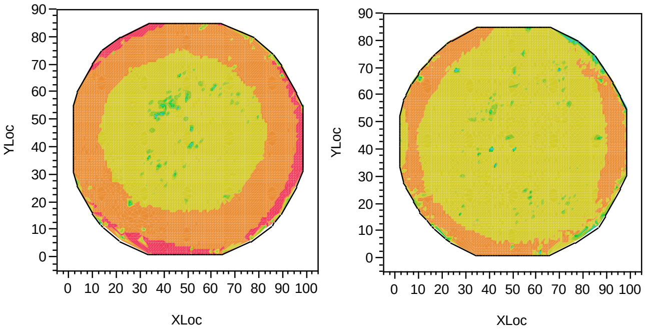
(a) (b)

Figure 5. The distribution of V_T (threshold voltage measured at V_{DS} of 10 V and I_{DS} of 1 mA/mm) from the group average value (a) before and (b) after the improvement. The standard deviation was improved from 0.12 to 0.09 V.

This improvement can be seen more profoundly if the data is plotted as a function of locations on a wafer. Figure 6 shows typical contours of normalized V_T across a wafer. The data is normalized to the group average of V_T and the color coding is described in Table 1. XLoc and YLoc indicate the die location on a 100 mm wafer.

Table1. Color coding of the normalized V_T map in Figure 6.

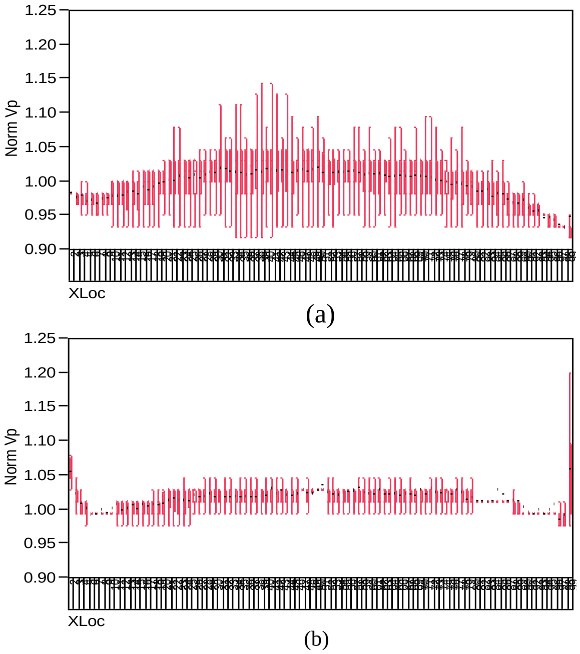
Color	🟦	🟩	🟩	🟩	🟨	🟧	🟥
Range	1.25	1.2	1.15	1.1	1.05	1.00	0.95



(a) (b)

Figure 6. The normalized V_T map of a typical wafer (a) before and (b) after the improvement. The V_T was tested at 10 V drain voltage. The color coding is explained in Table 1.

Figure 7 shows the distribution of normalized V_T as a function of XLoc on a wafer. It is very clear that overall V_T uniformity improved significantly.



(a)

(b)

Figure 7. The average (black dots) and 25-75% quartile (red lines) of normalized V_T as a function of XLoc of devices from the same wafers described in Figure 6. XLoc varies from 1 to 99. (a) before and (b) after the improvement.

To confirm the long term reliability, dc accelerated life testing (ALT) was assessed for 10 parts each from 3 wafers randomly selected from Lot3. The devices were biased at V_{DS} = 28 V and 6 W/mm power dissipation for 500 h. The estimated junction temperature was 375 °C. The packaging and the T_j calculation method were described in more detail in a previous report [16].

The dc and RF performance of the devices were examined at 0, 100, 300 and 500 hours of stress. Individual device failure criterion is determined by device functionality failure or 1 dB decrease in saturated power, compared to its initial value. Up to 500 h, only one failure was detected. To do the statistical analysis of time to failure (TTF), TTF was estimated by linear extrapolation instead of continuing the stress until failure occurred. Then, the estimated TTF distribution was compared with the previously reported ALT analysis, which was done for the same technology with a larger population of parts and for much longer stress time [16].

Figure 8 shows the lognormal plot of the cumulative density function of lifetime distribution. The solid line is the MTTF from the previous report, 1221 h, and the dashed line is from this study, 1414 h. The shaded area shows the 95% confidence interval. The previously reported MTTF is well within the confidence interval. The shape factor (lognormal sigma) was 0.45 from this assessment with 95% confidence interval of (0.35, 0.59).

