Large Volume Production of Large size GaAs Substrates and Epitaxial Wafers for Microwave Devices

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ABSTRACT

Recent mass production techniques for LEC substrates and MOVPE wafers for microwave devices are described. Huge GaAs semi-insulating ingots (150mm diam., 310mm long) was obtained by Multi-hot-zone very large size pullar. Three step boule annealing and fully-automated process enabled mass production of the large size substrates. Epitaxiial wafers with abrupt hetero interface, excellent uniformity and reproducibility are producing largely by face down horizontal flow type MOVPE system, which can be applied to 150mm diam..

1. INTRODUCTION

The demand for microwave GaAs devices are being dramatically increased due to the rapid expand of multi-media systems, especially cellular phones. Mass production of these devices should be supported by high volume manufacturing of semi-insulating substrate and epitaxial wafers with good crystal quality, good uniformity over the wafer, and good reproducibility. The demand of large size wafers, 125mm and 150mm diameter, is also increasing to expand the production capacity and to lower the device cost. LEC method and MOVPE are well known as useful techniques to realize mass production of substrates and epitaxial wafers, respectively. In this paper, recent progress of these techniques and their applications are described.

2. SEMI-INSULATING SUBSTRATE

2.1 Crystal Growth

Mass production of LEC semi-insulating substrates began with 50mm diam. wafers in early 1980's by using small size pullar. Every work, such as charging, handling of ingot and clearing the machine, can be done by hand. However, it's impossible "all by hand" in case of the newly developed large pular, shown in figure1(a), which can be loaded with up to 50kg of Ga and As mixture in a 400mm diam. pBN crucible and can provide 350-400mm long GaAs crystals. The puller starts the growth procedure automatically after manual loading of the materials. An automated chamber cleaner has been developed to protect operators from exposure to arsenic, as shown in figure1(b). The interfacial shape between growing crystal and the melt is maintained to be suitable during whole growth by using the multi-heating-zone system [1,2].

The puller is also equipped with sensors which measure the CO content of an ambient gas, and automatically control the partial pressure of CO. This allows control of carbon concentration and the relating resistivity [3] of a crystal in the very narrow respective range. Grown 150mm diam crystals(body length:310mm) and wafers are shown in Fig.2. Run-to-run reproducibility of obtaining single crystals has been confirmed good[4].

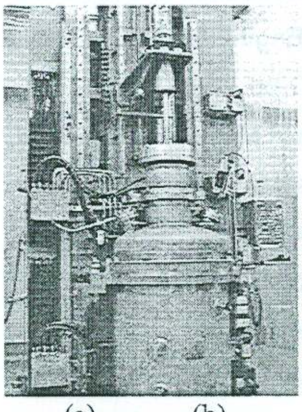

(a) (b)

Fig.1 (a)Crystal puller which can be loaded with up to 50kg of material, and (b)automated chamber cleaner

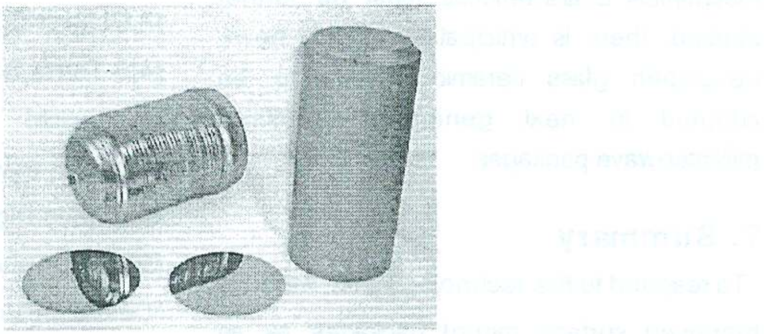


Fig.2 310mm long crystals and 150mm wafers

2.2 Bulk Characteristics

The average value of the etch pit density of 150mm wafers is 60,000-70,000cm-2, which is a bit higher than that of 100mm wafers. A furnace system for three-step boule annealing under arsenic atmosphere has been developed; grown crystals are annealed at three respective steps of 1000-1100 °C for the solid solution of excessively dissolved arsenic atoms, and at 500-600 °C for the pinning of homogeneously dispersed nuclei for EL2, and at 800-900 °C for the generation of EL2 essential for the semi-insulating [1,3]. Homogeneity has been improved by the above annealing method comparable to that of 100mm wafers, as shown in Fig3. Run-to-run reproducibility of the bulk characteristics has also been confirmed[4].

