4” InP based HEMT epitaxial wafers grown by MOVPE for volume production

Hajime Momoi, Koji Kakuta, Eiji Ikeda, and Hirofumi Nakata

Nikko Materials Co., Ltd.
3-17-35 Niizo-Minami, Toda-shi, Saitama, 335-8502, Japan
Phone: 81-48-433-2062, e-mail: momoi@nikko-materials.co.jp

Abstract

Epitaxial growth technology for InP based HEMT was developed on 4-inch substrate. Conventional horizontal MOVPE with 5x4” planetary system was evaluated to confirm thickness, composition and doping variation in a wafer. Lattice matched HEMT structure was then grown with good uniformity of less than 2% in one sigma.

INTRODUCTION

One of the promising devices for modern high-speed optical fiber communication or millimeter-wave applications is InP based high-electron-mobility-transistor (HEMT). Especially the most attractive characteristic of InP based HEMT is to operate at 300 GHz or higher frequencies as well as low noise figure and reasonable reliability for the high-end applications.

Epitaxial growth of InAlAs/InGaAs HEMT structures requires a certain challenge because of high content of aluminum in InAlAs layers. Both high purity InAlAs for buffer layers and high doping concentration InAlAs for carrier supply layers are required, respectively. In addition, the recent HEMT structure must include some etching stopper layer such as thin InP, which is easily obtained by MOVPE technology.

In this paper, the result of the MOVPE growth for volume production of HEMT epitaxial wafers is presented in terms of the uniformity and the reproducibility.

EXPERIMENTAL PROCEDURE

In-house 3” and 4” semi-insulating InP (100) wafers were used in this work. The wafers were etched prior to shipment (etch-and-pack in nitrogen) to be ready for epitaxial growth without any pretreatment. A load-lock chamber is pumped out by a turbo molecular pump to minimize background level of oxygen and water partial pressures. A production-proven MOVPE reactor is a conventional horizontal gas-flow system configured with a 5x4” planetary and face-down susceptor. Face-down set-up of substrates is beneficial to avoid gas convection and particle issue on wafers. The reactor is configured with two rotary pumps and several residual gas traps such as particle filters and a dry scrubber system for safety requirement. PC-based controller automates all growth sequence by using edited Excel data file. Control windows are prepared to switch most of hardware as operator interface. Six zone lamp heaters control susceptor temperature with a thermocouple close to the heater. Temperature profile on a wafer can be monitored by an optical pyrometer viewing through a lower susceptor. In this paper, growth temperature is represented by thermocouple temperature that is approximately 100 degrees higher than wafer surface temperature monitored by the pyrometer. Revolution speed of upper susceptor was set at 3 rpm to rotate wafers at 10 rpm.

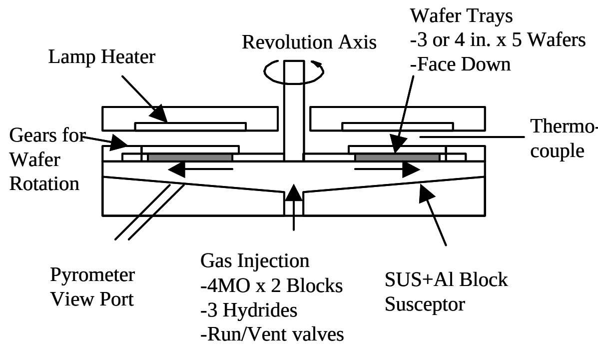

Figure 1. Schematic diagram of planetary MOVPE reactor

Trimethylindium, trimethylgallium and trimethylaluminum were used as group III precursors. Three hydride gases, 100% arsine, 100% phosphine for group V precursors, and 100ppm disilane for n-type dopant were used. For accurate flow-rate control of solid trimethylindium source, ultrasonic in-line gas concentration monitor was used. Pressure of the reactor was set at 35 Torr. Pressure fluctuation was eliminated by conventional run-vent manifold to obtain abrupt hetero interface. V/III ratio was set to 120 except for InAlAs buffer layer.

HEMT structure consists of seven layers as shown in Table 1. $In_{0.52}Al_{0.48}As$ and $In_{0.53}Ga_{0.47}As$ are lattice-matched to InP substrate. Thickness of InP etching stopper layer is typically 3 to 6 nm.

