Improvement of Substrate Related Uniformity of AlGaN/GaN HEMT Epi Wafers on ϕ3" Sapphire and SiC Substrates Grown by Multi-charged Large MOVPE Reactor

Takeshi Tanaka[1)], Yoshiharu Koji[2)], Takeshi Meguro[3)] and Yohei Otoki[2)]

[1)] Compound Semiconductor Dept., Materials Technology Research Center, Hitachi Cable, Ltd.
[2)] Semiconductor Engineering Dept., Takasago Works, Hitachi Cable, Ltd.
[3)] Semiconductor Production Dept., Takasago Works, Hitachi Cable, Ltd.
Isagozawa 880, Hitachi City, Ibaraki, Japan
Phone: +81-294-42-5071 / Fax: +81-294-42-6410 / Email: tanaka.takeshi@hitachi-cable.co.jp

Keywords: …Epitaxy, AlGaN, GaN, HEMT, MOVPE

Abstract

Feasibility study on growth of uniform AlGaN/GaN HEMT epi wafers in a multi-charged MOVPE system was performed. Modification on the contact of sapphire substrates with the system susceptor had a significant effect on controlling a factor that dominates the trend of sheet resistance variation. Multiple 3-inch HEMT epi growth was carried out and sheet resistance uniformity of less than 1% (sigma/average) was achieved.

INTRODUCTION

Because of supreme inherent physical properties of gallium nitride, AlGaN/GaN HEMTs are promising candidates for high frequency power amplifiers in devices for future wireless communication system. Most of the works of HEMTs are performed on 2-inch epitaxial wafers until recently, and lack of reproducible large diameter GaN materials at reasonable cost has kept the HEMTs in a research and development stage. In order to make the matured GaAs MMIC manufacturing technology applicable to GaN, at least 3-4 inches of diameter substrates grown with large scale multi-charged crystal growth equipments will be demanded. Thus, our project here is to achieve a stable GaN epi wafer manufacturing process and improve uniformity of epi properties on large diameter substrates to show the mass productivity of AlGaN/GaN HEMT epi wafers.

BACKGROUND

Limited process condition of AlGaN/GaN epi layers explains the difficulties in scaling up the MOVPE system. Around 1,000 degree centigrade susceptor temperature is demanded for high quality AlGaN/GaN structure growth to effectively decompose ammonia gas into active nitrogen hydrate. On the other hand, small fluctuation of temperature causes significant changes in growth rate and compositional ratio of AlGaN layer [1], which leads to huge variations in device performances of the HEMTs. Thus, in order to achieve high uniformity on the wafers in multi-charged MOVPE reactors, controlling heater and susceptor balance is one of the most crucial issues. Another uniformity issue will appear if wafer size is expanded from 2-inch to 3 or 4 inches; controlling actual temperature of the wafer surface. MOVPE growth of GaN uses purified hydrogen as a carrier gas to supply precursors in a contamination-free atmosphere. Hydrogen is known to have higher thermal conductivity and higher heat capacity than any other gases. For example, 16.82×10^{-2} $Wm^{-1}K^{-1}$ thermal conductivity of hydrogen is more than seven times higher than that of nitrogen (2.40×10^{-2} $Wm^{-1}K^{-1}$) or ammonia (2.18×10^{-2} $Wm^{-1}K^{-1}$), while 14.32×10^{3} $JKg^{-1}K^{-1}$ heat capacity of hydrogen is thirteen times higher than that of nitrogen (1.04×10^{3} $JKg^{-1}K^{-1}$). Thus, once wafers are exposed to source gases diluted with hydrogen, heat of the wafer surface is immediately taken by the gases. This effect causes temperature gradient inside the substrates, which sometimes degrades the flatness of the wafer, leading to loss of temperature uniformity on the wafer surface. The above mentioned two problems have to be overcome in order to achieve sufficient uniformity of AlGaN/GaN HEMT epi wafers on large diameter substrates. Additionally, if you use SiC as substrates, the existence of foreign polytypes, micropipes and other crystal defects on the substrates affect the uniformity also. Thus precise wafer inspection prior to the epi growth is definitely necessary to achieve high uniformity on SiC substrate.