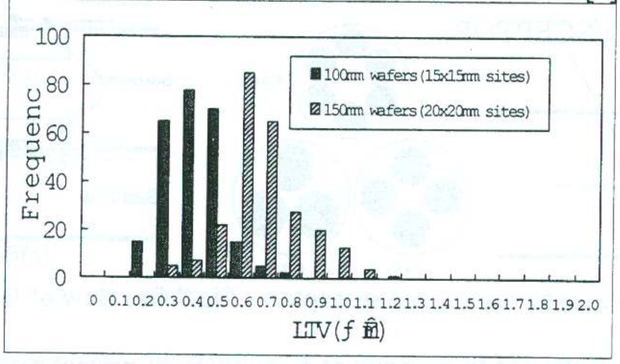


Fig.3 Distribution of PL intensity across a wafers Fig.4 LTV of 150mm wafers

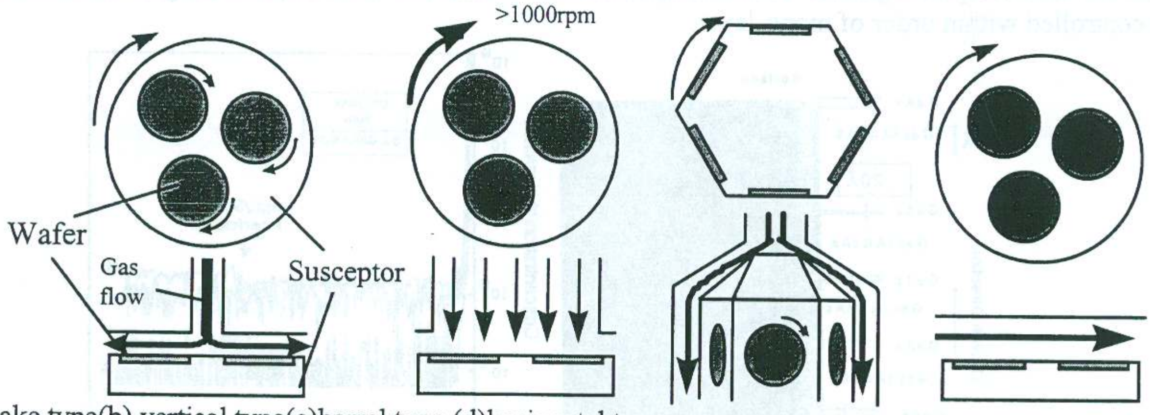
2.3 Wafer Characteristics

Wafer processing, lapping, polishing, etc., needed very high level skill in the early stage of 2" or 3" mass production. For the larger size wafer mass production, fully-automated wafer processing machines have been developed and installed. They include a wire-saw slicing machine with the capacity to cut 200 wafers at a time, a beveling machine which processes rounding at the periphery as well as a notch portion, a wafer surface grinder in which wafers are loaded and unloaded to and from cassettes, an automatic wafer mounter which can mount and adhere five 150mm wafers on a large alumina plate of 485mm diam. with liquid wax, and a polisher with a robotic-hand to load and unload the plates, and a wafer rinsing machine also equiped with robotic hands. With these technologies, we have succeeded in producing wafers with favorable surface quality. One of them is wafer flatness. The larger a wafer becomes, the more difficult it is to improve and maintain flatness, especially local flatness. The LTV(local thickness variation) of 150mm wafers as compared to that of 100mm wafers. Though site size differs in the cases of 100mm and 150mm wafers, the result shows that LTV has been improved to be comparable to 100mm wafers.