TABLE I
INP BASED HEMT STRUCTURE

Layer #	Name	Material	Dopant, Nd
7	Contact Layer	InGaAs	Si, 1e19
6	Etch Stopper	InP	None
5	Shottky	InAlAs	None
4	Carrier Supply	InAlAs	Si, 6e18
3	Spacer	InAlAs	None
2	Channel	InGaAs	None
1	Buffer	InAlAs	None
-	Substrate	InP	Fe-doped

INALAS BUFFER LAYER

First of all, the growth condition of InAlAs buffer layer was optimized, because it is essential to eliminate the influence of interface between substrate and epitaxial layer for evaluating the subsequent epitaxial layer correctly. In the case of InP based HEMT, InP-InAlAs interface creates type II hetero-interface that should be totally depleted. Semi-insulating InAlAs layer was obtained at relatively low growth temperatures of 650 degrees in Celsius or below. Although Hall measurement of the thin epitaxial layer is not accurate when the carrier concentration is low enough for the layer to be depleted from the surface, the measured resistance was at the same order of 10^7ohm cm as that of semi insulating substrate. From the temperature dependence of the resistivity, the activation energy of the deep level in the semi insulating buffer layer was estimated to be about 0.35 eV that is in good agreement with other publication.[1)] CV measurement was also performed to confirm that InP-InAlAs interface is completely depleted. In the following experiments, this semi-insulating buffer layer was used.

REACTOR EVALUATION BY INALAS GROWTH

Thickness distribution of InAlAs layer in a wafer was confirmed without wafer rotation during epitaxial growth as shown in figure 2. The film thickness decreased exponentially in the direction of gas flow. It was interpreted as depletion of the group III precursors along gas flow direction by assuming well-known hydrodynamic boundary-layer model of horizontal gas-flow reactor. From this result, group III utilization efficiency was estimated as 19%.

Even without wafer rotation, lattice mismatch of InAlAs or InGaAs to InP was confirmed to be less than +/-100 seconds over the whole area of 4-inch wafer measured by four-crystals X-ray diffraction method.

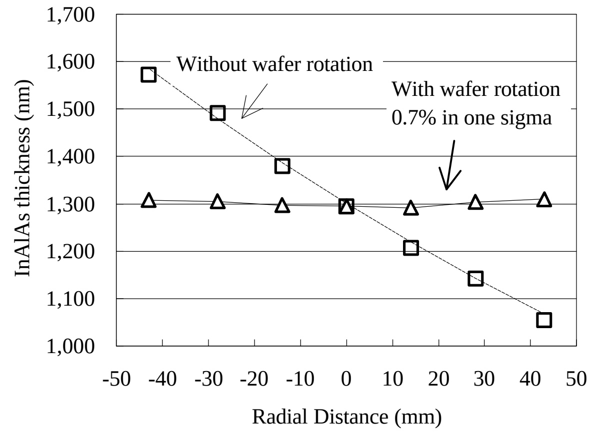

Figure 2. InAlAs thickness distribution in radial direction with and without wafer rotation. Dotted line shows fitting curve of exp(-x) function.

For silicon doping, distribution of carrier concentration without wafer was somehow unique. With wafer rotation, initial uniformity data was 3% or higher in one sigma. It hardly explained by the model that the depletion of group III precursors causes some change in gas ratio of dopant to group III precursors.

In order to compare with other chemistry, AlGaAs layer was evaluated. In the case of $Al_{0.25}Ga_{0.75}As$ on GaAs substrate, uniformity of sheet resistance was easily achieved to be less than 1.5% over the wide range of process window. The temperature dependences of Si doping into AlGaAs and

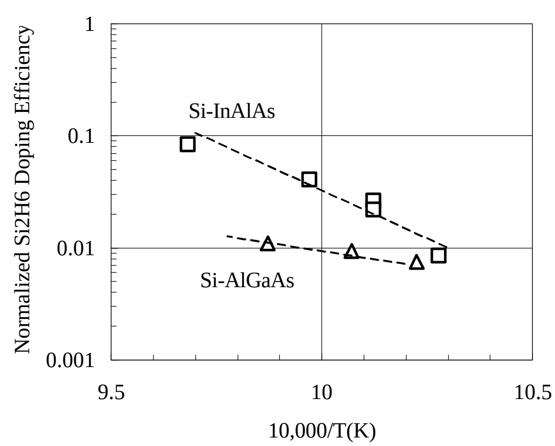

Figure 3. Arrhenius plot of normalized doping efficiency of Si_2H_6 to $In_{0.52}Al_{0.48}As$ and $Al_{0.25}Ga_{0.75}As$.

InAlAs were then evaluated as shown in figure 3. While the activation energy of Si doping in AlGaAs was about 0.8 eV from figure 3, we estimated that activation energy of Si doping into InAlAs was nearly 3.0 eV, that is corresponding to 3.5% increase by just 1-degree increase of temperature.

MODIFICATION OF REACTOR

In order to improve temperature uniformity, internal parts of the reactor around wafers were redesigned to achieve moderate temperature gradient from substrate surface to the lower susceptor. Wafer holders were experimentally changed for better heat transfer from backside of wafer to surface. Hydrodynamic simulation was also executed with full 3D coordinates of structure to confirm temperature gradient. After all, in-wafer temperature uniformity was fine-tuned to be less than 2 degrees in Celsius monitored by the pyrometer including some measurement error and uniformity of Si doping of InAlAs layer became less than 1.5%.

