4-inch GaN HEMT Epiwafers with less Wafer Bow

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Abstract

Feasibility study to reduce the bow of large diameter GaN HEMT epiwafers on sapphire substrates was performed. The warp of 4-inch GaN HEMT epiwafer including coalescence-promoted buffer layer by MOVPE was reduced to no more than 22.7 μm. Despite the thin buffer layers, high electron mobility of 1,457 cm^2/Vs and 436.1 Ohm/sq. sheet resistance was achieved in the developed sample. Prevention of facet formation at the initial stage of the buffer process by applying high temperature coalescence-promoted growth is responsible for the decent electrical characteristics.

INTRODUCTION

GaN HEMT, as the next generation RF power devices, receives much attention in compound semiconductor industry because of its excellent high power handling capability in high frequency operations [1-2]. To mass-produce GaN HEMT devices using existent GaAs conventional process lines, 4-inch or larger wafer diameter is favorable. However, the problem of wafer bow, which originates from the difference in thermal expansion coefficient between GaN epitaxial layer and sapphire or SiC substrates, becomes much more serious in larger diameter wafers. The wafer bow will deteriorate the contact between the substrates and the equipment stages or the susceptors during device process, which leads to degradation in the device uniformity or failures in lithography. Thus, prevention of the wafer bow is indispensable. There are some circumventions for the bow, insertion of low temperature interlayer to un-GaN buffer layer, e.g. But we believe that these methods could produce leak pass in the epi structure, and therefore would not be the best solution to this problem. To control the wafer bow intrinsically, we have to reduce the total AlGaN/GaN thickness as much as possible.

Hetero epitaxial GaN layers usually contain high density of defects, vacancies or impurities especially at several hundreds nanometer region from the epi / substrate interfaces, and therefore electrical properties of GaN HEMT epiwafer with thin buffer layer are strongly affected and deteriorated by these crystal imperfections. Facet formation, which occurs during island growth at initial GaN buffer process before coalescence, is thought to be the cause for these defects. In order to obtain decent un-GaN quality for electron device on thin buffer layers with less wafer bow, we have to promote coalescence of nucleuses to prevent facet formation.

In this paper, we describe optimization in MOVPE growth condition for the initial stage of high temperature nitride buffer growth after nucleation. Achievements in the bow reduction and electrical characteristics of 3-inch and 4-inch GaN HEMT epiwafers will be reported also.

EXPERIMENTAL

The bow of GaN epiwafer on sapphire substrates, as a function of layer thickness, was calculated first so that we could design wafer contour to meet specifications. The calculation was based on a simple elastodynamic model referring bimetal structure [3], applying equation (1);

$$h = -\frac{3}{4}\cdot\frac{E_{epi}}{E_{sub}}\cdot\frac{t_{epi}}{t_{sub}}\cdot\left(a_{sub} - a_{epi}\right)\cdot l^2\cdot\Delta T \qquad (1)$$

where h is the bow, E_{epi} and E_{sub} are the Young's modulus, t_{epi} and t_{sub} are thickness, α_{sub} and α_{epi} are the thermal expansion coefficient of epilayer and substrate, *l* is the wafer diameter, ΔT is the difference between the growth temperature and the room temperature. Parameters used for the calculation are as the followings; thermal expansion coefficient of GaN (5.59x10^{-6} K^{-1}) and sapphire (8.35x10^{-6} K^{-1}), Young's modulus of GaN (150 GPa) and sapphire (470 GPa), and ΔT is 1,000 ℃.

Epitaxial growth of GaN HEMT wafers was performed in vertical flow low pressure MOVPE reactor. Hydrogen was chosen as main carrier gas, and ammonia, TMG, TMA, TMI were used as material sources. Epi-ready single-side polished c-plane sapphires of 3-inch and 4-inch diameter were used as substrates. Epiwafers with 0.8 μm, 1.3 μm, and 2.3 μm buffer layers on 3-inch substrates, and with 1.0 μm buffer on 4-inch substrate were prepared for bow, mobility and sheet resistance characterization. The depositions were started with formation of nucleation layer on sapphire at 530 ℃, followed by growth of high temperature buffer layers. Unintentionally

