MOVPE Grown Metamorphic HEMT Epitaxial Wafers

T. Tanaka, T. Hashimoto, M. Washima, and H. Sakaguchi
Advanced Research Center, Hitachi Cable, Ltd., 3550 Kidamari, Tsuchiura, 300-0026, Japan
email: ttanaka@arc.hitachi-cable.co.jp , Phone: +81-298-26-7655
Y. Otoki
Hitaka Works, Hitachi Cable, Ltd., 5-1-1 Hitaka-cho, Hitachi, 319-1414, Japan

Abstract

A feasibility study was performed on the MOVPE growth of $In_{0.36}Ga_{0.64}As$ channel M-HEMT epitaxial wafers, which are expected to realize low production costs of high-power and low-noise applications for millimeter and microwave frequency devices. AFM images showed satisfactory morphology of the metamorphic $In_{0.35}Al_{0.65}As$ buffer layers and TEM cross sectional views revealed flat interfaces and uniform layer thickness throughout the $In_{0.35}Al_{0.65}As/In_{0.36}Ga_{0.64}As$ hetero-structures. The resistivity in the metamorphic $In_{0.35}Al_{0.65}As$ buffer was no less than 10^8 Ωcm and Hall mobility in the $In_{0.36}Ga_{0.64}As$ channel was 8,300cm^2/Vs, which is comparable with that of MBE-grown M-HEMT wafers. These results clearly indicate that MOVPE-grown M-HEMT epitaxial wafers have the correct characteristics to be a viable new material for high-speed circuit devices.

INTRODUCTION

Millimeter wave local area networks (LAN) and automobile radar for intelligent transport systems (ITS) are being rapidly realized, and thus there is an impending needs for devices with low noise characteristics and high power handling capability. High electron mobility transistor (HEMT) structures of $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$, which have higher electron mobility and saturation velocity than conventional GaAs field effect transistors (FET) or pseudomorphic HEMT (P-HEMT), are promising for such microwave and millimeter-wave region operation [1]. These $In_{0.53}Ga_{0.47}As$ HEMT epitaxial wafers are usually grown on lattice matched semi-insulating InP substrates, though InP has disadvantages in its fragility, lack of large diameter availability, and high production costs compared with GaAs. Additionally, unlike GaAs substrates, device processes needing back-side etching or wafer thinning are not yet mature for InP. Consequently, lattice-matched HEMT structures grown on InP substrates seem to be far from commercial production. In order to overcome the problems mentioned above, the metamorphic HEMT (M-HEMT) began to attract much attention, and its excellent characteristics and performance have been reported [2]. The M-HEMT is an InGaAs/InAlAs hetero-structure with linear or step graded lattice-mismatched buffer layers, which relax the strain between the epitaxial layers and the GaAs substrate. Until now, M-HEMT's have been grown experimentally by the molecular beam epitaxy (MBE), and the metal-organic vapor phase epitaxy (MOVPE)-grown M-HEMT has not yet appeared. MOVPE has some advantages in mass production and for phosphorus-containing materials such as GaInP and InP, which could be used as etch-stop layers and surface passivation layers, thus growth of M-HEMT structures by MOVPE is considered to be indispensable. In this study, we have investigated the feasibility of the MOVPE growth of M-HEMT epitaxial wafers, and have achieved satisfactory morphology by optimizing growth conditions. We will also report the Hall mobility and pinch-off performance of an MOVPE-grown M-HEMT structure.

EXPERIMENTAL

In M-HEMT epitaxial wafers, various kinds of materials and structures have been selected for the buffer layer [3, 4] and so far the optimum design has yet to be identified. The use of an antimonide buffer [5] is said to achieve superior surface flatness, but it leads to difficulties in the chemical etching process, and it's influence on the environment is also a source of concern. We chose a simple InAlAs buffer layer for basic research, and used step grading techniques by increasing the indium composition, which could decrease the density of misfit dislocations at each interface. The appropriate indium composition for InGaAs layers of M-HEMT material is still in

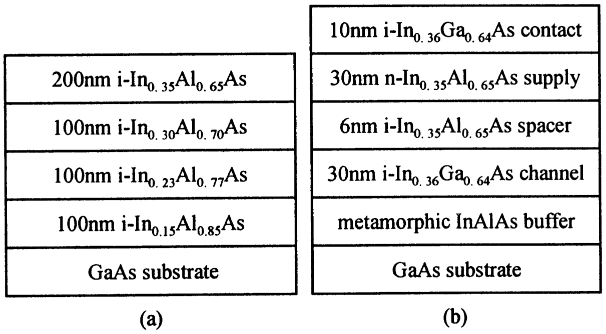


FIG. 1. Cross section of the epitaxial structure of (a) the metamorphic InAlAs buffer layers and (b) the M-HEMT structure grown on semi-insulating GaAs exact (001) substrates.

