RF GaN/Si HEMT Growth Development Using Single Wafer MOCVD Technology

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Abstract

In this work we report on MOCVD growth of GaN/Si HEMTs in a single wafer technology based cluster tool, which can be deployed into high volume manufacturing. Growth processes were developed for GaN HEMTs on large size high resistivity Si substrate, up to 200mm diameter. GaN/Si HEMTs with AlGaN barrier and InAlN barrier demonstrated excellent composition and thickness uniformity. Controllable and uniform carbon doping (up to ~2E19 cm^{-3}) and iron doping of 0.1-1E18cm^{-3} with rapid turn-off characteristics (~0.4µm/decade) were achieved. Parasitic channels in MOCVD AlN nucleation samples on Si were compared to that on plasma enhanced ALD AlN and PVD AlN.

INTRODUCTION

GaN/Si HEMT are becoming more and more attractive for radio frequency (RF) applications, due to a much lower cost and improved performance.[1-3] One of the advantages of RF GaN/Si HEMTs is the availability of large size high resistivity Si substrates now in commercial market. On the other hand, it requires a MOCVD platform that is able to achieve a good uniformity of epi growth on large size wafers. In Veeco, the Propel© MOCVD reactor was developed for epitaxial III-nitride growth on large size wafers, although it can be used for various types of wafers. By using this single wafer technology based cluster tool, we developed MOCVD growth processes for GaN HEMTs on up to 200mm Si substrate. A big challenge of large wafer size epi growth is to achieve a good uniformity of composition and thickness, which is affected easily by gas flow patterns and temperature patterns. Here, GaN/Si HEMTs with an AlGaN barrier and InAlN barrier demonstrated excellent epi wafer electrical properties and uniformity. One critical part in GaN HEMT growth is a well-controlled C-doping or Fe-doping process, which will ensure a high quality buffer and provide a good RF device performance. We have developed C-doping process and Fe-doping process to demonstrate a wide range of dopant concentrations suitable for GaN HEMTs applicable to various RF devices applications.

As commonly accepted, high power amplifier efficiency over a wide bandwidth requires devices with high transconductance and low RF losses. RF loss is governed primarily by buffer quality and each portion of the buffer stack contributes to RF loss. The most important contributor to RF loss is a parasitic channel formed at the interface of AlN nucleation layer and high resistivity Si. It has been reported in literature that the parasitic channel consists of two main parts: one is a *p*-type conductive channel caused by Al/Ga diffusing into Si during epi growth and another is a free-electron inversion layer induced by the strong polarization field of AlN nucleation layer.[4,5] In this paper, we used spreading resistance profiling (SRP) to analyze the *p*-type conductive channel in structures grown on atomic layer deposition (ALD) AlN and physical vapor deposition (PVD) AlN templates, which was compared to AlN nucleation done directly on Si wafer. By comparing SRP test results, buffer RF loss data and sheet resistance values, we should be able to understand better about the effects of parasitic channel on RF GaN/Si HEMTs.

EXPERIMENTAL

The MOCVD reactor used in this work was a Veeco Propel©. Trimethylaluminum (TMAl), trimethylindium (TMIn) and trimethylgallium (TMGa) were used as group III precursors and Ammonia (NH_3) was used as the nitrogen source. AlN nucleation was grown on different templates, including ALD AlN and PVD AlN, to compare with AlN grown directly on Si wafers. GaN/Si HEMTs with AlGaN and InAlN barriers, as illustrated in Figure 1, were grown on 100mm, 150mm and 200mm high resistivity Si substrates. Various metrologies were used to characterize the MOCVD grown samples. Al compositions in barrier layers were characterized using X-ray Diffraction (XRD) (PANalytical X'Pert MRD). Sheet resistance (R_{sh}) was measured on a Lehighton 1510EC instrument. By using spreading resistance profiling (SRP) method, the *p*-type conductive channel was measured. Secondary ion mass spectrometry (SIMS) was used to measure C-doping and Fe-doping concentration profiles.

