A Statistical Study of AlGaN/GaN HEMT Uniformity with Various Buffer and Barrier Structures

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Abstract

Sheet resistance uniformity of AlGaN/GaN HEMT structures with various barrier and buffer configurations grown on 4H and 6H SiC substrates has been studied. The best uniformity, at ~1%, has been obtained from wafers with a single AlGaN barrier layer. The uniformity was degraded when capped with GaN, possibly due to deterioration in the polarization field uniformity in the AlGaN barrier with the presence of less-than-perfectly uniform GaN cap, as well as being affected by the dynamic growth condition during the GaN cap growth. The back-barrier, including InGaN and AlGaN, was found to have a positive impact on the sheet resistance uniformity, although the improvement with InGaN is statistically insignificant.

INTRODUCTION

Since the successful early development of GaN based HEMT more than a decade ago [1-4], in recent years, demands for GaN based HEMT wafers grown on SiC have been increasing continuously due to advantage of high thermal conductivity of SiC and the fact that SiC is almost lattice matched to GaN. Figure 1 shows the quantity of wafers shipped by IQE RF since 2003 normalized to the total shipment in 2003; within which different substrate sizes, substrate poly-types, buffer materials, and barrier structures have been used. In the past years, great progress has been demonstrated in improving and sustaining good wafer uniformity for production growth of AlGaN/GaN based HEMTs on SiC substrates at IQE RF. Use of AlGaN or InGaN back barrier has been proven to be effective in confining electrons in the channel and minimize short channel effect for high speed applications [5-7]. As both production volume and wafer size increase, obtaining good wafer uniformity will become more critical for maintaining high yield and low production costs. In this paper, wafer sheet resistance (R_{sh}) uniformity is taken as the figure of merit in a statistical analysis of AlGaN/GaN HEMT performance with variations in buffer materials, barrier thickness, and the use of either an AlGaN or InGaN back-barrier.

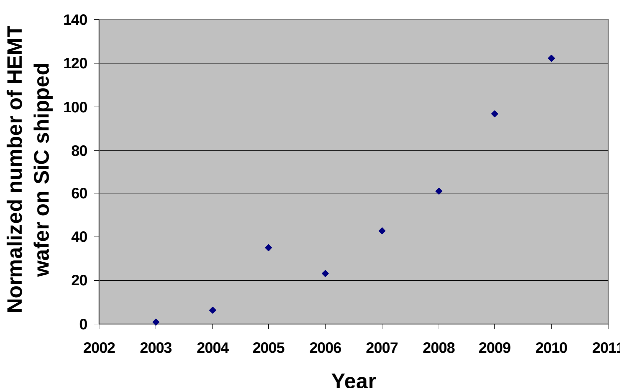

Figure 1: Normalized quantity of GaN HEMT wafers grown on SiC substrates shipped from IQE RF.

EXPERIMENTAL RESULTS AND DISCUSSION

All wafers have been grown in Veeco E300 metal-organic chemical vapor deposition (MOCVD) reactors. SiC substrates with either 4H or 6H poly-type are used. An AlN nucleation layer is grown on the SiC substrate prior to growth of either a GaN buffer or an AlGaN buffer. The AlGaN buffer also serves as a back barrier. The growth temperature for the buffer and subsequent barrier structure are greater than 1000°C. A semi-insulating buffer can be obtained by incorporation of carbon and/or Fe in the buffer. Therefore, only the two dimensional electron gas (2DEG) has significant conductivity to lower the R_{sh}, which is measured with a Lehighton Eddy current system. Average R_{sh} uniformity from 1% to 2.5% has been obtained for HEMT wafers with various barrier and buffer structures.

Little difference in R_{sh} and R_{sh} uniformity has been observed between the 4H and 6H substrates. Figure 2 shows a six wafer production run of 3" wafers on an eight wafer platter. Three 4H and three 6H SiC substrates were placed alternately. All wafers demonstrate better than 1% R_{sh} uniformity with wafer to wafer R_{sh} ranging from 414 Ω/□ to 418 Ω/□. GaN buffer crystal quality is evaluated by XRD with Ω-2ϑscans about the (002) and (102) reflections. Figure 3 shows the comparison of FWHM of the (002) and (102) scans from ~1.8 μm GaN buffer grown with same conditions on both 4H and 6H substrates. FWHM of (002) reflection is almost indistinguishable. FWHM of the (102) scan shows lower median value on 4H substrate comparing to 6H substrate, the difference is statistically significant, which is likely due to a difference in substrate thickness, which may in turn affect the subsequent growth conditions.