EXPERIMENTAL

The MOVPE system used in this study has low pressure vertical gas flow configuration with the capability of handling multiple 2, 3 and 4 inches wafers. Susceptor of the system was heated by concentric three-zone tungsten heater and the surface temperature was calibrated using four pyrometers. Use of the pyrometers ensures thermal uniformity across the whole susceptor. Hydrogen was chosen as the main carrier gas, and ammonia, TMGa, TMAl were used as material sources. Epi-ready single-side polished c-plane sapphires were mainly used as substrates. The depositions were started by the formation of nucleation layer on sapphire at 530 °C, followed by the growth of high-resistive buffer layer at high temperature. Unintentionally doped AlGaN/GaN HEMT structures were deposited on the high-resistive buffer layer to yield two dimensional electron gases at the interfaces. Sheet resistance mapping data was

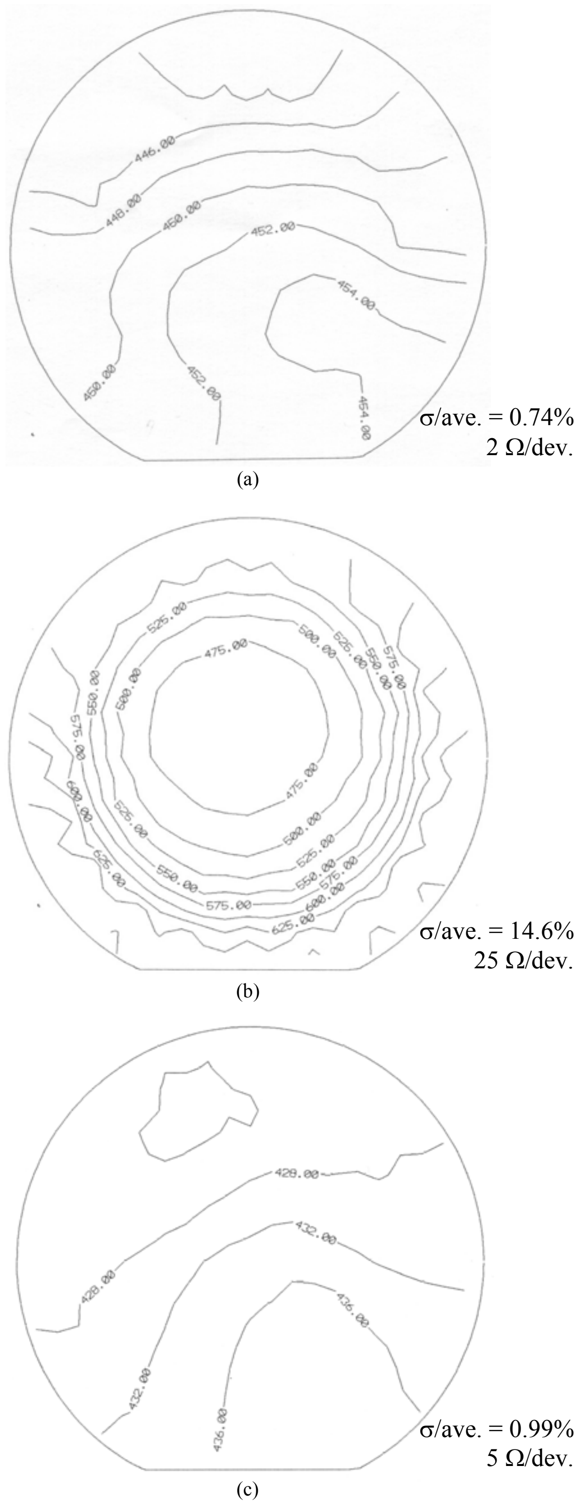


Figure 1. Sheet resistance mapping of AlGaN/GaN HEMT epi wafers grown on (a) ϕ 2 inch substrate at initial condition (b) ϕ 3 inch substrate at initial condition, and (c) ϕ 3 inch substrate at modified condition.

taken by non-contact characterization system of Lehighton. AlGaN compositional and thickness variation was analyzed from XRD rocking curve data. Mercury probe C-V measurement was carried out to evaluate the variation of 2DEG depth profile in the wafers. Electron mobility and sheet carrier concentration were characterized by the Van der Pauw method with Ti/Al Ohmic contact metallization. A semi-insulating SiC wafer was also used as a substrate for the same AlGaN/GaN epi growth process for applicability study, and its surface morphology was characterized by an optical surface analyzer.

