III-Nitride Epitaxial Material on Large Diameter Semi-Insulating SiC Substrates for High-Power RF Transistors

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ABSTRACT

Metalorganic chemical vapor deposition was employed to deposit high quality, highly uniform III-Nitride transistor structures on 100 mm diameter semi-insulating 4H-SiC substrates. Electron mobility was over 2000 cm^2/Vs at room temperature. Sheet resistivity uniformity was as low as 0.75%. Typical standard deviations were about 1% in most properties including sheet resistivity, carrier concentration, mobility, and AlGaN composition. Additionally, wafers maintained their flat shape after deposition of these structures. Wafer bow and warp were typically less than 20 μm for optimized structures and <5 μm for the best wafers.

INTRODUCTION

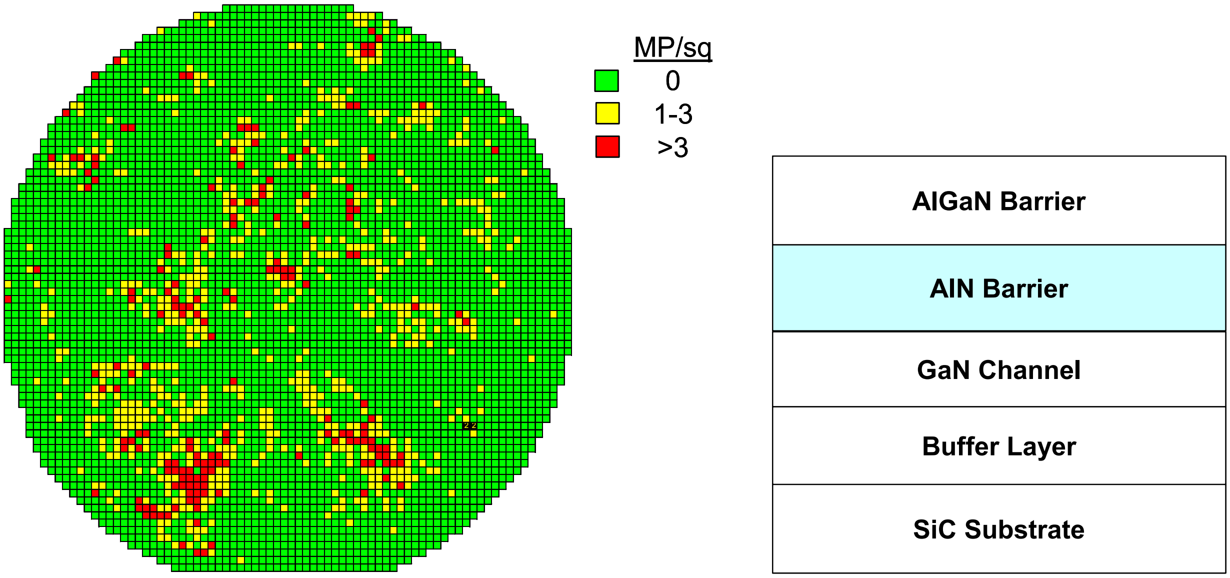
Interest in III-N based high electron mobility transistors (HEMTs) has been building as devices approach maturity. Exceptional device performance has recently been achieved for transistors based on III-Nitride material grown by metal-organic chemical vapor deposition (MOCVD) on high-purity semi-insulating (HPSI) 4H-SiC substrates.[1] The wide bandgap and high mobility of the III-Nitrides combined with the excellent thermal conductivity of the SiC substrate enable the devices to operate at extremely high power densities.

The first commercially available SiC substrates were less than two inches in diameter. Recently, 100 mm diameter 4H-SiC n-type substrates have been released for sale by Cree, Inc.[2] HPSI 4H-SiC 100 mm diameter substrates have been successfully demonstrated. However, epitaxial quality and uniformity equivalent to that shown on smaller diameter SiC substrates had not previously been demonstrated. In this paper, the uniformity and quality of III-Nitride HEMT epi structures grown on 100 mm diameter 4H-SiC substrates is shown to be suitable for device fabrication.