3.EPITAXITIAL GROWTH

3.1 Structure of MOVPE reactors for mass production

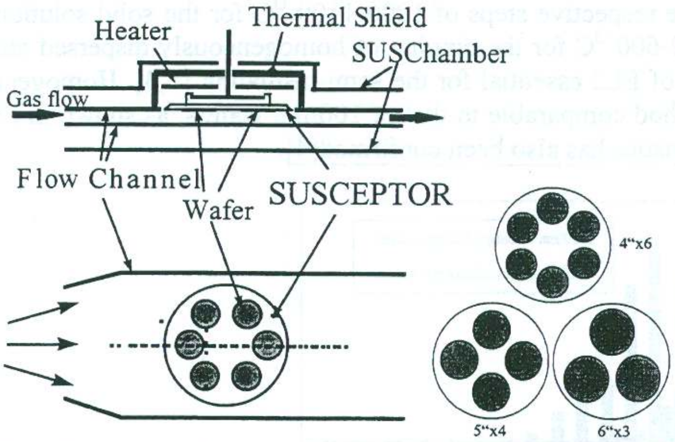
Four structures have been reported for the mass production of MOVPE wafers as shown in Fig.1: (a)pancake type[5], (b) vertical type with high speed rotation[6] , (c)barrel type[7] and (d)horizontal type.



a)pancake type(b) vertical type(c)barrel type (d)horizontal type.

Fig.5 Structure of MOVPE reactors for mass priduction

The structure described in this paper is a sort of horizontal type as shown in Fig.6. This type has realized large mass production of microwave devices due to the easy control of the thermal conditions and improvement of the total system[8]. Substrates are placed in a graphite susceptor (=wafer holder) set just beneath a carbon heater. Reactive gasses flow in a "flow channel" made of quartz and epitaxial layers are grown on the substrates. The susceptor rotates during the growth. Excellent uniformity throughout the wafer with high reproducibility has been achieved by the horizontal type reactor using the three important techniques.



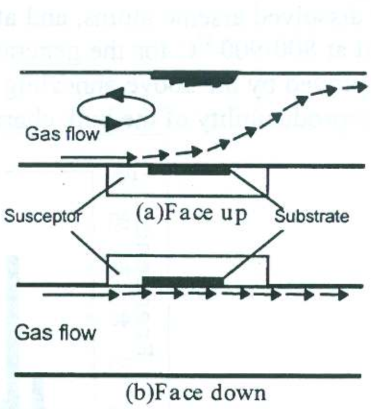


Fig.6 Face-down horizontal type reactor and susceptors Fig.7 Gas flow of face-up and face-down systems

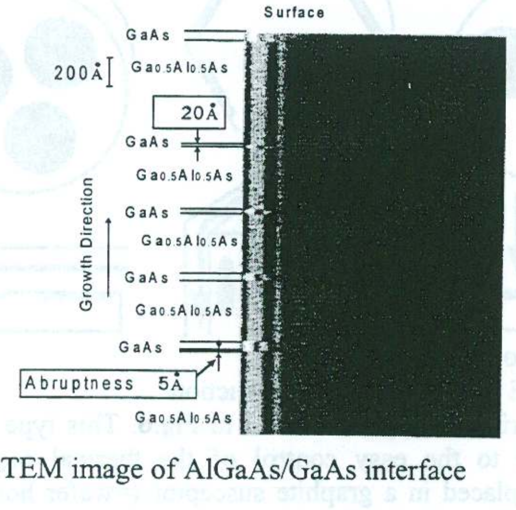
(1) Reaction of growth is controlled to maintain at a condition of perfect mass transport limited growth. To realize this condition, gas flow lines were carefully designed to smooth the flow and not to allow pre-reaction before reaching reactive chamber. This keeps growth rate of the epi-layers very stable even if the temperature at the surface of the substrate varies slightly.

(2) Volume of graphite susceptor is minimized to decrease thermal mass, thus allowing us easy and stable control of thermal conditions for the growth.