RESULT ON HEMT STRUCTURE

Typical thickness variation in HEMT structure is shown in figure 4 measured by X-ray reflection technique. Quality of InGaAs channel layer was simply improved by raising growth temperature as shown in figure 5.

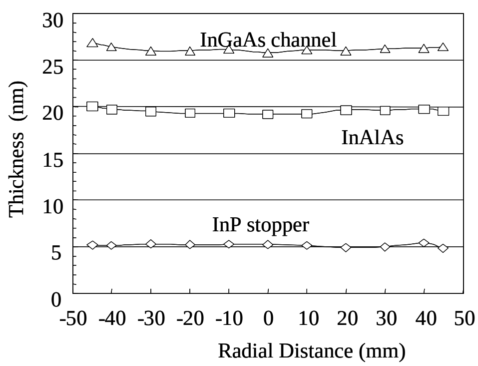

Figure 4. Thickness distribution in HEMT structure

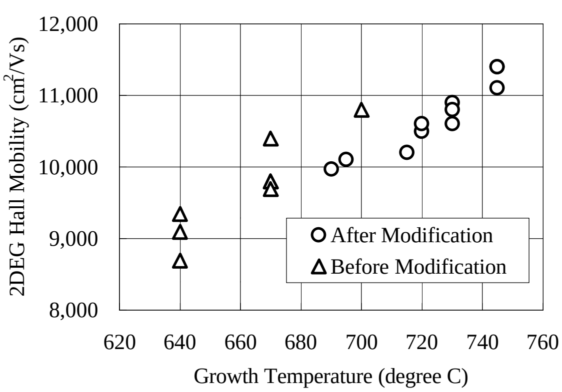

Figure 5. Hall mobility of 2DEG in HEMT structure

The highest mobility in this work was achieved at relatively higher growth temperatures. After modification of the wafer holders and the internal parts, wafer temperature seemed lowered by approximately 10 degrees in Celsius. The reason for higher mobilities at higher temperatures was not investigated yet, but it is supposed to be due to improvement in crystal quality and purity of InGaAs layer.

The best data of 2-DEG electron mobility and the uniformity were 10,600 cm2/Vs and 0.5% in one sigma, respectively. The sheet carrier concentration and the uniformity were $2.9 \times 10^{12} cm^{-2}$ and 1.6% as shown in figure 6. 36-points uniformity of sheet resistance was 1.2% as shown in figure 7.

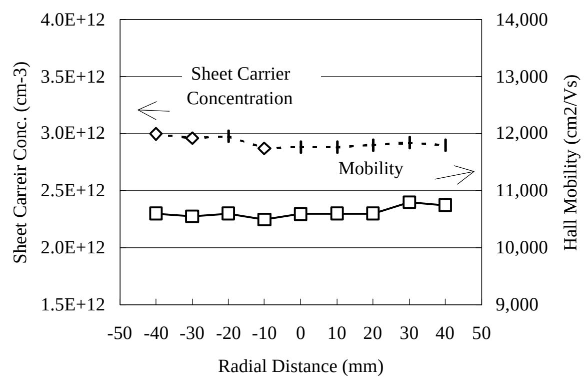

Figure 6. In-wafer uniformity of 2DEG sheet carrier concentration and Hall mobility

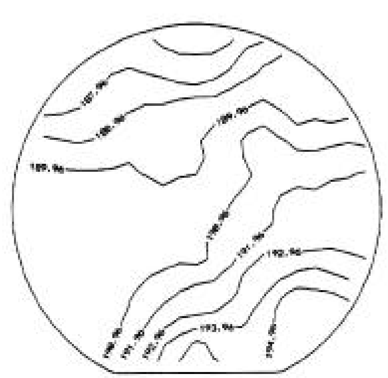

Figure 7. Sheet resistance mapping data of sheet resistance of HEMT structure without contact layer

CONCLUSIONS

Modified MOVPE reactor for volume production was evaluated for InP HEMT epitaxial wafers. One of key points which needed a breakthrough was strong temperature dependence of Si doping to InAlAs. Temperature distribution in a wafer was improved by redesigning internal structure of the reactor. Sheet resistance uniformity of the resulting HEMT was less than 2% in one sigma in 4-inch wafer.

ACKNOWLEDGEMENTS

The authors would like to thank Misao Takakusaki, Kazuhiro Akamatsu, Masashi Nakamura and Dr. Ryuichi Hirano for the informative discussions, InP substrate support and measurements of HEMT structure.

REFERENCES

[1] T.Kimura etc al., J.Cryst. Growth 145, 963 (1994)

ACRONYMS

HEMT: High Electron Mobility Transistor
MOVPE: Metal-Organic Vapor-Phase Epitaxy
2DEG: Two Dimensional Electron Gas