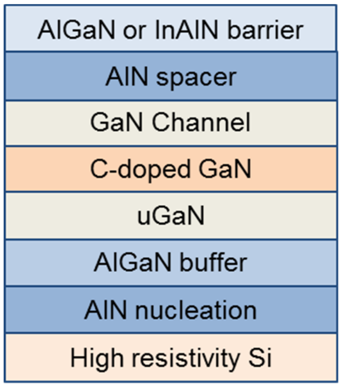

Fig. 1. Schematic diagram of GaN/Si HEMT structure with AlGaN barrier or InAlN barrier on high resistivity Si

RESULTS AND DISCUSSIONS

To evaluate the epi-layer quality of GaN/Si HEMTs on relatively large size wafers, AlGaN and InAlN barriers were grown on 200nm Si and characterized by an omega-2theta XRD measurement. As shown in Figure 2, a radial seven point cross wafer analysis demonstrated a good uniformity of Al composition and thickness of the barrier layer. The AlGaN barrier had an average Al composition of 25.25%, with a uniformity of 0.38%. The average thickness of this AlGaN barrier layer was 22 nm, with a uniformity of 1.51%.

Structures with InAlN barrier layers grown on 200mm Si substrates also demonstrated a good uniformity of composition and thickness from a seven points cross wafer XRD measurement as shown Figure 3. The average In% across these points was 16.6% with a uniformity of 1.5%. The average InAlN barrier layer thickness was 107nm, with a uniformity of 1.05%.

The full GaN/Si HEMT structure with InAlN barrier having an In composition of ~17% and grown on 200mm high resistivity Si wafer was measured by Lehighton to evaluate the electrical property of epi-wafer. A sheet resistance map, as shown in Figure 4, demonstrated an average Rsh as low as 211Ω/□ and a uniformity of 0.88%.

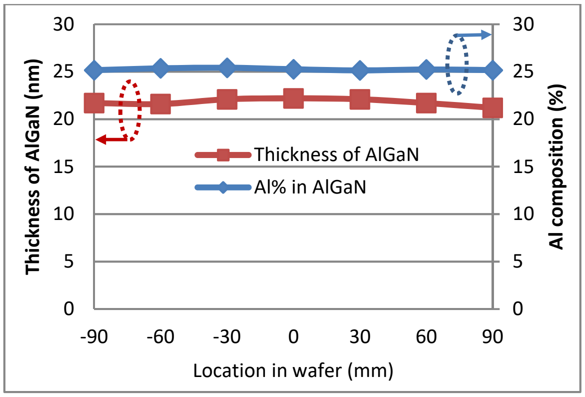

Fig. 2. Results from a seven point XRD (002) scan of AlGaN on 200mm Si: average 25.25% Al, with a uniformity of 0.38% and 22nm thickness with a uniformity of 1.51%.

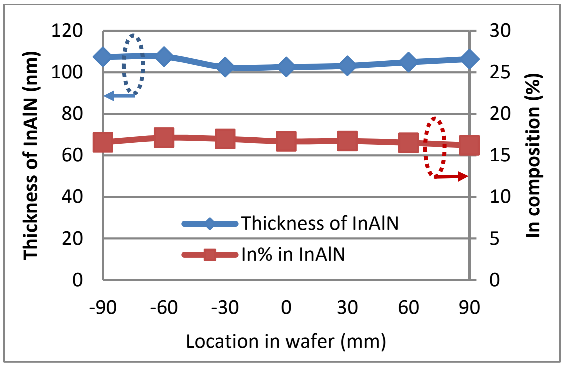

Fig. 3. Results from a seven point XRD (002) scan of InAlN on 200mm Si: average thickness of 105nm with uniformity 1.96%; average In composition 16.7%, with an uniformity of 1.67%

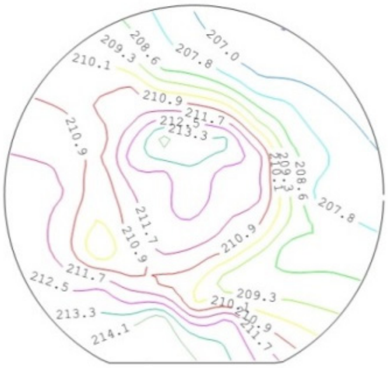

Fig. 4. GaN/Si HEMT with InAlN barrier on 200mm high resistance Si: average R_{sh} 211Ω/□, uniformity 0.88%.

Carbon doping process with internal C source was developed for the GaN/Si HEMTs having a C-doped GaN electron blocking layer and was well controlled up to 2E19cm^{-3}. Meanwhile, iron doping processes were also developed for GaN buffer growth and well controlled from 1E17 to 1E18cm^{-3} range, with a sharp decline slope of 0.4µm/decade. C-doping profile and Fe-doping profile are shown in Figure 5 and Figure 6. Furthermore, SIMS analysis also indicates that the Fe-residual is negligible, as shown in Figure 6.