RESULTS AND DISCUSSION

Sheet resistance mapping of 2 inch AlGaN/GaN HEMT epi wafer obtained in our initial growth experiment is shown in figure 1.(a). Because 2DEG was formed by piezo-electric effect and spontaneous polarization of coherent AlGaN layer in AlGaN/GaN HEMT structure, it can be understood that the variation of the sheet resistance is caused by the fluctuation of aluminum composition and the thickness of AlGaN layer. Variation of sheet resistance on 2 inch HEMT wafer is fairly sufficient and showed 0.74 % uniformity (sigma/average). Resistance map had a small trend vertically toward orientational flat. The flats of the wafers were directed to the periphery of the susceptor in our system, thus the trend was estimated to be caused by balancing of three-zone heater settings or gas flow effect. Sheet resistance mapping of 3 inch AlGaN/GaN HEMT epi wafer, which was grown at the same growth condition of 2 inch wafer, is shown in figure 1.(b). The uniformity of the resistance on the 3 inch HEMT wafer, on the other hand, was 14.6% (sigma/average) with the lowest value at the center of the wafer. It is noticed that scaling up the wafer diameter not only degraded its uniformity, but also changed the trend of variation across the wafer. Because the concentric trend on 3 inch wafer does not relate to the heater contour, precursor gas stream or any other physical or mechanical parts in the system, it seemed that the substrate itself had a huge temperature variation with concentric direction. Here, we reckoned that large diameter wafers are quite vulnerable to temperature gradient caused by hydrogen gas flow. We assume that the substrate with vertical temperature difference will receive thermal stress and thus will be bent to lose its flatness. Consequently, O-shaped area of the wafer lost close contact between the susceptor surfaces, leading to poor uniformity in the surface temperature of the substrate. Based on this experimental results and assumptions, we made modification in the method of contact of wafers with the susceptor to keep the surface temperature of the wafers uniform. Figure 1(c) shows sheet resistance mapping of 3 inch AlGaN/GaN HEMT epi wafer after this modification. The uniformity was significantly improved to less than 1% (sigma/average), with an average sheet resistance of 431.2Ω/sq. It seemed that surface temperature was flattened across the wafer after this modification. It was also noticed that the resistance map started to form a trend vertically toward orientational flat, which was actually the heater balancing direction. We understand that this result shows the feasibility of controlling the factor that dominates the

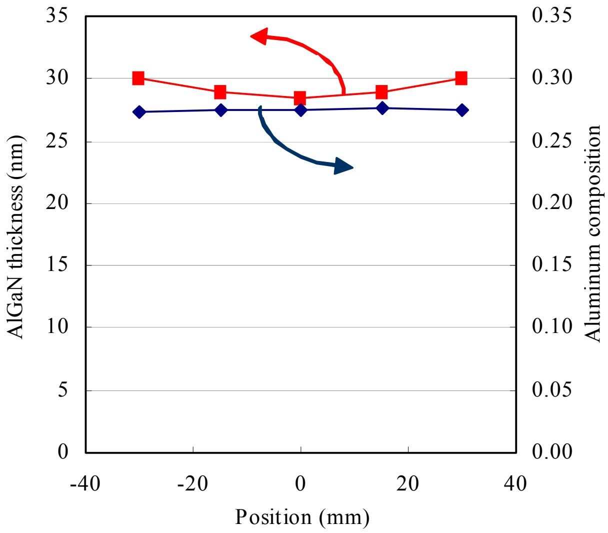


Figure 2. Thickness and aluminum composition variation of AlGaN layer on 3 inch HEMT epi wafer characterized using XRD.

uniformity trend of the AlGaN/GaN HEMT epi wafers using our method. The balancing could be adjustable with more attention on temperature calibration, thus we still have room to improve the uniformity. Figure 2 shows the thickness and aluminum composition variation across the uniformity-improved 3 inch AlGaN/GaN HEMT wafer. Aluminum composition was 0.275 ± 0.002 range and AlGaN thickness was 29.25 ± 0.75 nm. This flat AlGaN structure with high quality un-GaN and high-resistive buffer layers explains the high uniformity of sheet resistance of the wafer. Carrier depth profile at the AlGaN/GaN interface in the wafer is