discussion, because high indium composition leads not only to high electron mobility and saturation velocity, but also brings the possibility of impact ionization, with lowering of breakdown voltages. Thus it is estimated that In=0.35-0.40 is the most suitable combination. The structures of the metamorphic InAlAs buffer and the M-HEMT investigated in this study are shown in Figs. 1(a) and (b), respectively. The indium composition in each layer could be estimated from 4-crystal XRD rocking curves. All the samples were grown by LP-MOVPE, and MBE was also used for comparison. TMI, TMA, TMG, AsH_3 and Si_2H_6 were used as the precursors for MOVPE growth. It is reported that low temperature (350-450°C) growth was needed for M-HEMT structure to achieve high electron mobility in MBE growth [3]. However, in MOVPE growth, such low temperatures lead to insufficient decomposition of the precursors, and hence growth temperatures of 550°C and above were used. The surface morphology of the metamorphic InAlAs buffer layers were observed by atomic force microscopy (AFM). Dislocations and defects distribution in the metamorphic buffer layers caused by lattice mismatch was observed by cross sectional transmission electron microscopy (TEM), where interface flatness between the InGaAs channel and the InAlAs buffer layer was also investigated. The resistivity of the metamorphic buffer layer grown on Si-doped GaAs substrates was estimated by I-V measurement. Hall mobility and sheet carrier concentration of the M-HEMT wafer was measured by the van der Pauw method. Pinch-off performance was confirmed using C-V characterization.

RESULT AND DISCUSSION

Figure 2(a) and (b) show the surface morphology of metamorphic $In_{0.35}Al_{0.65}As$ buffer layer grown by MOVPE. It is noticed that the surface consists of small islands that array along the [110] direction, and thus periodic roughness is formed along the [$\bar{1}$10] direction. Stranski-Krastanov growth, caused by the lattice mismatch with the substrate, and the anisotropic growth rate could be the origins of this striped surface morphology. However, despite the existence of a large lattice mismatch, (2.6%), the roughness is no more than 5nm in a period of about 1μm. Note that vertical direction was

