New Barrel Type MOVPE Reactor for 6" Epitaxial Wafers

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Abstruct

A unique designed barrel type MOVPE reactor with 8 graphite susceptors capable of holding wafers from 4" up to 6" in diameter has been developed. The uniformity of carrier concentration, layer thickness, and composition of 6" epitaxial wafers were investigated. Optimizing the susceptor design and the crystal growth condition, uniformity of ±1.8% for carrier concentration, ±1.2% for layer thickness of n-GaAs layer, ±0.6% for Al composition of AlGaAs and ±1.2% for In composition of InGaAs over 6" wafer have been achieved.

InGaP layer with lattice matched on GaAs substrate also showed an excellent layer thickness uniformity of ±2.5%, and energy gap at room temperature, Eg, 1.844eV over 6" diameter wafer with standard deviation of 6meV.

MESFETs were fabricated on 6" wafers and threshold voltage (Vth) uniformity as low as ±40 mV on average Vth= -2.9V was obtained, which was comparable value to that of 4" MESFET. InGaP-HBTs were also fabricated on 6" wafers and its performance including DC current gain and its uniformity, I-V characteristics were studied. Current gain of 145±6 at base sheet resistance of 310±12ohm/sq. was obtained. Also, uniformity of ±1.9% and ±2.2% for current gain and base sheet resistance has been achieved. These performances are comparable to those of conventional AlGaAs-GaAs HBTs.

These results show the promising capability of our manufacturing equipment and show that the growth process on 5" and 6" epitaxial wafers was successfully optimized. Also, it is shown that this growth technology can be applied to the large volume production of MESFETs, pHEMTs and HBTs made of AlGaAs, GaAs, InGaAs, and InGaP.

Introduction

One of the most effective ways for the cost reduction of the epitaxial wafer production is to use larger wafer sizes. For this purpose, many companies and institutes have been attempting to move from 4" wafers to 5" or 6" wafers. The larger the wafer size, the larger the temperature difference and the less uniformity of epitaxial layer occurs over the wafer. Also, it becomes more difficult to obtain the stability and the reproducibility for the large volume production. Therefore, optimizing the growth conditions for the larger wafer size becomes of great importance. Furthermore, not only establishing the growth conditions, but also the availability of high purity and uniform substrates is especially important.

For high power applications, MESFET and HEMT have been used as a mature technology. In last few years, HBT is increasingly important as a candidate device for the next commercialization as its advantages of high efficiency, single power supply operation, and high linearity. In particular, InGaP-HBT is considered as the most attractive device because of the higher reliability than that of conventional AlGaAs-HBTs.

Since the flow rate of Group V sources is usually large in MOVPE, for the fabrication of InGaP-HBTs, a control of the interface between InGaP and GaAs is essential. Also, for the lager size wafer, this control and the uniformity over the wafer become more important and difficult.

In this paper, performances of our new barrel type reactor including uniformity of thickness, carrier concentration and composition on 5" and 6" wafer will be presented. Also, device characteristics of MESFET and pHEMT on large size wafer such as threshold voltage uniformity over the wafer and its reproducibility for wafer to wafer will be described. Moreover, InGaP growth on large size wafer and its application to InGaP-HBTs will be discussed.

Experimental

The epitaxial wafers were grown by MOVPE with original designed barrel type reactor. The susceptor part rotates itself simultaneously with the rotation of the whole reactor to enhance the epitaxial layer uniformity. The rotation rate of the susceptor was about 6rpm. Growth parameters such as reactor pressure, main carrier gas flow rate were optimized to obtain the high uniformity. The reactor pressure was 76Torr and main carrier gas flow rate was 120SLM. Eight wafers for 6" can be grown at one growth batch. Susceptor parts were designed for wafer size from 3" to 6". The pressure turbulence when Group III precursor and Group V sources were switched was minimized by adjusting the vent-line gas flow rate, the pressure difference between run-line and vent-line. The peak height of the spike-like pressure turbulence in the run-line was less than 1.5Torr when arsine and phosphine gas was switched. A high uniformity of thermal condition over the large size wafer has been achieved by controlling the thermal flow of the back and side of the susceptor, so that the temperature variation estimated from the carrier density of p-GaAs layer determined by Hall effect measurement was less than 1 degree over 6" wafer.