(3) The substrates are placed face down as shown in Fig.6. The advantage of this system is shown in Fig.7 compared with a face up system. The reactive gas is heated near the susceptor and rises in the flow channel. This turbulence of the gas flow causes a variation in epitaxial layer properties and also causes a non-uniform deposition of reactant on the wall of the flow channel as shown in Fig.7(a). This deposited reactant sometimes falls onto the surface of the wafer, contaminating the surface. The face down system solved these problems as can be seen in Fig.7 (b).

3.2 Characteristecs of epi-layer grown by face down holizontal system

It's important in order to get good device performance using hetero structure to have abrupt hetero-interface such as AlGaAs/GaAs. It has been said that getting abrupt interface is difficult in the case of MOVPE, mainly caused by residual reactive gas in the chamber. However, abrupt interface can be achieved by the smooth gas flow system and by improved gas tubes and valves to avoid mixture of gases. Fig.8 shows the evaluation result of abruptness of AlGaAs/GaAs by CAT-TEM method which can detect variation of Al-composition at the interface with very high sensitivity[9]. A very thin GaAs layer of 20A between AlGaAs layers can be clearly recognized. Then, abruptness is estimated less than 5A, that is, growth of the interface was controlled within order of mono-layer.



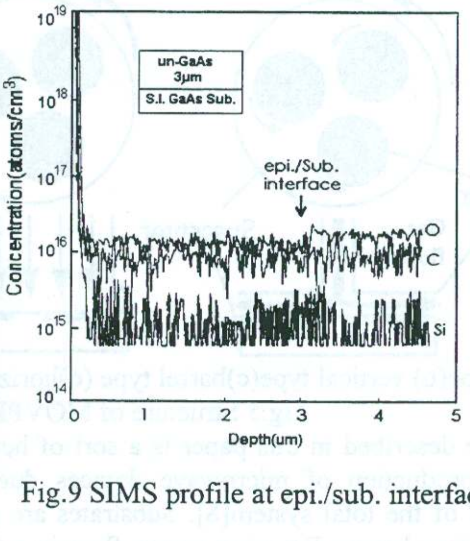


Fig.8 CAT-TEM image of AlGaAs/GaAs interface Fig.9 SIMS profile at epi./sub. interface

High uniformity of each layer with the abrupt interface is not enough to obtain good FET yield. The uniformity of the device's properties such as threshold voltage (Vth), saturated drain current and breakdown voltage are more important. These are influenced not only by properties of the channel layer but by the quality and layer design of buffer layers[9]. Buffer quality is based on purification at the interface between the buffer layer and the substrate. Unintentional impurities, such as oxygen, carbon and silicon, often contaminated the interface and caused instability of device properties. These are well controlled at a very low level in our system. Figure 9 shows an example of impurity analysis at the interface of epi-layer (undoped GaAs) and substrate (semi-insulating GaAs wafer). No contamination can be seen at the interface.

Epi-wafers for pseudomorphic HEMT with double supplied layers, whose structure (shown in Fig.10) has been widely used for power FET application, were grown using the techniques described below and their uniformity measured. Undoped AlGaAs/GaAs multi-layers were used as buffer layer here. The pinch off voltages (Vp) were measured in a 100mm wafer using the C-V method. The Vp was defined as the bias voltage where carrier concentration was $1x10^{15}cm^{-3}$. The standard deviation of Vp was as low as 20mV (Fig.10). This uniformity has also been achieved in the practical stage (highest data was below 10mV).