EXPERIMENT AND DISCUSSION

Bulk HPSI 4H-SiC boules were grown by physical vapor transport and fabricated into 100 mm diameter substrates approximately 0.6 mm thick. A micropipe map for one of the best wafers is shown in Figure 1(a). This wafer had 77% of the cells free of micropipes and an average density of only 26 cm^{-2}.

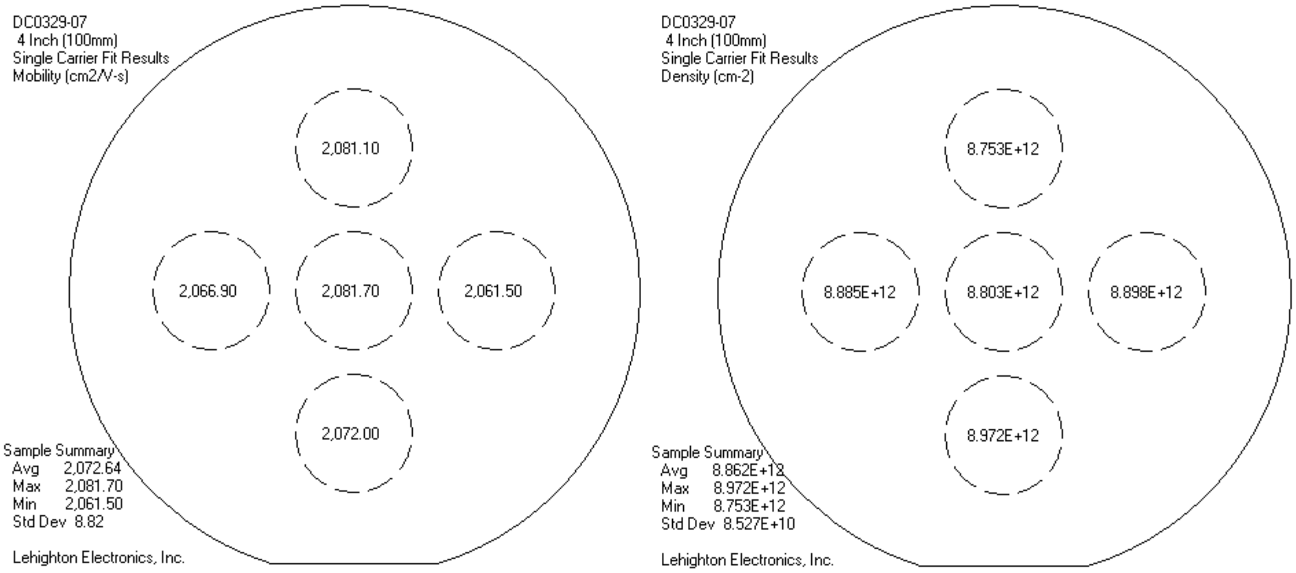
The III-Nitride layers were deposited in a multi-wafer MOCVD tool capable of growing on up to eight - 100 mm diameter wafers at a time. After deposition of a nucleation layer, an iron doped GaN buffer layer was deposited followed by an unintentionally doped GaN channel layer. In order to enhance the mobility by reducing alloy scattering, an AlN barrier layer was grown on top of the GaN channel before deposition of an AlGaN cap layer. The layer structure is sketched in Figure 1 (b).



(a) (b)

Figure 1. (a) Micropipe map for a 100-mm high-purity semi-insulating 4H-SiC substrate. The micropipe density is 26 cm^{-2} and 77% of the squares are micropipe free. (b) Schematic drawing of the epi layer structure.