Trimethylgallium or triethylgallium, trimethyl-aluminum, trimethylindium was used for Group III precursor. Pure arsine and phosphine was used for Group V sources. Dopant for n-type was silicon, and p-type was $CBrCl_3$.

V/III ratio was optimized to minimize the background impurity. Under this condition, the background impurity determined by Hall measurement was p-type and its concentration was less than $5x10^{15}cm^{-3}$ for AlGaAs, which results in a high purity for the buffer layer for FETs.

*R*esults and *D*iscussion

(1) Uniformity of n-GaAs, n-AlGaAs and n-InGaAs Layer on 5" and 6" wafer

The uniformity of thickness, carrier concentration, and composition of the epitaxial layers of GaAs, AlGaAs and InGaAs on 5" and 6" wafers were studied and described.

Fig. 1 shows a thickness uniformity of n-GaAs on 6" wafer. Thickness uniformity (variation/mean) of ±1.2% was obtained including the data point 3mm from the wafer edge. Also, the comparable uniformity of ±1.2% was obtained for the n-GaAs layer thickness on 5" wafer.

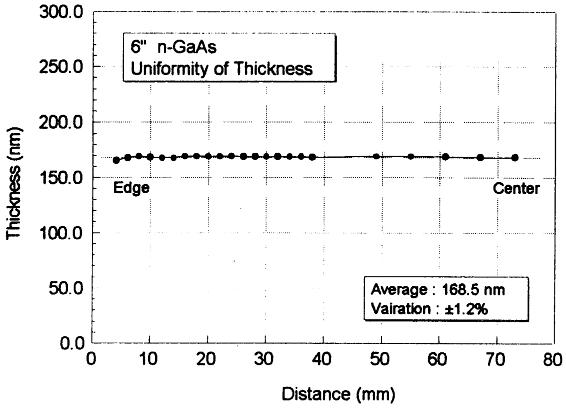


Fig. 1 Uniformity of thickness of n-GaAs layer on 6" wafer. Comparable value of thickness uniformity also obtained for 5" wafer.

Carrier concentration uniformity of n-GaAs is indicated in Fig. 2. Uniformity of ±1.8% was obtained at average carrier concentration of $2.2\mathrm{x}10^{17}\mathrm{cm}^{-3}$. This value is also comparable to that of the n-GaAs on 5" wafer.

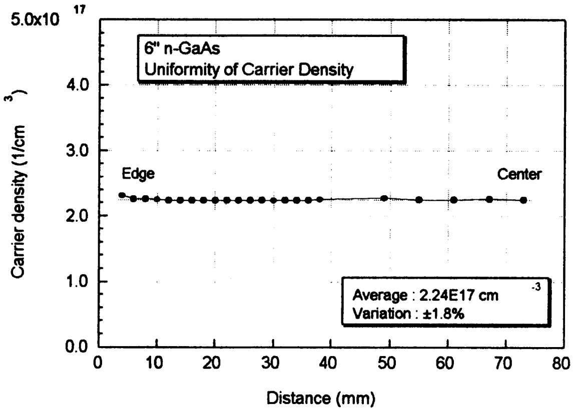


Fig. 2 Uniformity of carrier concentration of n-GaAs layer on 6" wafer. Comparable value of uniformity also obtained for 5" wafer.

Thickness and carrier concentration uniformity of n-AlGaAs was also studied, which is obviously important for the HEMT application in which threshold voltage (Vth) depends on the thickness and carrier concentration of n-AlGaAs layer. On 5" wafer, thickness uniformity of ±1.8%, carrier concentration uniformity of ±0.9% was obtained, which resulted in a high uniformity of the Vth on large size wafer as expected (See Fig. 4).

In Table 1, uniformity of Al and In composition of AlGaAs and InGaAs layer were summarized.

Table 1 Al and In composition of AlGaAs and InGaAs determined by PL at room temperature.