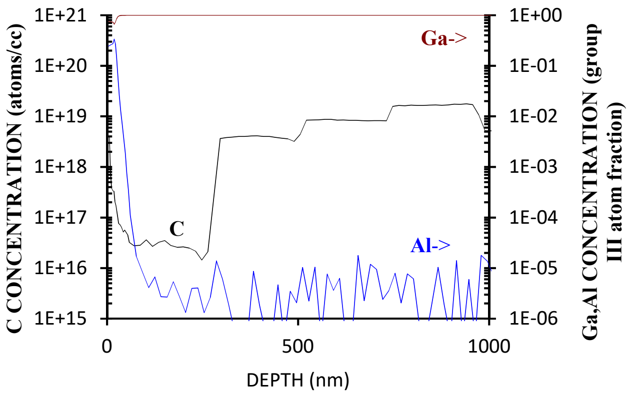

Fig. 5 SIMS analysis on staircase C-doping profile, demonstrating C concentration in 0.3-2E19cm^{-3} range

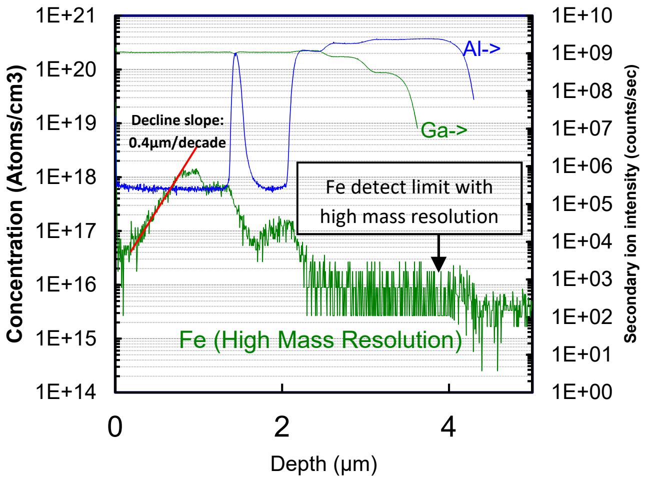

Fig. 6 SIMS profile of Fe in GaN, demonstrating a well-controlled doping level in 0.1-1E18cm^{-3}, with a sharp decline slope of 0.4µm/decade, and that Fe concentration in AlN nucleation and AlGaN buffer under detection limit.

Parasitic channel formed at the interface of AlN layer and Si substrate has been considered as a large contribution to the RF loss of GaN/Si HEMT. To explore methods to suppress parasitic channel, we used SRP to analyze parasitic channel in AlN nucleation samples grown on Kyma PVD AlN template (Sample A), on NRL ALD AlN template (Sample B) and on Si with different conditions (Sample C and D). SRP profiles were illustrated in Figure 7. The channel thickness and *p*-type carrier concentration were summarized in Table I.