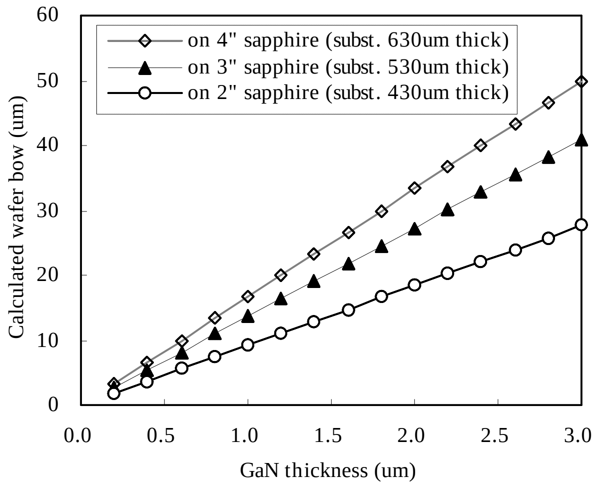

Fig. 1. Calculated wafer bow of GaN epitaxial layers on sapphire substrates as a function of GaN thickness. Substrate thickness of 430 um, 530 um and 630 um are chosen for 2", 3" and 4" sapphire wafers, respectively.

doped AlGaN / GaN HEMT structures were deposited on the buffer layer to yield 2DEG at the interfaces. Reflectivity of epi surface was observed in-situ by interferometer, and the state of surface re-construction was estimated from its transient. Mercury probe C-V measurement was carried out to evaluate 2DEG depth profile in the wafer. The bow of the wafers was characterized with Corning Tropel FM200Wafer system. Sheet resistance mapping data was taken by non-contact characterization system of Lehighton. The electron mobility measurement was also performed by non-contact method.

RESULTS AND DISCUSSION

Figure 1 shows calculated wafer bow of GaN epilayers on sapphire substrate. Substrate thicknesses, that are one of the influential parameters in the calculation, are set to 430 μm, 530 μm and 630 μm for 2, 3 and 4-inch sapphire wafers, respectively. The bow is simply proportional to the GaN buffer thickness. 2-inch GaN wafer with typical thickness of 2 μm shows roughly 20 μm bow. At the same GaN thickness, 3 and 4-inch wafer bowed no less than 25 μm and 35 μm. Supposing that 20 μm is the acceptable maximum wafer bow, referring to the 2-inch wafer, buffer thickness is limited to 1.5 μm and 1 μm for 3 and 4-inch substrates, respectively.

However, to simply reduce the GaN buffer thickness really affects and deteriorates electrical performances of HEMT structures. Figure 2 (dashed line) shows carrier depth profile in GaN HEMT epi structures using conventional buffer growth sequences. It is noticed that buried charge layer exists at epi / substrate interface in the profile. The facet formation at initial growth of un-GaN is thought to be responsible for the charge generation. If the 2DEG is located close to the interface charge in thin buffer structure, the charge would seriously deteriorate the electron transport in the structure. The pinch-off or the isolation behavior of the devices might also be affected. Thus the charge should be controlled by appropriate process conditions for the initial layers in the thin buffer. The facet formation at initial growth of un-GaN caused another disadvantage. Figure 3 (a) shows reflectivity transient of conventional GaN MOVPE growth, which is conventionally applied to grow epilayers for GaN optical devices (LED and LD, e.g.) and is useful to reduce dislocation densities. Reduced reflectivity in this process sequences after nucleation implies rough surface morphology of three dimensional island growth, i.e. facet formation at this thickness region. Electron conduction in horizontal direction in such thin layer is strongly scattered by grain boundaries and thus mobility, which contribute to transport property in HEMT, is largely deteriorated.

In order to solve the abovementioned problems and

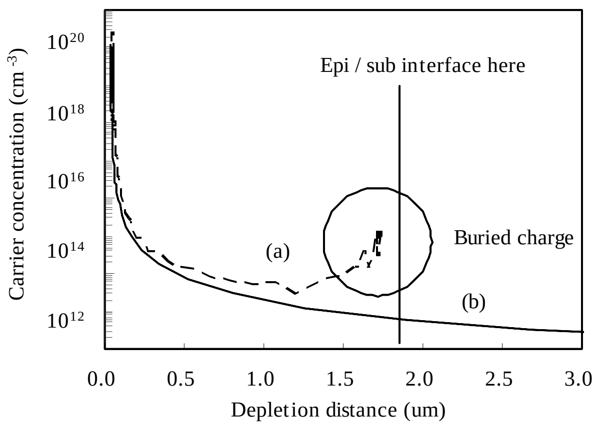

Fig. 2. Carrier concentration depth profile in GaN HEMT epilayers, measured by C-V method. Sample (a) was grown by conventional process sequence, whereas sample (b) was grown using coalescence-promoted technique.

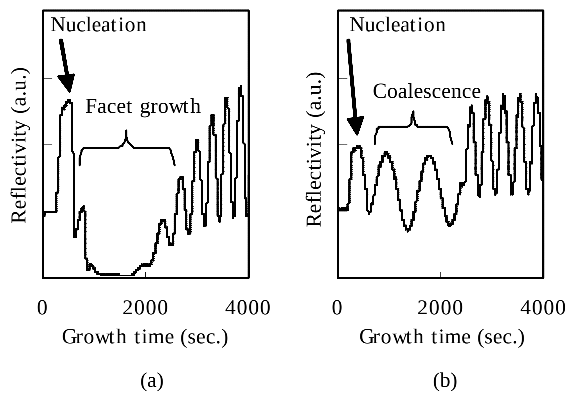

Fig. 3. Reflectivity transients for nucleation and initial growth of GaN layers on GaN HEMT epiwafers, taken in site by interferometer for (a) conventional process condition, (b) coalescence-promoted growth.