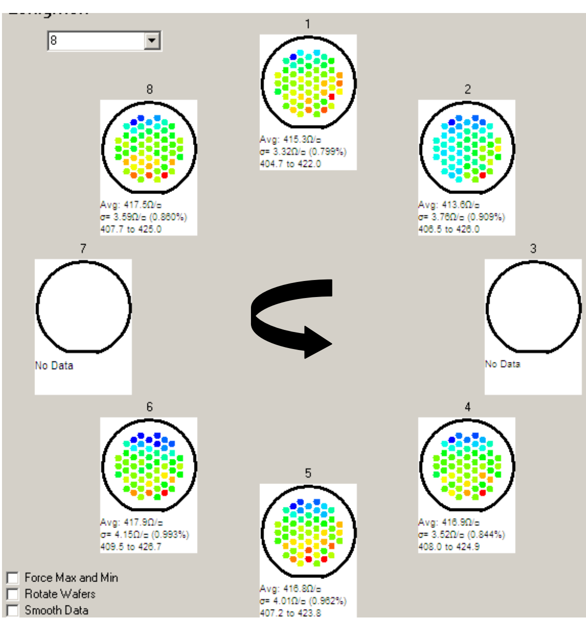

Figure 2: Rsh and Rsh uniformity from six 3" HEMT wafers grown with an 8 wafer platter.

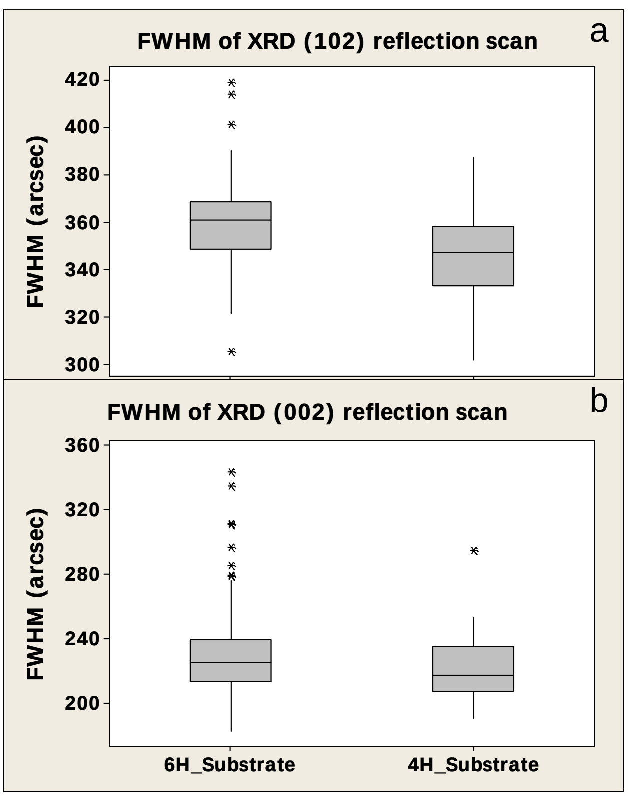

Figure 3. Comparison of FWHM of XRD taken from AlGaN/GaN HEMT wafers grown on 4H and 6H SiC substrates. a) (102) reflection scan results. b). (002) reflection scan results.

A typical GaN buffer thickness pattern from a wafer of 100 mm diameter is shown in Figure 4. The measurement was carried out by white light interference using RPM4000 photoluminescence instrument. The arrow of the profile line points to the center of the platter. This thickness profile is a characteristic signature of a Veeco E300 MOCVD system with multiple precursor gas injection zones. At 1.63%, the thickness uniformity is among the best that can be achieved from these systems at IQE RF. Historical average of the thickness uniformity is ~2.4%. Thickness uniformity of AlGaN is comparable to GaN, but with a different pattern, due to the difference in incorporation efficiency between Ga and Al.