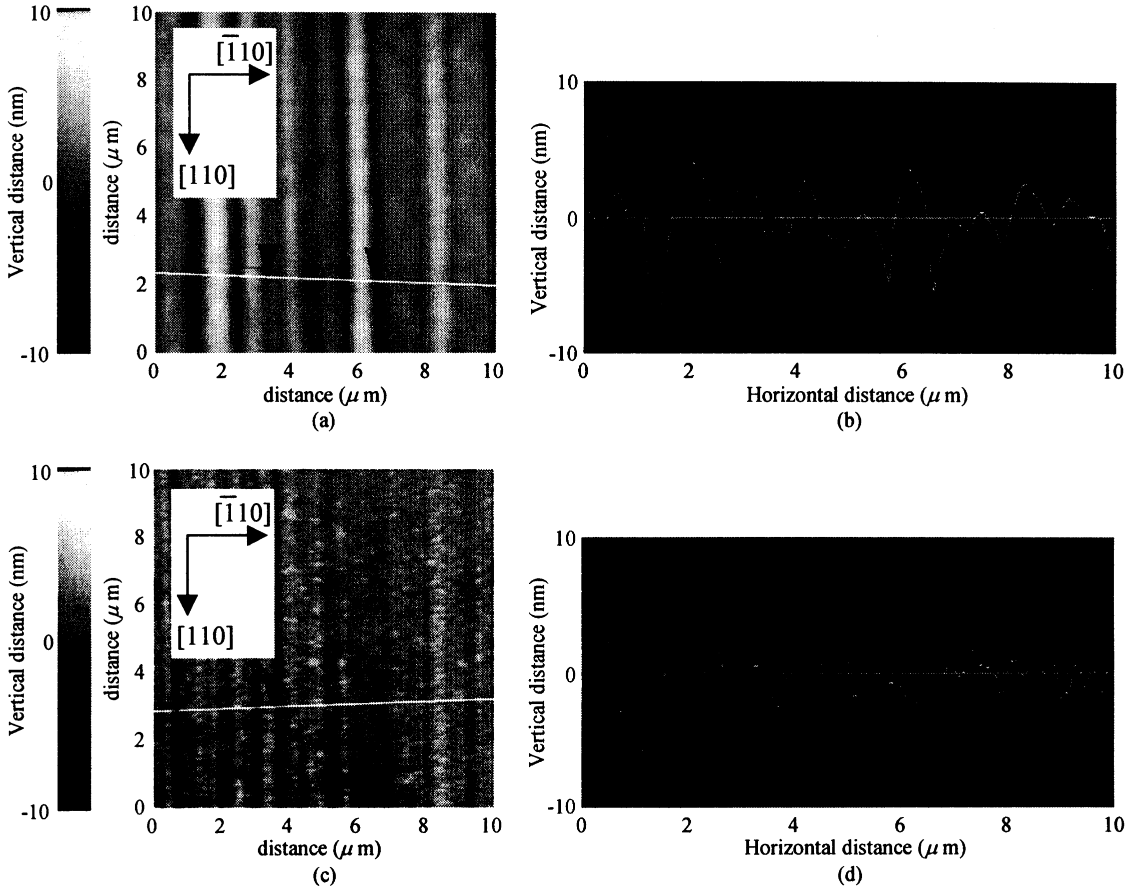
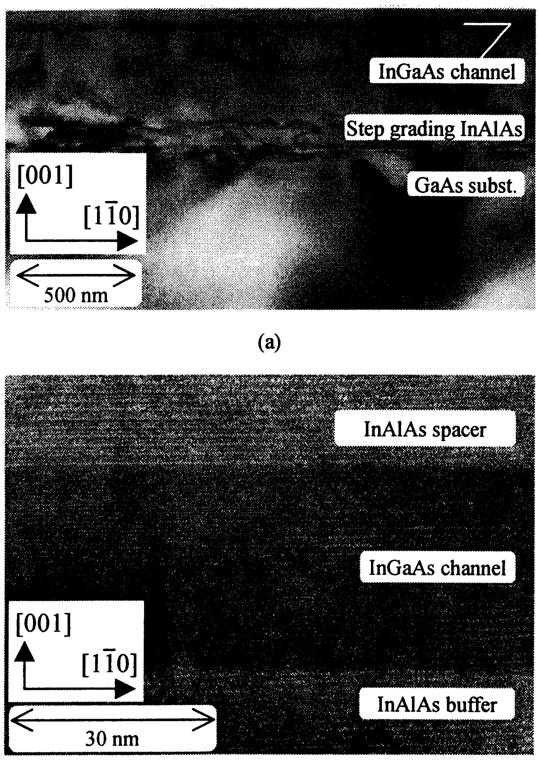


FIG. 2. AFM plan and cross sectional views of metamorphic $In_{0.35}Al_{0.65}As$ buffer layers, where (a) is a plan view of an MOVPE sample, (b) is a cross section of an MOVPE sample, (c) is a plan view of an MBE sample, and (d) is a cross section of an MBE sample, respectively. Note that the units are different for the vertical (nm) and horizontal (μ m) distances. Vertical roughness in (b) and (d) were magnified about 260 times and they seemed to have quite flat surfaces when vertical and horizontal magnifications were normalized.



(a)

(b)

FIG. 3. TEM [110] cross sectional views of (a) whole M-HEMT epitaxial wafer and (b) InGaAs channel layer grown by MOVPE.

emphasized in Fig. 2, and thus it could be concluded that the metamorphic InAlAs buffer layer grown by MOVPE using a step-grading buffer technique has satisfactory flatness. The surface of the MBE-grown metamorphic $In_{0.35}Al_{0.65}As$ is also shown in Fig. 2(c) and (d), for comparison. It is noticed that the size of islands is smaller and thus roughness appears more frequently on MBE sample. The difference in growth temperature of each sample would cause changes in the density of nucleation, which could be the reason for this deference in surface morphology.

