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Large-Area MOVPE Growth of an n-InGaP/InGaAs/GaAs HEMT Structure Using TBP

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We developed a barrel-type MOVPE reactor using TBP to fabricate n-InGaP/InGaAs/GaAs HEMTs. It can grow five 3-inch wafers in a run. The variations in lattice mismatch, thickness, and donor concentration of the n-InGaP layer were $\pm 7.6\times10^{-6}$, ± 1.1 %, and ± 1.5 % across the entire 3-inch wafer. The electron mobility of an n-InGaP/InGaAs/GaAs selectively doped structure with a 2.5-nm spacer layer was 17,100 $cm^2V^{-1}s^{-1}$ at 77 K and the sheet carrier concentration was 1.66×10^{12} cm^{-2}. We fabricated HEMTs with 0.4 μm gate length, and obtained a maximum transconductance and K-value of 608 $mSmm^{-1}$ and 930 $mAV^{-2}mm^{-1}$.

1. Introduction

InGaP-based HEMTs have many advantages compared with AlGaAs-based HEMTs. The absence of DX centers in Si-doped InGaP prevents I-V collapse at low temperatures.[1,2] The high band offset at the InGaP/GaAs heterointerface improves device performance, and the low Schottky barrier height[3] lets the n-InGaP thickness be reduced, suppressing short channel effects and decreasing power dissipation.[2] In production, multiple-wafer growth is indispensable to increase throughput and reduce running costs. Several researchers have reported large-area growth of GaAs and AlGaAs by metalorganic vapor phase epitaxy (MOVPE),[4-7] but few studies made of InGaP-based structures. Safety concerns remain due to the use of highly toxic group-V hydride gas in the manufacturing phase. Less toxic and liquid organic phosphorous sources such as tertiarybutylphosphine (TBP) have received much attention,[8-10] but few studies on multiple-wafer growth using TBP have been done because it is difficult to obtain a high V/III ratio in a large reactor. We previously developed a large-area MOVPE growth system using TBP.[11] In this paper, we used the reactor for large-area MOVPE-growth of InGaP-based HEMTs and evaluated the epitaxial layer quality. We also fabricated n-InGaP/InGaAs/GaAs HEMTs and evaluated their performance.

2. Experiment

The reduced-pressure barrel reactor holds five 3-inch wafers on its graphite susceptor (Fig. 1). Wafers are heated by an infrared halogen lamp inside the graphite susceptor and each wafer simultaneously rotates on its own local axis at 15 rpm and revolves around the central axis of the reactor at 8 rpm to ensure highly uniform layers. Because phosphorous (P_2, P_4, and P_6) is pyrophoric, the exhaust system was designed carefully. We used the oil-free pumping system and a water cooling baffle to concentrate and dispose of the phosphorous. To obtain a high V/III ratio using TBP, we developed a new direct-feed-control technique[11].

Wafers are LEC-grown GaAs (100) misoriented 2.5° towards the <110>. The growth temperature was varied from 600 to 700 °C with the growth pressure at 50 torr. The Group-III precursors were trimethylgallium (TMGa) for GaAs, and triethylgallium (TEGa) and trimethylindium (TMIn) for InGaAs and InGaP. AsH_3 was used as the arsenic source, PH_3 and TBP as the phosphorous source, and Si_2H_6 as the n-type dopant. We varied the V/III ratio of InGaP between 70 and 600 and grew GaAs and

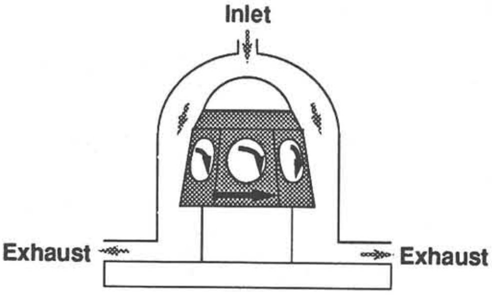

Fig. 1 MOVPE reactor for n-InGaP/InGaAs/GaAs growth.

InGaAs with V/III ratios of 26 and 160. The InGaP, GaAs, and InGaAs growth rates were 0.94, 1.3, and 0.59 μm/h.

Lattice mismatch was measured by double-crystal X-ray diffraction using the Cu-Kα line. Electrical properties of the films were measured using the capacitance-voltage (C-V) and Van der Pauw methods. Small defects were examined using a surface contamination analyzer (Surfscan 4500, Tencor Instruments).