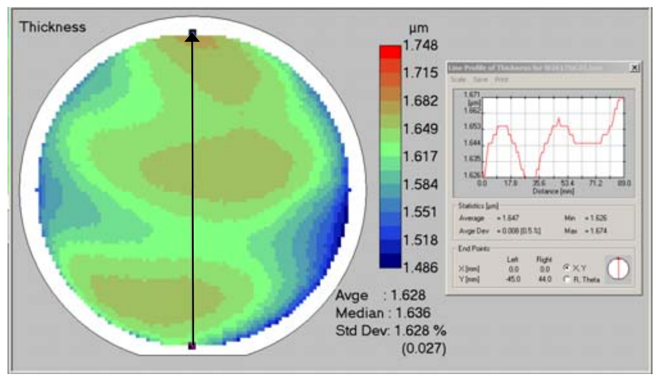

Figure 4: Total thickness pattern of GaN wafer grown on 100 mm SiC substrate in a Veeco E300 MOCVD reactor.

The barrier used in all AlGaN/GaN HEMT wafers consists of an AlGaN layer with a homogeneous Al mole fraction in the range of 24%-28%. Some wafers were also capped with a few nanometers of GaN. Both the AlGaN barrier and GaN cap are un-doped. AlGaN and InGaN back-barriers are also used in some structures. In this layer configuration an AlGaN back barrier behaves as the buffer for the structure. An InGaN back barrier acts as a pseudomorphic quantum well inserted between the GaN buffer and the GaN channel, which is also used in the AlGaN back barrier system between the buffer and barrier. The 2DEG is formed at the interface of the GaN channel and the AlGaN barrier. A detailed breakdown of the structures is shown in Table I, and the epitaxial stack is illustrated in Figure 5. As shown in Figure 6, R_{sh} uniformity distributes randomly verses the Al mole percentage of the AlGaN barrier.

Structures A to D were grown without any back-barriers, within which structures C and D were capped with GaN. A thinner AlGaN barrier is used in structure A compared to structure B, and the GaN cap thickness in structure D is ~2 nm thicker than that in structure C. AlGaN and InGaN back barriers were used in structures E and F, respectively. Sheet resistance uniformity obtained from structures A through E is shown in Figure 7. The R_{sh} uniformity data presented in Figure 7 were measured from the HEMT wafers grown on prime SiC substrates over the last few years.

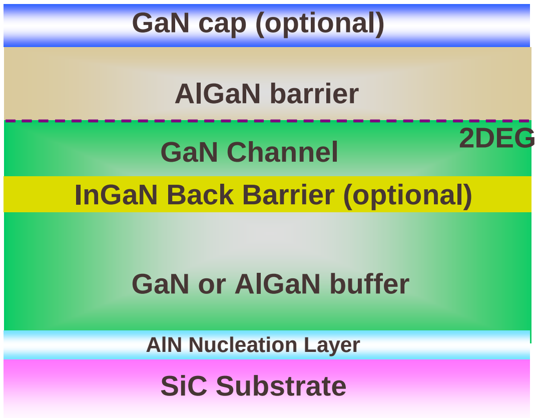

Figure 5: Epi stack of AlGaN/GaN HEMT structures grown on SiC substrate.

TABLE I

BREAKDOWN OF STRUCTURES OF ALGAN/GAN HEMTS

Structure ID	Buffer	Back-barrier	Barrier	GaN Cap
A	GaN	NA	$Al_{26}Ga_{75}N$ (~20 nm)	No
B	GaN	NA	$Al_{26}Ga_{75}N$ (~25 nm)	No
C	GaN	NA	$Al_{26}Ga_{75}N$ (~20 nm)	Yes
D	GaN	NA	$Al_{26}Ga_{73}N$ (~16 nm)	Yes
E	AlGaN	AlGaN	$Al_{30}Ga_{70}N$ (~20 nm) [a]	No
F	GaN	InGaN	$Al_{26}Ga_{75}N$ (~25 nm)	No

[a]Al percentage of the AlGaN barrier is higher in structure E comparing to structure A. The XRD (006) peak separation between the AlGaN barrier and AlGaN buffer of structure E is identical to that of structure A.