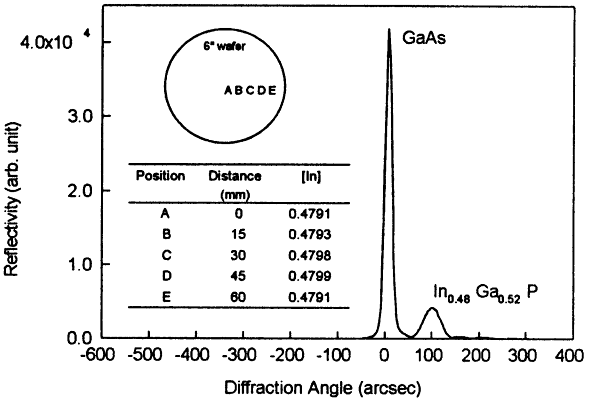
	AlGaAs			InGaAs		
	PL peak (nm)	Eg (eV)	[Al]	PL peak (nm)	Eg (eV)	[In]
Max.	729.6	1.6996	0.154	993.3	1.2484	0.115
Min.	728.6	1.7019	0.155	990.1	1.2524	0.113
Average	729.1	1.7007	0.155	991.8	1.2502	0.114
Variation	□|	□|	0.61 %	□|	□|	1.2 %

Composition was determined by PL measurement at room temperature. Very high uniformity of Al composition of ±0.6% and In composition of ±1.2% was obtained. Although it is generally considered to be very difficult to control for In composition, especially on large size wafer, because of its low decomposition temperature of In precursor, no In composition decreasing was observed at the edge of the wafer, indicating high capability of the equipment.

A high uniformity of thickness, carrier concentration and composition on large size wafer indicates that the growth condition such as reactor pressure and carrier gas flow rate for the large size wafer has been well optimized and controlled.

(2) Crystal Growth of InGaP Layer

XRD profile of InGaP layer lattice matched on GaAs substrate is shown in Fig. 3. Lattice match condition was expected within the diffraction angle of 100 to 200 sec. In composition determined by the curve fitting was also shown in inset table in Fig. 3. Uniformity of In composition was ±0.08% over 6" wafer including the data point from the center to 60mm point. There was no In composition decreasing from the center to the outside of the wafer as in the case of InGaAs layer.



Position	Distance (mm)	[In]
A	0	0.4791
B	15	0.4793
C	30	0.4798
D	45	0.4799
E	60	0.4791

Fig. 3 XRD profile of InGaP lattice matched on GaAs substrate. Inset table shows the uniformity of In composition over 6" wafer.

In Tabel 2, energy gap, Eg, uniformity at room temperature on 6" wafer determined by PL was summarized. Average Eg of 1.844eV with standard deviation of 4.1meV was obtained. Since In composition uniformity is very high of less than ±0.1%, variation of Eg over the wafer is attributed to the variation of the degree of ordering of InGaP layer. It is well known that Eg of fully disordered state is 1.92eV, and Eg decreases with the degree of ordering [1]. InGaP layer was found to be a partially ordered state by electron diffraction measurement [2-5]. High uniformity of Eg shows the high homogeneity of this partially ordering state over the 6" wafer.

	PL peak (nm)	Eg (eV)
Max.	674.40	1.8387
Min.	667.40	1.8580
Average	672.33	1.8443
Std. Dev.		4.1 meV

Table 2 Eg uniformity of InGaP layer lattice matched on 6" GaAs substrate. Eg was determined by PL at room temperature.

(3) Device characteristics

(a) Uniformity of threshold voltage (Vth) of pHEMT and MESFET

Double hetero pesudomorphic HEMT was fabricated on 5" wafer to investigate the device performance and wafer uniformity. Device structure consists of n-AlGaAs/InGaAs/n-AlGaAs. Sheet carrier density of $2.5 \times 10^{12} cm^{-2}$ and mobility of $6200 cm^2/Vs$ at room temperature was obtained. Also, MESFET was fabricated on 6" wafer so that Vth uniformity was tested.

Uniformity of Vth is shown in Fig. 4. Vth uniformity of ±38mV for 5" pHEMT at average Vth of - 2.19V, and ±43mV for 6" MESFET at average Vth of - 2.89V have been achieved. High uniformity of n-GaAs and n-AlGaAs thickness, carrier density and high purity of buffer layer accounts for the high uniformity of Vth even on large size wafer. Note that there is no Vth variation at the edge of the wafer. Vth of FETs is very sensitive for the thickness, carrier density, and buffer layer impurity variation. Therefore, high uniformity of Vth even at the edge of the large size wafer indicates that these factors are well controlled in our growth equipment.