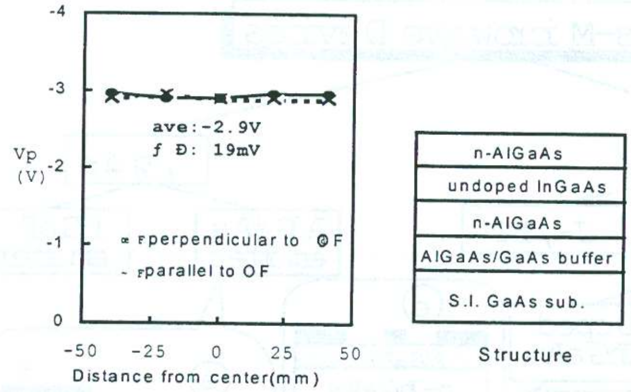


Fig.10 Uniformity and structureof Double doped pHEMT

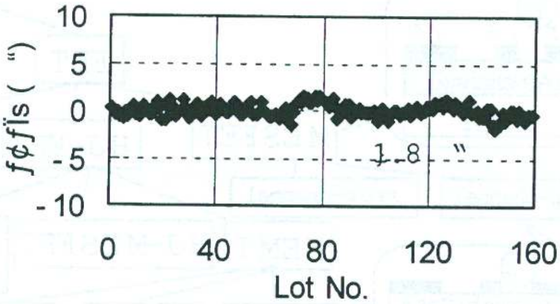


Fig.11 Stability of sheet resistance among long term growth lots in production
s:difference from average(%)

Long-term stability of the Vp was measured for 6 months, and the variation was a low 0.05V. Stability of sheet resistivity of the pHEMT wafers with an n+GaAs contact layer on top of them was also measured among production lots. The variation among 160 lots was within 1.8% as shown in Fig.11. Thus, uniformity, reproducibility and quality have all been achieved, and these wafers have realized mass production of high performance integrated circuit in high yield.

3.3 Growth of large size wafer

This simple system also enables us to easily grow epitaxial layers on large size wafers without any other additional change to the reactor system, but just exchanging the susceptor. Our technique of fabricating the susceptors allows us to grow four wafers of 125mm diameter or three wafers of 150mm diameter simultaneously as shown in Fig.6. In regard to uniformity, the 150mm epitaxial wafers were as good as the 100mm wafer. Also, no difference was recognized between crystal properties of the epitaxial layers on the 100mm wafers and those of the large wafers (Figure12). For example, mobility of the double doped HEMT structure were about 6500 cm^2/vsec or higher for all sizes.

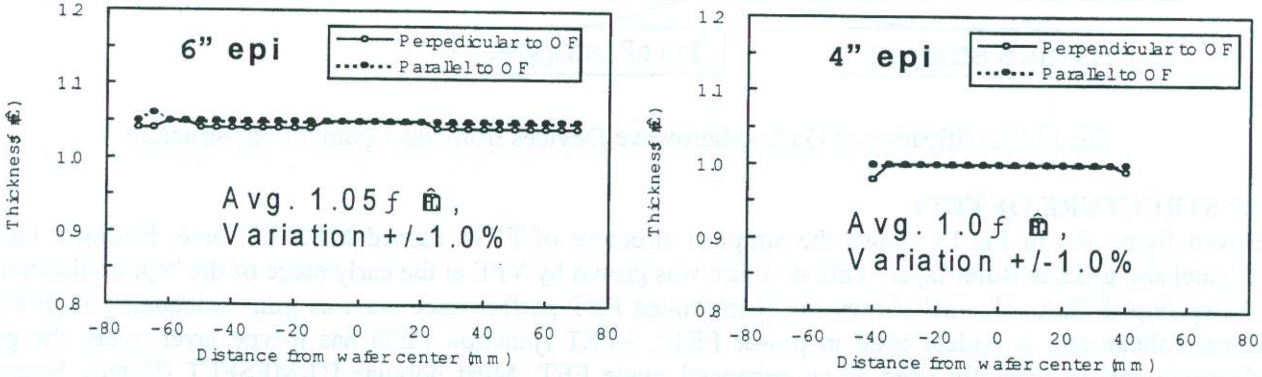


Fig.12 Uniformity of AlGaAs layer on 150mm and 100mm wafer

Using the system and techniques described in this section, very large capacity of the epi-production (more than 10,000 of 100mm diam./month) is achieved in practical stage.[10]

4. EVOLUTION OF EPI-STRUCTURE

4.1Classification of epi-structure

Using the techniques mentioned above, microwave devices using epitaxitial wafers have been widely used in a practical stage. Since recent epitaxitial technique enabled us to grow any kinds of hetero-structure, the layer structure of the wafer has been becoming complex. These new structures realized higher performance and wider application of the devices. In other word, the epi-structure is evoluating. Fig.13 shows the evolution of epi-wafer for GaAs microwave devices. The devices in practical use are classified into FETs and HBTs. Really many kinds of structures are used in FETs as shown in the figure. The figure shows only two kinds of HBTs (boxed figure (a) in Fig.13), AlGaAs emitter type and InGaP type, but new structure of HBT's such as double hetero type has been proposed recently. Most of them will come out on the practical stage in very near future, because HBT is a promised device to achieve high efficiency and good linearity on high frequency performance.