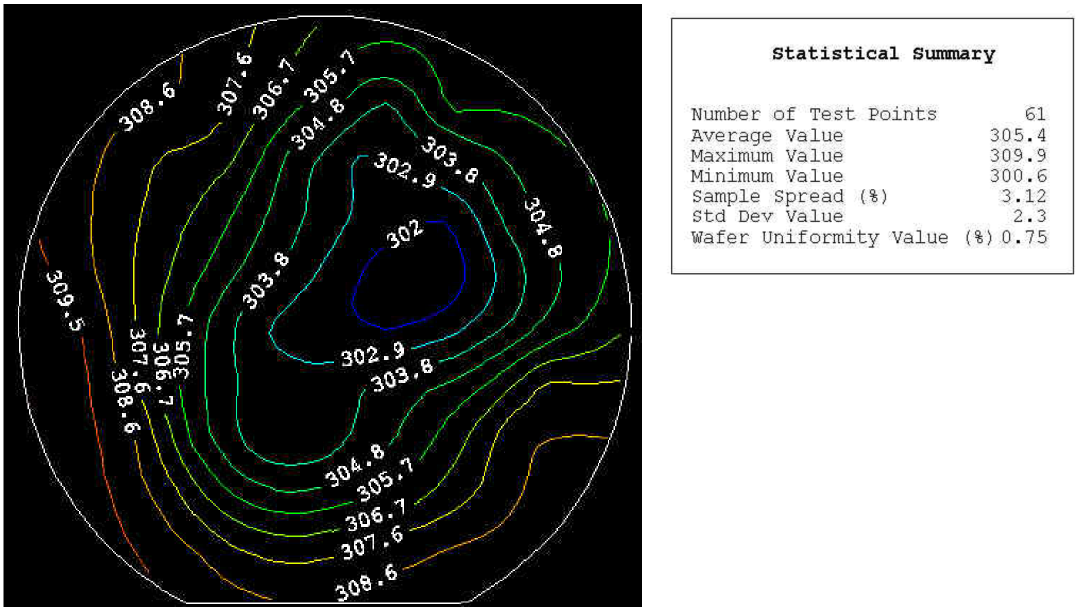
Electrical measurements were performed using Lehighton instruments. A model 1600 instrument at Lehighton was used to measure mobility and carrier concentration, at five points approximately one inch in diameter as shown in Figure 2. The mobility was 2070 cm^2/Vs with a standard deviation of only 0.4 %. The sheet carrier concentration was 8.9 x 10^{12} cm^{-2} with a standard deviation of 1.0 %. Combined, this gives a sheet resistivity of 340 Ω/square with a standard deviation of 0.8 %.



(a) (b)

Figure 2. Room temperature mobility (a) and sheet carrier concentration (b) maps of a 100 mm HEMT wafer on HPSI 4H-SiC.

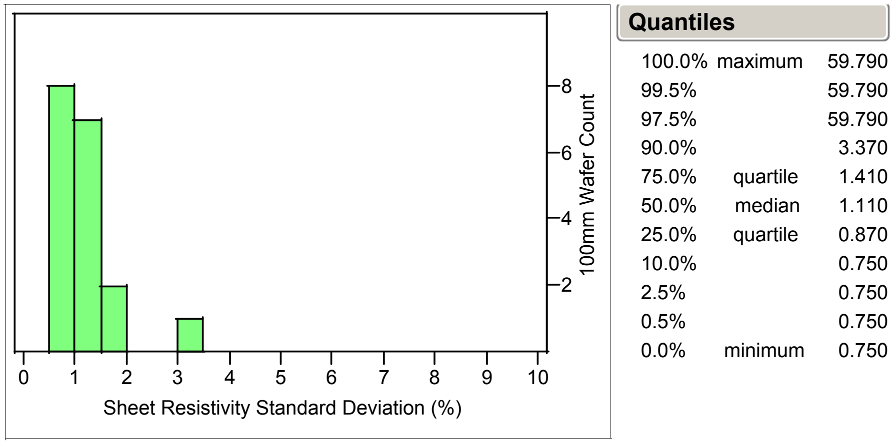
A Lehighton model 1510 located at Cree was used to measure resistivity at 61 points with a 14 mm diameter head. The edge of the head came within 2 mm of the wafer edge during the mapping process. A map of a III-Nitride HEMT with an average sheet resistivity of 305 Ω/square and a standard deviation of only 0.75% is shown in Figure 3. Statistics for 19 wafers are shown in Figure 4 with a median sheet resistivity standard deviation of only 1.1%.



Statistical Summary

Number of Test Points	61
Average Value	305.4
Maximum Value	309.9
Minimum Value	300.6
Sample Spread (%)	3.12
Std Dev Value	2.3
Wafer Uniformity Value (%)	0.75

Figure 3. Sheet resistivity map of a III-Nitride HEMT on a 100 mm HPSI 4H-SiC substrate showing excellent uniformity with only 2 mm edge exclusion.