3. Epitaxial Layer Quality

We obtained variations in lattice mismatch, thickness, and donor concentration of less than $\pm 7.6 \times 10^{-6}$, ±1.1%, and ±1.5% in the InGaP across an entire 3-inch wafer (Fig. 2). To evaluate the epitaxial layer quality, we grew n-$In_{0.49}Ga_{0.51}P$/GaAs selectively doped heterostructures with a 2.5-nm spacer layer. We varied the V/III ratios, P-sources, and growth temperature. We also optimized the gas switching sequence to obtain an abrupt heterointerface. A long interruption at the GaAs surface under P-sources resulted in a rough surface. The optimum gas switching sequence was an interruption of 0.5 s under H_2 followed by 0.5 s under P-sources. Using only PH_3, high-quality layers could not be obtained at any growth temperature, though the V/III ratio was very high (Fig. 3). In contrast, using TBP, we obtained a mobility of 21,000 $cm^2V^{-1}s^{-1}$ and a sheet carrier concentration of 1.1×10^{12} cm^{-2} despite the low V/III ratio of 116. Since the decomposition temperature of TBP is very low, large amounts of P-species radicals are produced. This indicates that a large amount of P-species radicals is needed to obtain an acceptable InGaP/GaAs heterointerface.[13)]

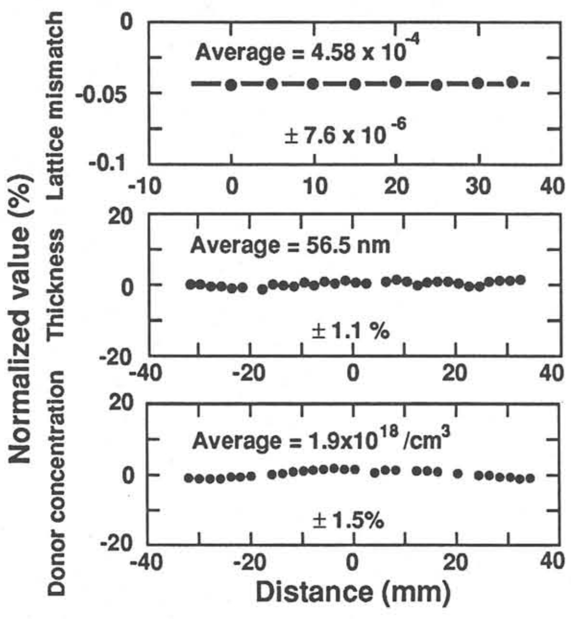

Fig. 2 Variation in lattice mismatch, thickness, and donor concentration of n-InGaP layers in a 3-inch wafer.

Using a mixture of TBP and PH_3, the optimum growth temperature falls to 660 °C. It is considered that larger amounts of P-species radicals are produced at a lower temperature because TBP accelerates the decomposition of PH_3.

Before fabricating n-InGaP/InGaAs/GaAs HEMTs, we examined the optimum condition for n-InGaP/InGaAs/GaAs selectively doped heterostructures. Figure 4 shows the dependence of the relationship between mobility and sheet carrier concentration with 2.5 nm spacer layer at 77 K on the InAs mole fraction (y). At y=0.2 the sheet carrier concentration showed an increase by 60 % compared to y=0 with only a slight decrease in mobility, i.e., an electron mobility of 17,100 $cm^2V^{-1}s^{-1}$ and a sheet carrier concentration of 1.66×10^{12} cm^{-2}. In LSI applications, the uniformity of the threshold

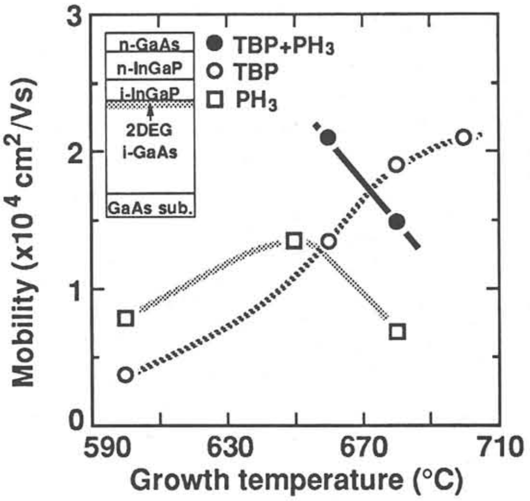

Fig. 3 Dependence of the electron mobility at 77 K of n-InGaP/GaAs heterostructures with a 2.5-nm spacer layer on the growth temperature.