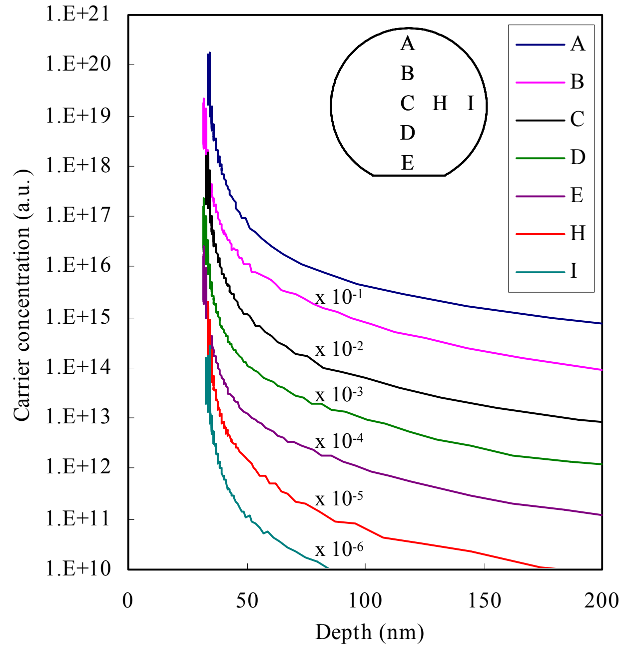
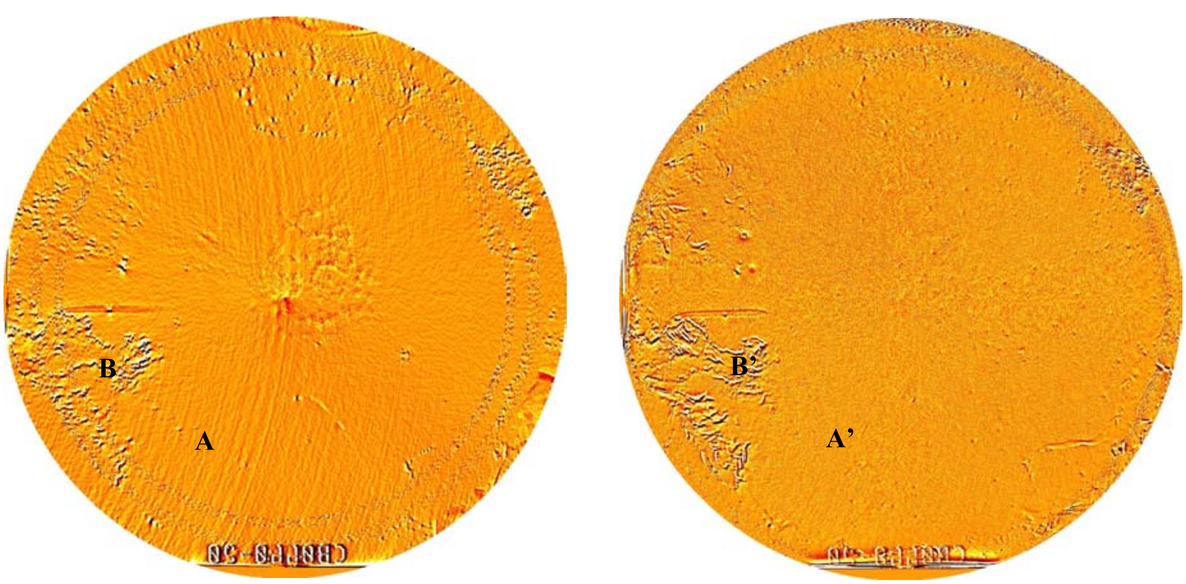