Fig. 4 Threshold voltage (Vth) uniformity of pHEMT on 5" and MESFET on 6" wafer.

(b) Sheet resistance reproducibility

In terms of the large volume production, not only the uniformity of each wafer, but also the repoducibility from wafer to wafer should be considered. In Fig. 5, sheet resistance uniformity variation from wafer to wafer of full structure device are shown. Six wafers of pHEMT on 5" wafer and of MESFET on 6" wafer grown at one growth batch were tested, respectively. The variations of sheet resistance of the full structure devices were within ±2.1% for 6" wafer and ±1.6% for 5" wafer. In this case, sheet resistance measured was the combined value of channel layer and gate contact layer. Variation of the sheet resistance gives the estimation of the thickness and carrier concentration variation by non-destructive measurement. Considering that Vth depends on carrier concentration and thickness of channel layer, Vth variation on wafer to wafer would be ±80mV at average Vth of -2.9 V for MESFET on 6" wafer. This variation comes from the thickness variation caused by the variation of the distance between the surface of the wafer and inner wall of the reactor jacket.

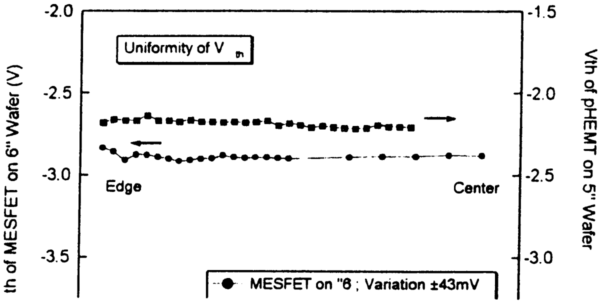
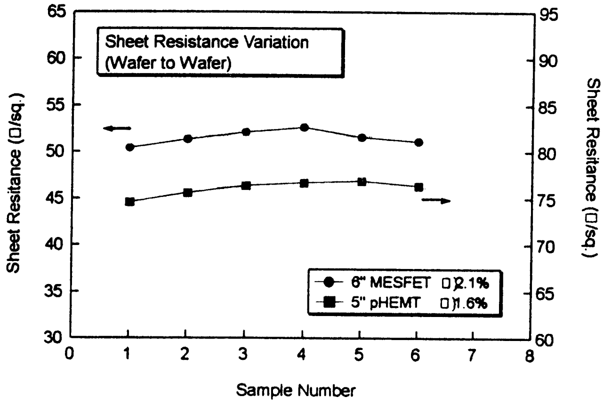


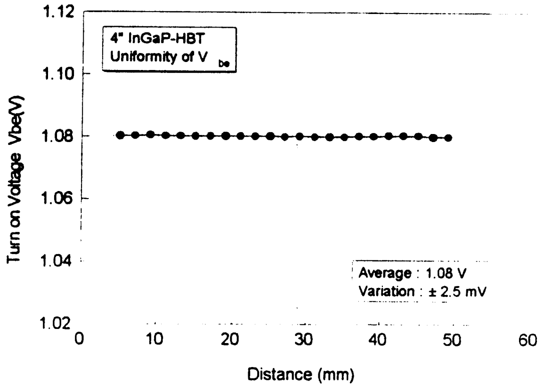
Fig. 5 Reproducibility of sheet resistance of pHEMT on 5" and MESFET on 6" wafer. Six wafers were grown at the same growth batch.

(c) Performances of InGaP-HBT

Device characteristics of InGaP-HBT on 6" wafer were studied. InGaP with partially ordered structure as showed in Fig. 3 and Table 2 was employed as an emitter layer. Device structure consists of InGaAs nonalloy/n-GaAs Emitter contact/n-InGaP Emitter/p-GaAs Base/n-GaAs Collector/n-GaAs Sub collector with device dimension of $100 \times 100 \mu m^2$.



The diode factor (n value) of base current Ib derived from Gummel plot was 1.2 indicating good quality of p-GaAs base layer and base/emitter interface region. Residual hydrogen concentration of base layer determined by SIMS was $1 \times 10^{18} cm^{-3}$. No initial drift of current gain at current density of $10kA/cm^2$ was observed. In Fig. 6, DC current gain



(=Ic/Ib) is plotted versus base sheet resistance Rs. Carrier concentration ranged from $3.5\times10^{19}cm^{-3}$ to $4.0\times10^{19}cm^{-3}$. The figure of merit of gain/Rs ratio was used to compare characteristics of HBTs prepared by different base thickness and carrier concentration [6]. This ratio was 0.5 for the InGaP-HBT on 6" wafer, which is comparable value with that of conventional AlGaAs-HBTs.