Quantiles

100.0%	maximum	59.790
99.5%		59.790
97.5%		59.790
90.0%		3.370
75.0%	quartile	1.410
50.0%	median	1.110
25.0%	quartile	0.870
10.0%		0.750
2.5%		0.750
0.5%		0.750
0.0%	minimum	0.750

Figure 4. Statistics for sheet resistivity uniformity on 19 wafers with a median of only 1.1%.

The composition and thickness of the AlGaN were determined from x-ray diffraction measurements on 21 points over the wafer. The composition and thickness maps for two wafers are shown in Figure 5 and Figure 7 respectively illustrating the uniformity. Statistics on 19 wafers are presented in Figure 6 and Figure 8. The best aluminum composition standard deviation was only 0.9% with a slightly higher median of only 1.3%.

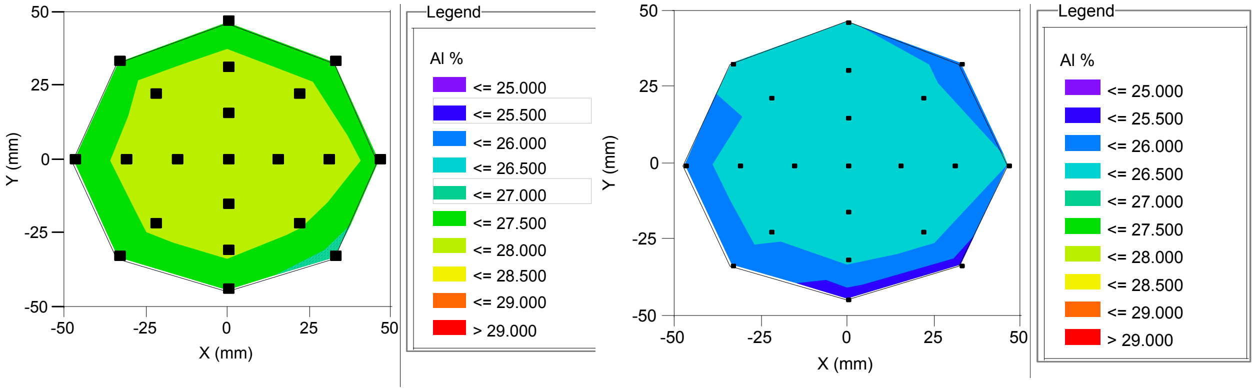
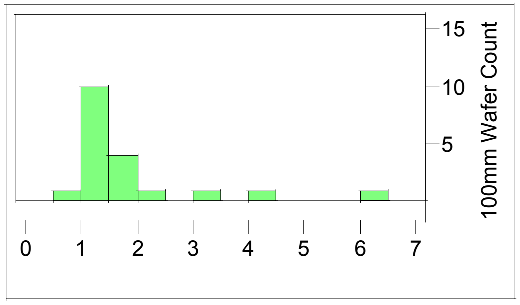


Figure 5. Aluminum mole fraction of the cap layer in two III-Nitride HEMT layers grown on 100 mm HPSI 4H-SiC substrates. Each contour represents 0.5% change in Al mole fraction.

Al %std dev/mean



Quantiles

100.0%	maximum	6.2573
99.5%		6.2573
97.5%		6.2573
90.0%		4.4913
75.0%	quartile	1.9515
50.0%	median	1.3358
25.0%	quartile	1.1429
10.0%		1.1236
2.5%		0.9268
0.5%		0.9268
0.0%	minimum	0.9268

Moments

Mean	1.8836714
Std Dev	1.3599005
Std Err Mean	0.3119826
upper 95% Mean	2.5391225
lower 95% Mean	1.2282204
N	19

Figure 6. HEMT aluminum mole fraction uniformity on nineteen 100 mm 4H-SiC wafers measured by XRD.