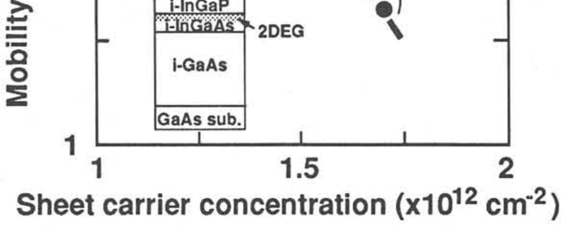

Fig. 4 Dependence of the relationship between electron mobility and sheet carrier concentration on the InAs mole fraction with a 2.5-nm spacer layer at 77 K.

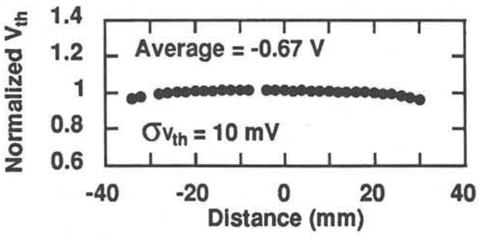

Fig. 5 Threshold voltage variation in an n-InGaP/InGaAs/GaAs heterostructure for a 3-inch wafer.

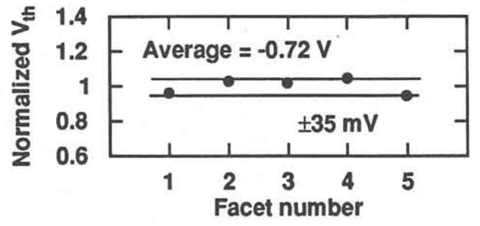

Fig. 6 Threshold voltage variation in n-InGaP/InGaAs/GaAs heterostructures among five wafers in a run.

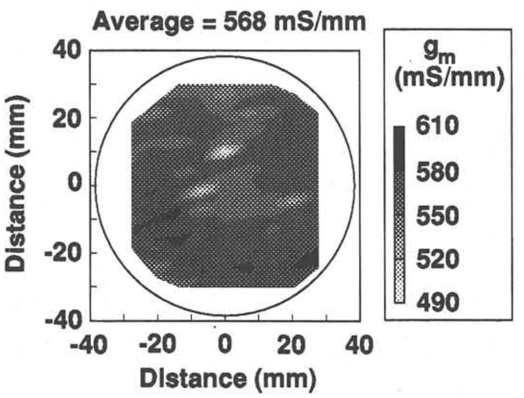

Fig. 7 Transconductance variation of E-mode HEMTs across a 3-inch wafer.

voltage (V_{th}) in actual devices is one of the most important parameters. The threshold voltage was evaluated from pinch-off voltage of the selectively doped heterostructures by C-V measurement.[12] It is easy to predict the actual V_{th} without fabricating devices. We obtained a standard deviation of 10 mV for a V_{th} of -0.67 V (Fig. 5). In batch processing, the uniformity among wafers is very important. We achieved a variation in V_{th} among five wafers of ±35 mV around -0.72 V (Fig. 6).

Surface defects must be reduced to get an acceptable chip yield. We obtained the typical defect density of 5.1 cm^{-2} on the epitaxial layers of LSI structures exceeding the scattering cross section of 0.24 μm^2. These results are sufficient for HEMT-LSI applications.

4. Fabrication of HEMTs

We fabricated HEMTs with 0.4 µm gate length on an MOVPE-grown wafer. The HEMTs had maximum transconductance (g_m) of 608 $mSmm^{-1}$ and a K-value of 930 $mAV^{-2}mm^{-1}$. Figure 7 shows the variation in g_m for E-mode HEMTs over a 3-inch wafer. The standard deviation of g_m was 12 $mSmm^{-1}$. These values satisfy the requirements for LSI operation.

5. Conclusion

We developed a reduced-pressure barrel MOVPE reactor for n-InGaP/InGaAs/GaAs HEMTs. Using TBP, we obtained uniform and high-quality epitaxial layers. A HEMT fabricated on an MOVPE-grown wafer showed good performance.

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