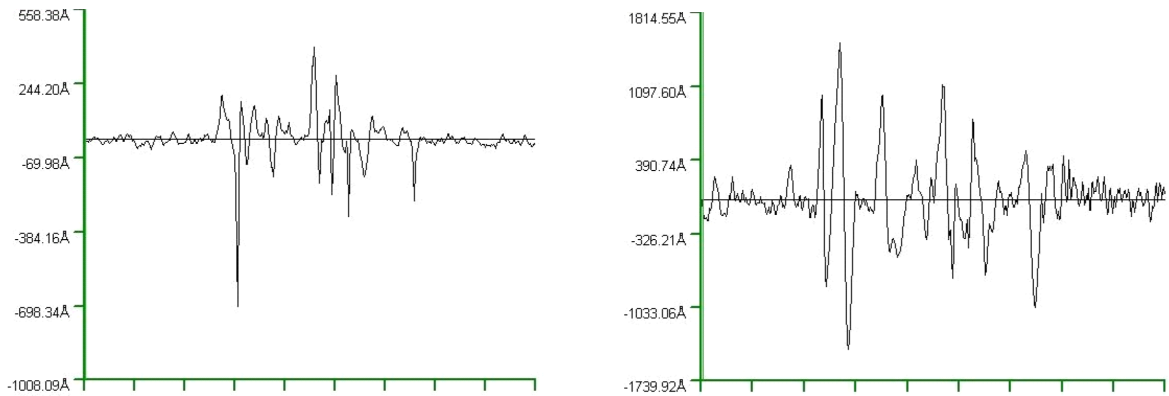
Figure 3. Carrier depth profile of 3 inch AlGaN/GaN HEMT epi wafer measured by C-V method.

shown in figure 3. Because of the flat AlGaN thickness variation, 2DEG depth was uniformly controlled across the wafer. Thickness of surface depletion layer was 32.44 ± 0.88nm range, which well corresponds to the variation of AlGaN thickness. Additionally, van der Pauw measurement showed fairly reasonable average carrier mobility of $1{,}100 cm^2V^{-1}s^{-1}$ and 1.19×10^{13} cm^{-3} sheet carrier



(a) (b)

Figure 4. Surface morphology of AlGaN/GaN HEMT epi wafer grown on semi insulating SiC substrate. (a) bare substrate surface without deposition, (b) after epi growth with AlGaN/GaN layers.



(a) (b)

Figure 5. Cross-section views of surface roughness of "**B**" region on the AlGaN/GaN HEMT epi wafer grown on semi insulating SiC substrate. (a) bare substrate surface without deposition, (b) after epi growth with AlGaN/GaN layers.

concentration at room temperature. Figure 4 shows the surface morphology of AlGaN/GaN HEMT epi wafer grown on SiC substrate. The bare SiC substrate has scratch patterns (noted as **A**), foreign polytype or other crystal defects (noted as **B**), and micro pipes. After the epi growth, most of the scratch patterns were buried in GaN buffer layer, and the patterns became inconspicuous (noted as **A'**). Figure 5 shows surface cross-sections of the epi wafers around the crystal defects region **B** before and after the growth. In contrast to the scratches, micro pipes and other crystal defects still exist on the surface or even exaggerate the local surface roughness. Monitoring the SiC substrate quality with the surface analyzer has a key importance on controlling uniformity and reproducibility of the AlGaN/GaN epi wafers on SiC.

CONCLUSIONS

Feasibility study on growth of uniform AlGaN/GaN HEMT epi wafers in multi-charged MOVPE system was carried out. Modification on the contact fixture between sapphire substrates and the susceptor had a significant performance on controlling the factor that dominates the sheet resistance variation trend. Multiple wafer HEMT epi growth was performed and sheet resistance uniformity of 0.99% (sigma/average) was achieved. Along with the 2DEG uniformity across the wafer, these data were encouraging results for mass production of AlGaN/GaN HEMT epi wafers.

REFERENCES

[1] Y. Otoki, et al., *"GaN-HEMT on 100mm Diameter Sapphire Substrate Grown by MOVPE"*, 2003 GaAs MANTECH Technical Digest, pp. 331-334, May 2003.

ACRONYMS

AlGaN: Aluminum Gallium Nitride
GaN: Gallium Nitride
HEMT: High Electron Mobility Transistor
MOVPE: MetalOrganic Vapor Phase Epitaxy
GaAs: Gallium Arsenide
MMIC: Monolithic Microwave Integrated Circuit
TMGa: TriMethyl Gallium
TMAl: TriMethyl Aluminum
XRD: X-Ray Diffraction
C-V: Capacitance-Voltage
2DEG: 2 Dimensional Electron Gas
SiC: Silicon Carbide