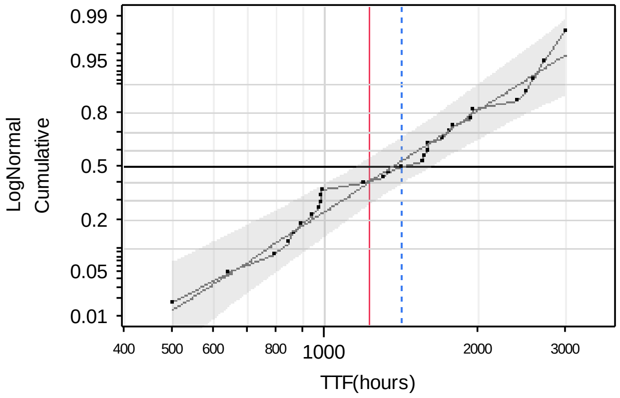


Figure 8. Lognormal CDF(cumulative density function) of TTF(time to failure). Horizontal line shows 50% survival. The MTTF was estimated to be 1414 h (dashed line) from this assessment. The solid line is 1221 h, the previously reported MTTF from the same technology [16]. The shaded area is the 95% confidence interval.

CONCLUSIONS

As a path to lower cost and a more manufacturable process for GaN HEMTs on SiC, improvement has been made in the AlGaN thickness. As a result, a ~25% improvement in the standard deviation of V_T has been confirmed. The final yield and dc/RF performance of the devices were comparable or slightly better than before the change. The ALT test was done for a total of 30 CGH40010 products from 3 randomly selected wafers at 375 °C T_j for 500 h. The MTTF was estimated to be 1414 h from this assessment and the previously reported MTTF of 1221 h is well within the 95% confidence interval.

ACKNOWLEDGEMENTS

The authors like to thank those in the epitaxy operations group, wafer fabrication facility, and package and test who contributed to the fabrication and data collection for this effort. Useful discussions with the research and development group are also appreciated.

REFERENCES

[1] A.P. Zhang, et al., *Microwave power SiC MESFETs and GaN HEMTs*, 2003 Solid State Electronics, Volume 47, Issue 5, pp. 821 – 826

[2] S. J. Pearton et. Al., *GaN electronics for high power, high temperature applications*, 2001, Materials Science & Engineering B, Volume 82, Issue 1, pp. 227 – 231

[3] *Cree sampling GaN HEMTs*, 2006, III-Vs Review, Volume 19, Issue 9, p. 8

[4] R. S. Pengelly et al, *A Review of GaN on SiC High Electron-Mobility Power Transistors and MMICs*, 2012, IEEE Transactions on Microwave Theory and Techniques, Volume 60, Issue 6, pp. 1764 - 1783

[5] *Cree Unveils New Gallium Nitride GaN RF MMIC Process Technologies to Enable Lower Cost for Higher Performance Telecommunication and Radar Systems*, 2012, Telecommunications Weekly, June 2012, p. 53

[6] J. Milligan, *GaN BENEFITS: CREE VIEWPOINT*, 2012, Microwave Journal, Jun2012, Vol. 55 Issue 6, p26-28

[7] http://www.cree.com/news-and-events/cree-news/press-releases/2011/june/110606-10-million-watts, last visited at 11/06/2012

[8] P. Hindle, *Future RF Market Opportunities for GaN*, 2012, Microwave Journal, June 2012, Vol. 55, Issue 6, p22-24

[9] E. J. Lum, *The Evolution of the BTS Market: Towards 4G Technology* , 2010, CSMANTECH technical Digest, pp. 37-40

[10] J. W. Palmour et. al., *100 mm GaN-on-SiC RF MMIC technology*, 2010, Microwave Symposium Digest (MTT), IEEE MTT-S International , pp. 1226-1229

[11] A. W. Saxler et. al., *III-Nitride Epitaxial Material on Large-Diameter Semi-Insulating SiC Substrates for High-Power RF Transistors*, Mater. Res. Soc. Symp. Proc. FF15-01.1, 2006, pp. 377-382

[12] X. Gao et. al., *A Statistical Study of AlGaN/GaN HEMT Uniformity with Various Buffer and Barrier Structures*, 2011, CS MANTECH Technical Digest, 6b.1

[13] U. Forsberg et. al., *Improved hot-wall MOCVD growth of highly uniform AlGaN/GaN/HEMT structures*, 2009, Journal of Crystal Growth, Vol. 311, pp. 3007-3010

[14] http://www.cree.com/~/media/Files/Cree/RF/Data%20Sheets/CGH40010.pdf, last visited at 11/06/2012

[15] http://www.cree.com/~/media/Files/Cree/RF/Data%20Sheets/CGH40120F.pdf , last visited at 11/06/2012

[16] D. Gajewski, et al., Reliability of GaN/AlGaN HEMT MMIC Technology on 100-mm 4H-SiC, 2011, Reliability of Compound Semiconductor Conference Digest (ROCS) 2011

ACRONYMS

HEMT – High Electron Mobility Transistor
MMIC- Monolithic Microwave Integrated Circuit
LTE – Long Term Evolution
MOCVD – Metal Organic Chemical Vapor Deposition
ALT – Accelerated Life Test
FIT – Failure In Time
MTTF – Median Time To Failure