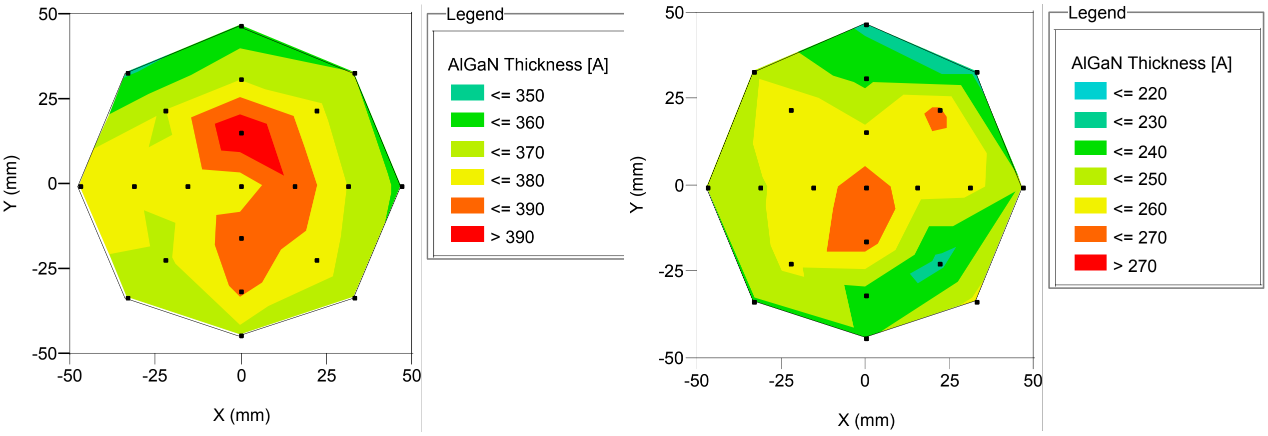
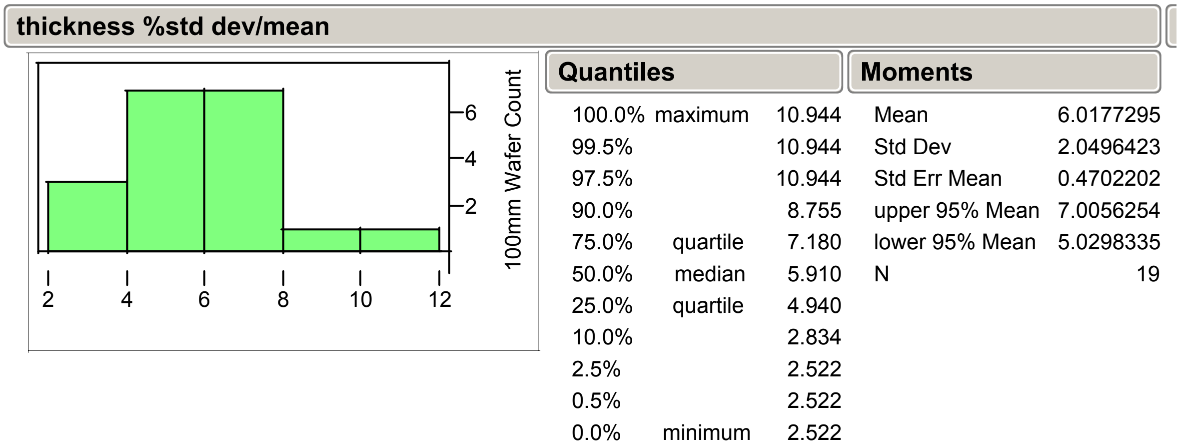


Figure 7. Thickness of the AlGaN cap layer in two III-Nitride HEMT layers grown on 100 mm HPSI 4H-SiC substrates. Each contour represents 1 nm change in thickness.



thickness %std dev/mean

Quantiles

100.0%	maximum	10.944
99.5%		10.944
97.5%		10.944
90.0%		8.755
75.0%	quartile	7.180
50.0%	median	5.910
25.0%	quartile	4.940
10.0%		2.834
2.5%		2.522
0.5%		2.522
0.0%	minimum	2.522

Moments

Mean	6.0177295
Std Dev	2.0496423
Std Err Mean	0.4702202
upper 95% Mean	7.0056254
lower 95% Mean	5.0298335
N	19

Figure 8. AlGaN thickness uniformity on 100 mm 4H-SiC wafers measured by XRD.