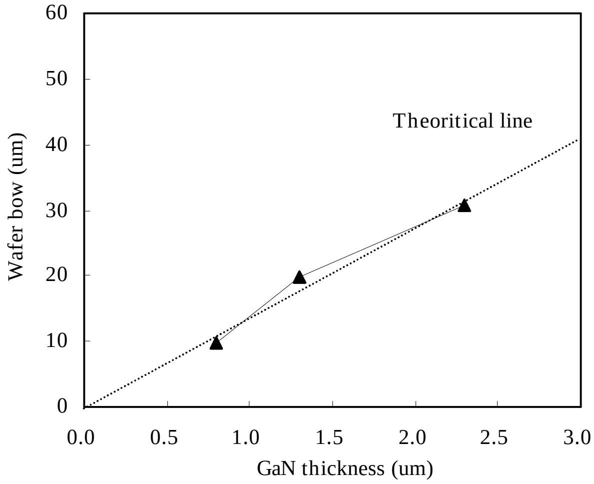

Fig. 4. 3-inch GaN HEMT wafer bow as a function o fGaN buffer thickness derived by Tropel FM200Wafer system measurements.

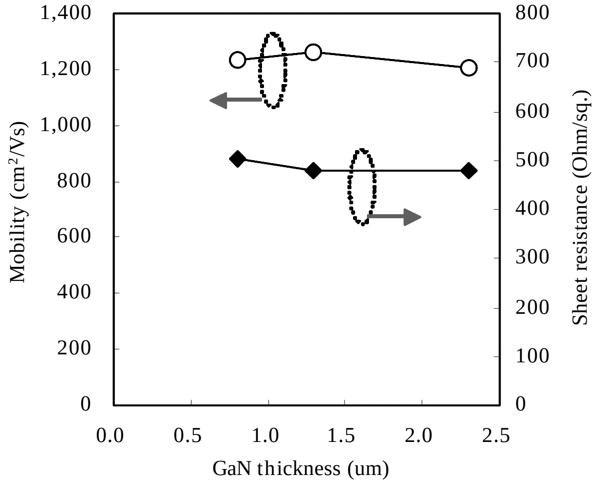

Fig. 5. Mobility and sheet resistance in 3-inch GaN HEMT epiwafers.

obtain decent un-GaN quality for electron device with thin buffer layers, we have to promote coalescence of nucleuses and prevent facet formation at initial buffer growth. Our idea is that the initial nitride layers should be grown at higher temperature so that precursors migrate efficiently to promote coalescence. Regarding the high temperature, the GaN decomposition and re-evaporation becomes dominant at temperature over 1,100℃. Thus we invented unique structural and compositional control of the group-III nitrides so that it could prevent decomposition of the nitride layers at such high temperature. Figure 3 (b) shows reflectivity transient of the “coalescence-promoted” buffer growth. The oscillation kept constant maximum intensity from the beginning of buffer sequence, indicating that 2 dimensional growth of the layers was performed. In figure 2 (solid line), no residual carrier at the epi / substrate interface was observed in the developed sample by eliminating facet growth.

Figure 4 shows the measured wafer bow of 3-inch GaN HEMT epiwafers with varying buffer thickness, grown by the coalescence-promoted method. It is noticed that the actual bow values are almost comparable to that of the theoretical ones in Fig.1, although original warp in sapphire substrate could affect consequential total bow. Less than 20um bow could be achieved when GaN thickness is thinner than 1.3 um as is estimated by the calculation. Figure 5 shows electron mobility and sheet resistance in the three 3-inch HEMT epiwafers, again with varying buffer thickness. Even at buffer thickness of less than 1 µm, 2DEG properties were not affected by the thinness of the buffer with the coalescence-promoted method.

The wafer bow of 4-inch GaN HEMT with 1um buffer

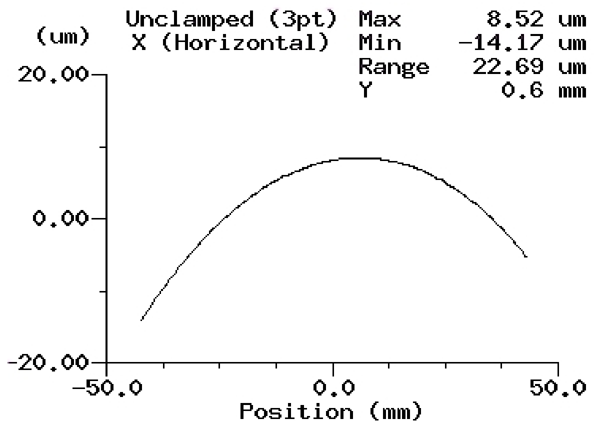

Fig. 6. Cross sectional image of the bow measurement for the 4-inch GaN HEMT epiwafer on sapphire substrate.