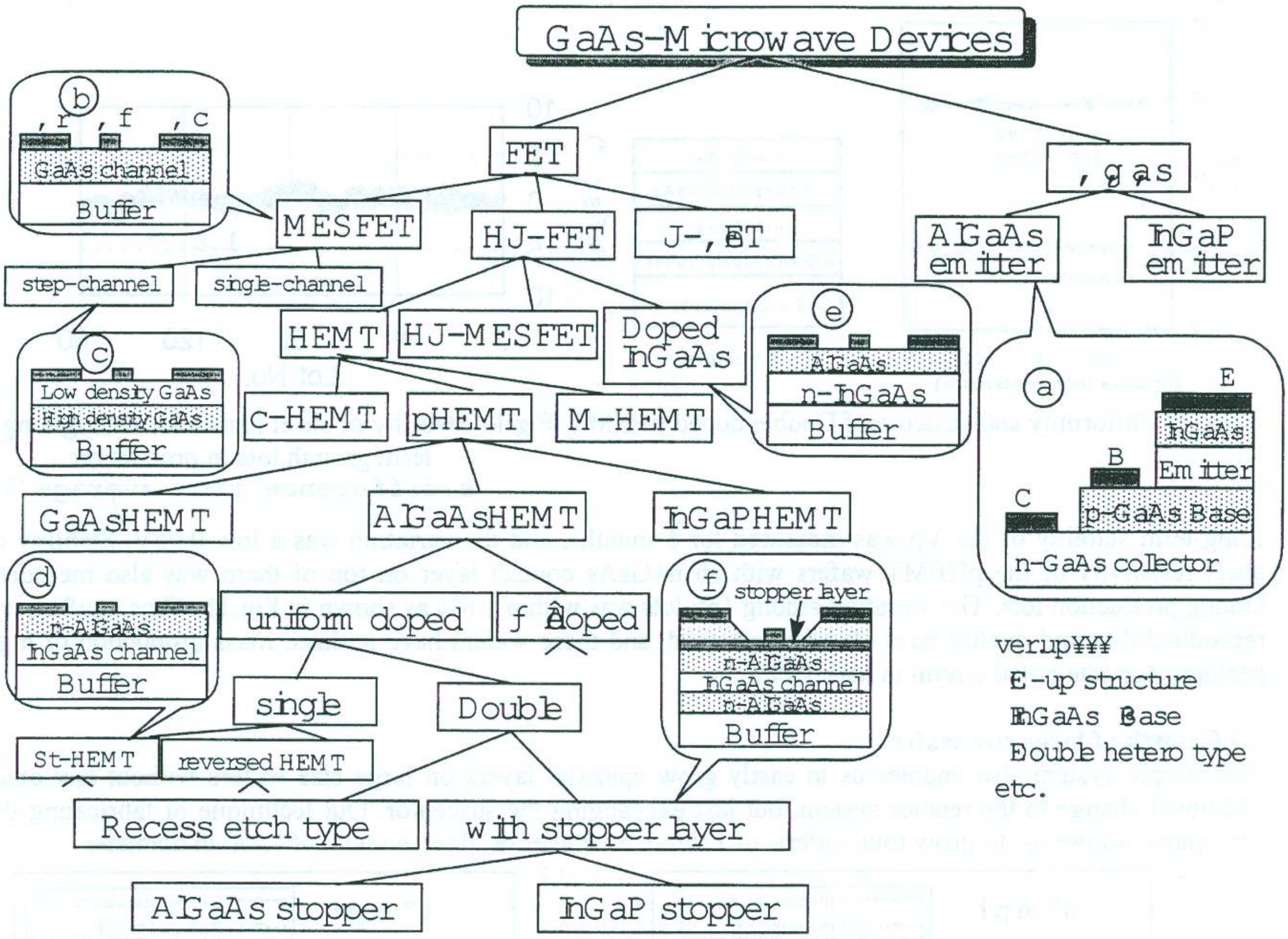


Fig.13 Classification of GaAs-Microwave Devices from view point of epi-structure

4.2 STRUCTURE OF FETs

Boxed figure (b) in Fig.13 shows the simplest structure of FETs named MESFET here, having a GaAs channel and a GaAs Bufer layer. This structure was grown by VPE at the early stage of the "epi-application". A step doped GaAs channel shown in (c) improved FET performance such as gm, maintaining high beak down voltage and is widely used in power FETs. J-FET (junction FET) has p-type layer under the gate electrode and is generally used as an enhanced mode FET. Most popular HJ-MESFET (Hetero Junction MESFET) is well-known HEMT[11] as shown in boxed fig.(d), which has n-type AlGaAs layer as "electron supply layer" on the undoped (=high purity) InGaAs channel layer. This type is still major in low noise applications. The opposite structure has been proposed, that is, the structure having n-type doped InGaAs channel with undoped AlGaAs on it[12] as shown in boxed fig.(e). This type has high breakdown voltage and is used in power applications. M-HEMT (Metamorphic HEMT) has been known to be promised device for next generation, such as high power milliwave system. In M-HEMT wafer, InAlAs or InAlSb is used as "latice reluxing buffer layer" which enable us to grow high molfluction InGaAs channel on it without any distortion. To realize this device on practical stage, progress of device fabrication process and improvement of epitaxitial quality and reliability are highly required.

There are two doping methods, uniform doping and delta doping (=pulse doping, planer doping). It's not

easy to determine which method is better for total performance of the device. It's depended on process and device design. Double doped HEMT as shown in boxed figure (f) have been major in power applications of digital systems. This type has a much higher carrier concentration in undoped InGaAs layer compared with conventional single type and enables us to get high power with high efficiency with low voltage battery under 3V[13]. Conventionally, the recess etching process is applied to reveal the Schottky surface where the gate electrode is formed. This recess etching causes inhomogeneity over a wafer of device performance such as pinch off voltage due to variation of etching depth. To