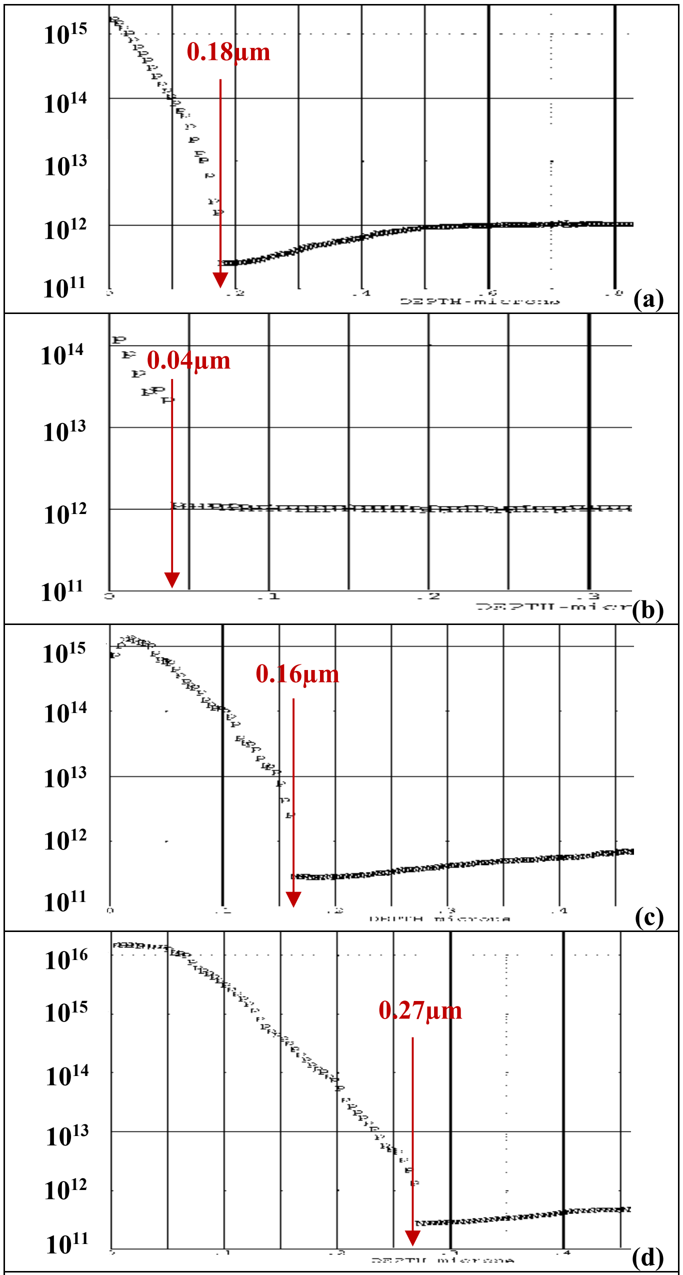

Fig. 7 *p*-channel depth and carrier concentration of AlN nucleation on (a) 200nm PVD AlN, (b) 100nm ALD AlN, (c) Si and (d) Si with modified growth condition.

TABLE I

P- CHANNEL DEPTH AND *P*-TYPE CARRIER CONCENTRATION BY SRP AND SHEET RESISTANCE BY LEHIGHTON

SRP Sample	A	B	C	D
p-channel depth (μm)	0.18	0.04	0.16	0.27
p-carrier conc. (cm^{-3})	2.0E+15	1.0E+14	1.3E+15	1.5E+16
Ave Rsh (Ω/□)	4566	4982	2301	15208

A	HR-Si/200nmPVD-AlN/100nmAlN
B	HR-Si/100nmALD-AlN/100nmAlN
C	HR-Si/100nmAlN
D	HR-Si/100nm HLH-AlN

It is interesting to see that although the integrated areas formed by depth and carrier concentration in Sample A and B from Figure 7(a) and (b) are very different, measured R_{sh} values are close. On the other hand, the integrated areas in Sample A and C are of the same order; however, R_{sh} of Sample C is only a half of A. Compared to Sample C, Sample D has a much larger *p*-type region. However, R_{sh} value of D is much higher than that of C, indicating a total Eddy current in D is significantly lower than that in C. As being discussed in [4] and [5], a free-electron inversion layer exists between Si substrate and AlN nucleation layer due to the strong polarization property of AlN crystal structure. Besides the *p*-type channel layer, this inversion layer significantly affects the materials electrical property and one would expect that the Eddy current would be affected, too. In sample D, by using a modified AlN nucleation growth process with high-low-high growth temperatures, similar to Luong *et al.* [4], the Eddy current caused by inversion layer was obviously reduced, resulting in an increased R_{sh}.

Based on the above established AlN nucleation processes, a set of GaN/Si buffer samples which contains AlN/AlGaN/uGaN/C-GaN/uGaN were grown, as listed in Table II, and measured in Lehighton to characterize the electrical property. It can be seen that the R_{sh} value of buffer sample D+ (with high-low-high temperature MOCVD AlN nucleation) is similar to that with PVD AlN, indicating A+ and D+ have a similar electrical characteristics. A clear increase of R_{sh} value from sample C+, D+ to E indicates that the parasitic channel in GaN/Si buffer can be significantly suppressed by modifying MOCVD AlN nucleation process and buffer layer process. Next, it would be useful to test the RF loss of these GaN/Si buffer samples to find out the correlation of RF loss, parasitic channel and sheet resistance. This work is currently in progress.

TABLE II

GaN/Si BUFFER SAMPLES AND R_{sh} BY LEHIGHTON

Buffer Sample	A+	C+	D+	E
Description	Buffer on Sample A	Buffer on Sample C	Buffer on Sample D	modified Buffer on Sample D
Rsh (Ω/□)	4493	2437	4759	6648

CONCLUSIONS

MOCVD growth processes of GaN/Si HEMTs for RF application were developed. High composition uniformity and thickness uniformity were achieved in GaN/Si HEMTs with AlGaN and InAlN barriers. Besides Al/Ga diffusion caused *p*-type conductive channel, the AlN polarization induced free-electron inversion layer plays an important role in parasitic channel. By modifying AlN nucleation growth process, inversion layer contribution can be suppressed tremendously, hence improving the epi wafer electrical properties.

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