Grazing-incidence interferometry was used to determine the wafer shape. This shape data is plotted in Figure 9 for one of the flattest wafers, showing a bow of only 2 µm and warp of only 5 µm. Statistics of the bow and warp magnitudes for 19 wafers are shown in Figure 10 and Figure 11 respectively. The dark shaded regions are for HEMT epi with an optimized nucleation layer that typically had under 20 µm bow and warp over the 100 mm wafer.

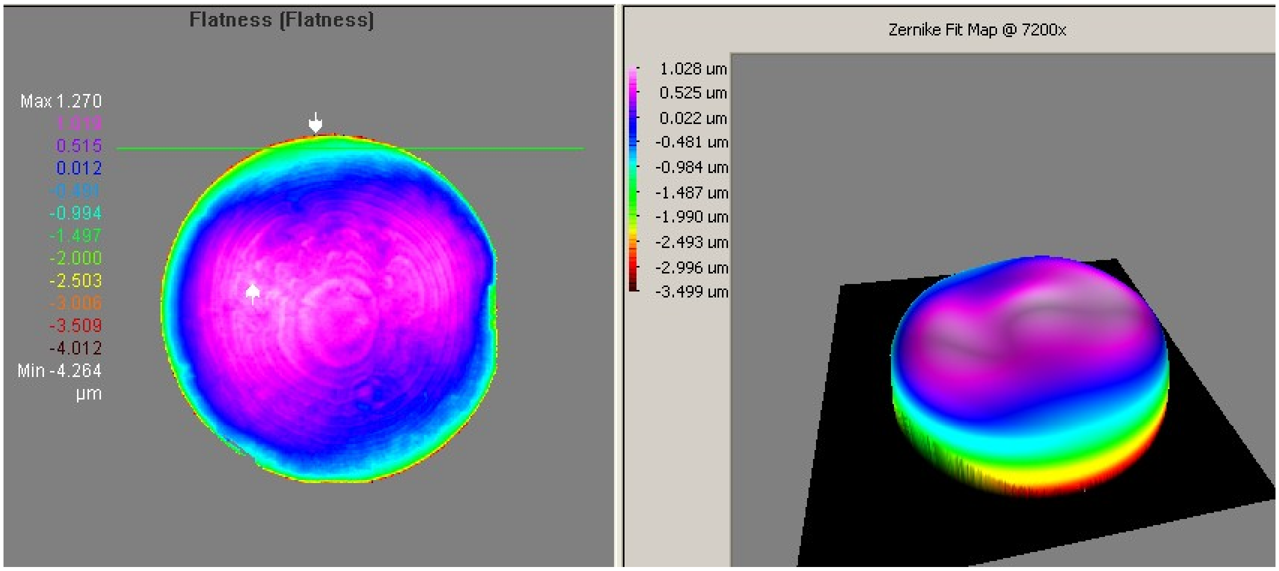
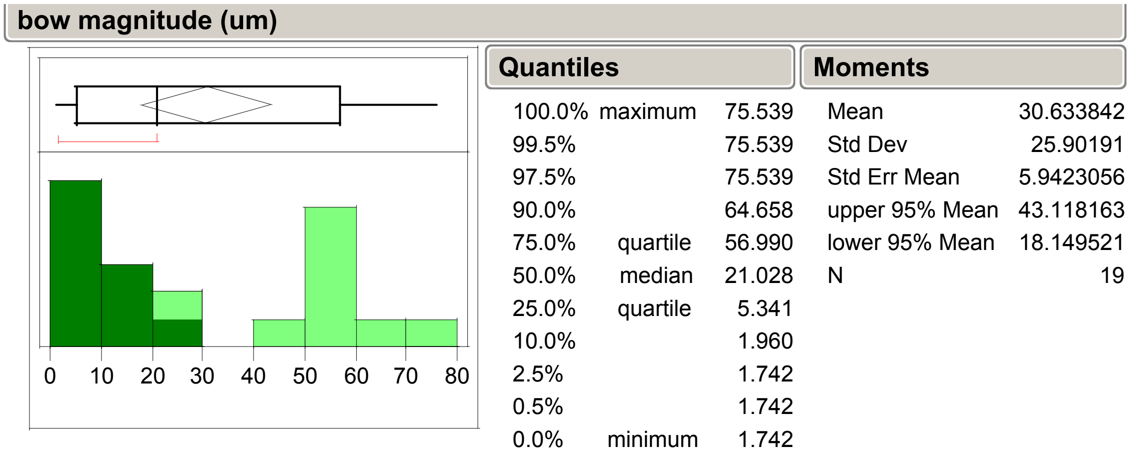