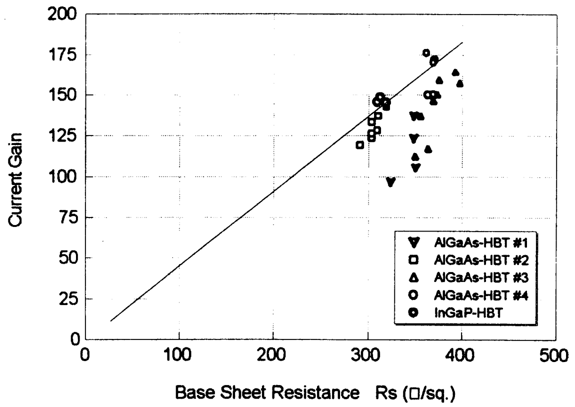


Fig. 6 DC current gain-base resistance plot of InGaP-HBT on 6" wafer. Data of AlGaAs-HBT are also shown for comparison

Uniformity of current gain and base sheet resistance are shown in Fig. 7. Over 6" wafer, uniformity of ±2.2% for current gain, ±1.9% for base sheet resistance was obtained. These values are also comparable to those of AlGaAs-HBT on 4" wafer.

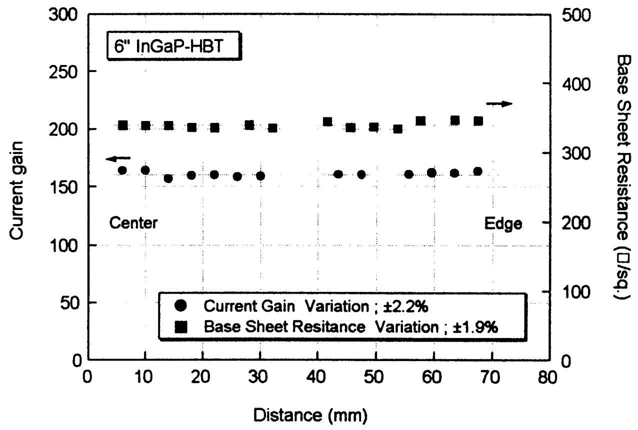


Fig. 7 Uniformity of DC current gain and base sheet resistance of InGaP-HBT on 6" wafer.

Turn on voltage Vbe at collector current density of $1.0A/cm^2$ over 4" wafer was plotted in Fig. 8. Uniformity of Vbe was ±2.5mV at average Vbe of 1.08V. High uniformity of Vbe observed is based on the results that InGaP emitter layer used has high uniformity of Eg over the wafer as showed in Table2.

Fig. 8 Turn on voltage Vbe of InGaP-HBT on 4" GaAs wafer. Vbe was determined at which

Conclusion

The basic performances of new barrel-type reactor designed for large epitaxial wafer including 5" and 6" and InGaP cryastal growth have been described. Uniformity of ±1.8% for carrier concentration, ±1.2% for layer thickness of n-GaAs, and ±0.6% for Al composition of AlGaAs and ±1.2% for In composition of InGaAs over 6" wafer have been achieved. Threshold voltage, Vth, uniformity as low as ±40 mV on average Vth= - 2.9V was obtained for MESFET on 6" wafer, which was comparable value to that of 4" MESFET. Also, reproducibility from wafer to wafer was confirmed. InGaP layer with lattice matched on GaAs substrate also shows an excellent layer thickness uniformity of ±2.5%, and energy gap at room temperature, Eg, 1.844eV over 6" diameter wafer with standard deviation of 6meV. InGaP-HBTs were fabricated on 6" wafers and DC current gain of 145±6 at base sheet resistance of 310±12ohm/sq. was obtained. Also, uniformity of ±1.9% and ±2.2% for current gain and base sheet resistance has been achieved. These performances are comparable to those of conventional AlGaAs-GaAs HBTs. These results show the promising capability of our manufacturing equipment, and that the growth process on 5" and 6" epitaxial wafers was successfully optimized.

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