improve the uniformity, stopping layer for the etching is often supplied on the Schottky surface as shown in boxed figure (f). Etching is stopped at the layer by using large selectivity between stopping layer and the layer on it, AlGaAs and GaAs, respectively, for example. Thus, excellent uniformity, as shown in Fig.8 for example, can be realized in actual FETs[14].
InGaP is recently noticed as promised material to get high performance and high yield due to (1) very high etching selectivity to GaAs and AlGaAs[15], (2)wide bandgap with no deep level (no DX center and very little contamination of oxygen) and (3) low density of surface and hetero interface states. Application of InGaP is very wide because of the good features. InGaPHEMT has been reported to have high low-noise performance at high frequency of milliwave application[16]. Excellent uniformity and high breakdown voltage can be achieved by using InGaP as Schottky layer of D-HEMT. InGaP HBT was reported to have High RF performance and good reliability[17]. This material is thought to appear in a practical stage in any application very soon.

5. SUMMARY

The techniques for mass producing LEC substrate and MOVPE wafers for use in microwave devices have been discussed. GaAs semi-insulating ingots (150mm diam., 350mml long) was obtained by Multi-hot-zone very large size pullar. Three step boule annealing and fully-automated process enabled mass production of the large size substrates.Growth reaction under conditions of perfect mass transport limited growth, minimized susceptor heat mass and use of face down system are keys to achieving excellent uniformity with high reproducibility. Design and quality control of buffer layers are also important for excellent power transistors performance. Using these techniques, Vp of a double doped pHEMT wafer can be controlled to less than 20mV in the practical stage. The dual susceptor system are very useful to increase throughput of the reactors. These techniques have been instrumented in realizing mass production of microwave devices with high performance. Structure of the epi-wafers has been complex accompany with a progress of growth technique, device process and device design. InGaP will be key material on the high performance devices of next generation.

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