Figure 9. Wafer shape data for a III-Nitride HEMT grown on a 100 mm HPSI 4H-SiC substrate.



bow magnitude (um)

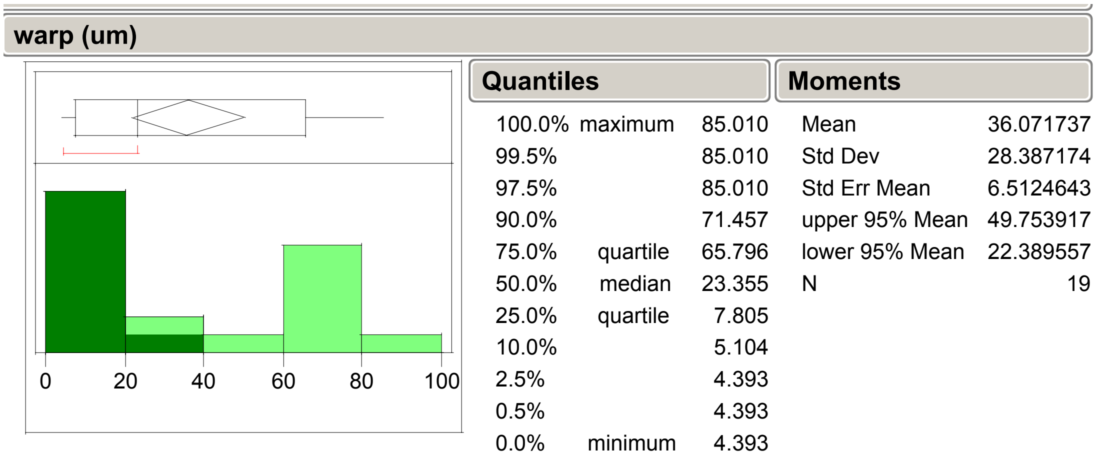
Quantiles

100.0%	maximum	75.539
99.5%		75.539
97.5%		75.539
90.0%		64.658
75.0%	quartile	56.990
50.0%	median	21.028
25.0%	quartile	5.341
10.0%		1.960
2.5%		1.742
0.5%		1.742
0.0%	minimum	1.742

Moments

Mean	30.633842
Std Dev	25.90191
Std Err Mean	5.9423056
upper 95% Mean	43.118163
lower 95% Mean	18.149521
N	19

Figure 10. Magnitude of wafer bow in µm for 19 HEMTs on 100mm HPSI 4H-SiC wafers.



warp (um)

Quantiles

100.0%	maximum	85.010
99.5%		85.010
97.5%		85.010
90.0%		71.457
75.0%	quartile	65.796
50.0%	median	23.355
25.0%	quartile	7.805
10.0%		5.104
2.5%		4.393
0.5%		4.393
0.0%	minimum	4.393

Moments

Mean	36.071737
Std Dev	28.387174
Std Err Mean	6.5124643
upper 95% Mean	49.753917
lower 95% Mean	22.389557
N	19

Figure 11. Wafer warp in µm for 19 HEMTs on 100mm HPSI 4H-SiC wafers.

CONCLUSIONS

Highly uniform, device quality III-Nitride layers were deposited by MOCVD on 100 mm diameter SiC substrates.

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REFERENCES

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[1] Y.-F. Wu, A. Saxler, M. Moore, R. P. Smith, S. Sheppard, P. M. Chavarkar, T. Wisleder, U. K. Mishra, and P. Parikh, *IEEE Elec. Dev. Lett.* **25**, 117 (2004).

[2] www.cree.com