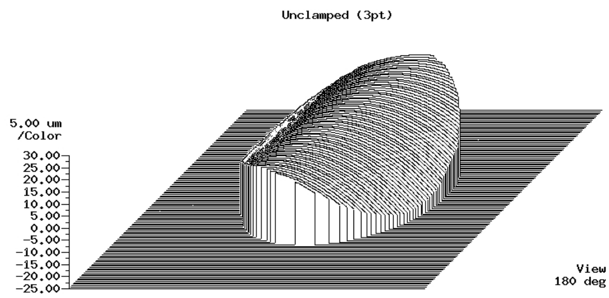

Fig. 7. 3D wafer couture image of 4-inch GaN HEMT epiwafer on sapphire substrate.

Number of points	:	190
Average measurement	:	436.1 ohm/sq.
Max. value	:	461.1 ohm/sq.
Min. value	:	424.6 ohm/sq.
Variation in measurement	:	8.374 %
Std. dev. from average	:	9.41 ohm/sq.
Uniformity of wafer	:	2.15 %

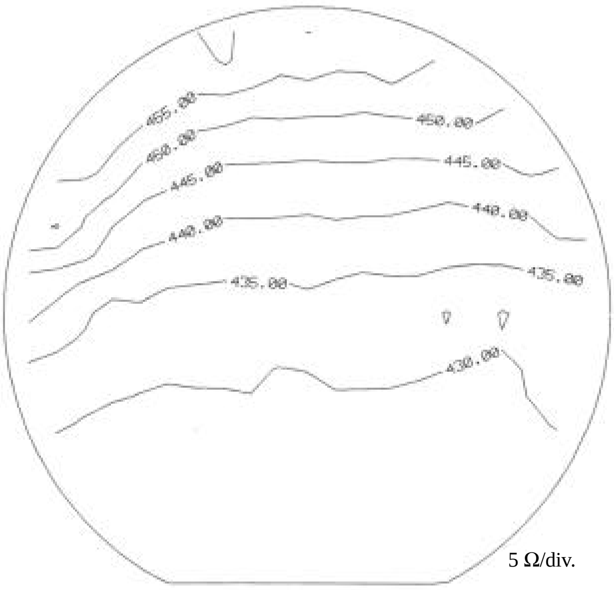

Fig. 8. Sheet resistance mapping of 4-inch GaN HEMT epiwafer.

thickness is shown Fig. 6 (cross section). and Fig. 7 (3D contour). Actual wafer bow was 22.7 µm, as is also estimated from the calculation, which could suffice our bow suppression target to bring the warp of large diameter wafers into that of typical 2-inch wafer's value. Sheet resistance mapping of the GaN HEMT wafer is shown in Fig. 8. Average measurement value of 436.1 Ohm/sq. with 9.41 Ohm/sq. standard deviation form the average was obtained in the measurement, showing supreme resistance uniformity across the 4-inch diameter. Electron mobility was also measured by non-contact method and as high as 1,457 cm^2/Vs was achieved at room temperature, indicating that the coalescence-promoted growth could remove negative effect of initial un-GaN layer onto the carrier transport property in HEMT structure. These results show that our coalescence-promoted technique can reduce the bow of GaN HEMT epiwafer without sacrificing proper electrical characteristics on thin buffer layers.

CONCLUSIONS

In summery, we made structural and compositional modification on high temperature nitride buffer layers in MOVPE grown GaN HEMT epiwafers so that we could achieve both less bow and decent electrical characteristics on large diameters. Our coalescence-promoted technique realized no more than 22.7 µm wafer bow, reasonable electron mobility of 1,457 cm^2/Vs and 436.1 Ohm/sq. sheet resistance with excellent uniformity on 4-inch GaN HEMT epiwafer on sapphire substrate. We are confident that these results could help to utilize the matured 4-inch GaAs process for GaN device productions.

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ACRONYMS

GaN: Gallium Nitride
HEMT: High Electron Mobility Transistor
MOVPE: Metal Organic Vapor Phase Epitaxy
TMG: TriMethyl Gallium
TMA: TriMethyl Aluminum
TMI: TriMethyl Indium
C-V: Capacitance-Voltage
2DEG: 2-Dimensional Electron Gas