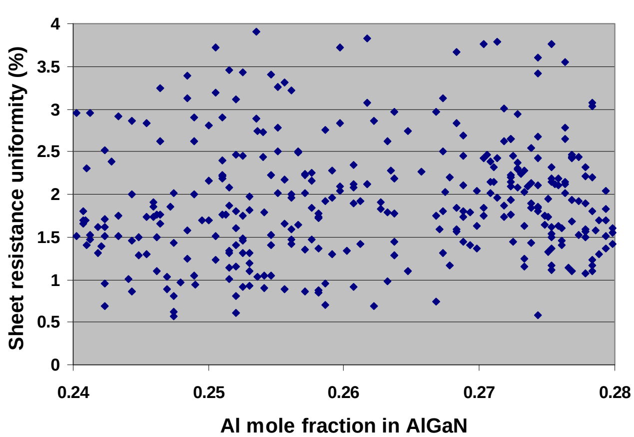

Figure 6: R_{sh} uniformity vs. Al mole percentage.

Table II shows the statistical p-values of 2-sample t-test calculated between each pair of the structures A through E listed in Table I. With a median value of 1.90%, the worst uniformity is obtained for structure C, which consisted of the thinnest AlGaN barrier and the thickest GaN cap. The best uniformities (1.07% and 1.11%) were obtained from structures A and F with the thickest AlGaN barrier. The p-value (0.446) of the t-test indicates that R_{sh} uniformity is statistically indistinguishable between structures A and F, which have the same barrier thickness, however, it should be noted that structure F contains an InGaN back barrier.

The trend of R_{sh} uniformity shown in Figure 7 (with the confident level defined by the p-values of t-test listed in Table II) indicates that the presence of a GaN cap may change the piezoelectric condition of the AlGaN barrier. The degree of non-uniformity of the GaN cap and the dynamic interaction occurred during the growth of the GaN cap could deteriorate the piezoelectric field distribution, and in turn the 2DEG charge density uniformity as well as the R_{sh} uniformity will potentially be affected. When a thicker GaN cap is grown, positive charge may accumulate at the GaN/AlGaN interface, which could also inversely affect the measured R_{sh} uniformity.

Utilizing the same barrier thickness and same amount of lattice mismatch between the barrier and buffer, wafers grown on AlGaN buffer (structure E) demonstrates statistically better uniformity than that of structure A with GaN buffer. This, along with the slightly better uniformity obtained from structure F with InGaN back-barrier, could result from better 2DEG confinement thanks to the present of the back-barriers.

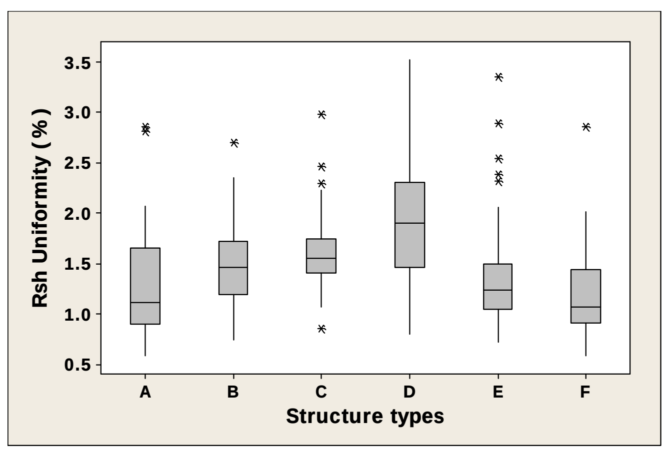

Figure 7: R_{sh} uniformity vs. epitaxial structures A to E..

TABLE II

P-VALUES OF 2-SAMPLE-T-TEST MEASURED BETWEEN THE RSH UNIFORMITY DATA SHOWN IN FIGURE 7

Structure types	A	B	C	D	E	F
A	-	0.038	0.001	0	0	0.446
B		-	0	0	0	0
C			-	0	0	0
D				-	0	0
E					-	0.074

CONCLUSIONS

Differences in sheet resistance uniformity have been observed with different buffer, barrier and cap structures. The best R_{sh} uniformity and controllability have been obtained from structures with an AlGaN barrier layer with fixed composition; independent of whether or not a back barrier is used. Structures containing a GaN cap layer show slightly degraded uniformityand it is believed to be caused by an increased of variation in the polarization states within the AlGaN layer. Other sources of R_{sh} uniformity degradation may come from change in interface and surface conditions, such as the potential interface charge resulted from an un-depleted thick GaN cap. Presence of AlGaN and possibly InGaN back barrier can improve R_{sh} uniformity thanks to the better 2DEG confinement.

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ACRONYMS

HEMT: High Electron Mobility Transistor
FWHM: Full width at half maxim