Figure 3 shows cross-sectional TEM views of the MOVPE grown M-HEMT, where the whole epitaxial structure is shown in 3(a) and the interfaces with the InGaAs channel layer in 3(b). It is apparent that high-density dislocations or defects were generated very near to the interface between the lowest InAlAs buffer layer and the GaAs substrate. The fact that misfit dislocations concentrate only at the interface is explained by two reasons. Firstly, we designed the metamorphic buffer layers to have the highest mismatch at the $In_{0.15}Al_{0.85}As$/substrate interface (see Fig. 1 (a)). Secondly, the upper layers where compressive stress is applied are harder than the lower layers where tensile stress is applied, because brittle materials like III-V semiconductors are said to have more tolerance to compressive stress than to tensile stress. Consequently, the surface side of the M-HEMT structure, including the channel layer, is almost free from dislocations. The InGaAs channel lattice matched to the metamorphic buffer layer was shown in Fig. 3(b), where dislocations are not observed. It is also confirmed that sufficiently flat interfaces were formed, and that the required thickness uniformity of InGaAs channel was also accomplished.

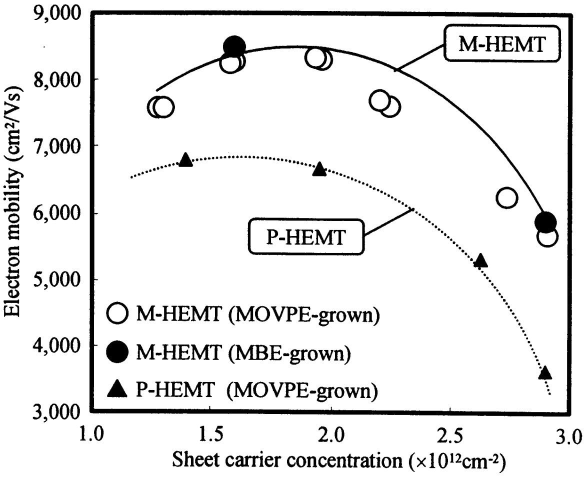


FIG. 4. Electron mobility and sheet carrier concentration in $In_{0.36}Ga_{0.64}As$ M-HEMT and $In_{0.20}Ga_{0.80}As$ P-HEMT. Sheet carrier concentration was controlled by the Si- doping density.

Then the resistivity of the InAlAs buffer layer grown by MOVPE was evaluated. Metamorphic InAlAs layer as shown in Fig. 1(a) was grown on a Si-doped GaAs(001) substrate, and a Si-doped $In_{0.36}Ga_{0.64}As$(10nm) layer was also grown on InAlAs to achieve an ohmic contact. AuGe(600Å)/Ni(100 Å)/Au(3000 Å) electrodes were formed on both the Si-InGaAs and the back-side of the substrate. I-V measurement through the vertical direction of this structure resulted in no less than $10^8\Omega$cm resistivity for the metamorphic InAlAs layers, which was high enough to be used as a current blocking layer for electrical isolation of the HEMT structure. This high resistivity was probably obtained not only by the wide band gap due to the high aluminum composition, (65%) InAlAs, but also because of the possible existence of impurity carrier traps caused by compound defects in the metamorphic buffer.

Figure 4 shows the electron mobilities as a function of sheet carrier concentrations in the M-HEMT and in a conventional P-HEMT for comparison. The low mobility in the small sheet carrier concentration region was caused by the lack of screening effect and the degradation of mobility in the high sheet carrier concentration region was caused by parallel conduction in the Si-doped InAlAs layer and/or remote ionized impurity scattering. The results show that MOVPE-grown M-HEMT's had high electron mobility as high as that of MBE-grown devices, and no differences in channel conduction characteristics were observed between both samples. The formation of the excellent interfaces shown in

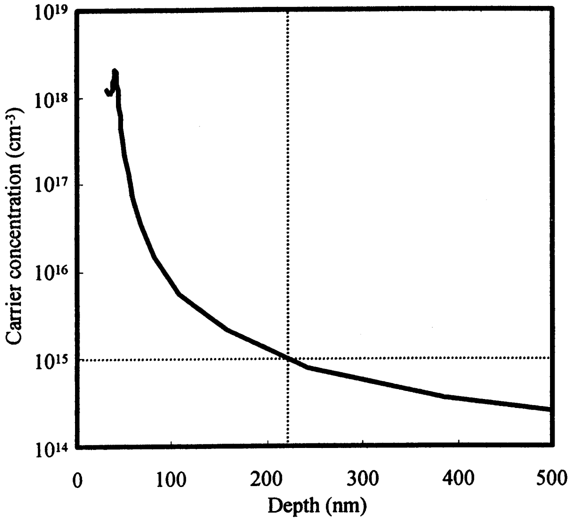


FIG. 5. Carrier profile in MOVPE-grown M-HEMT epitaxial wafer.

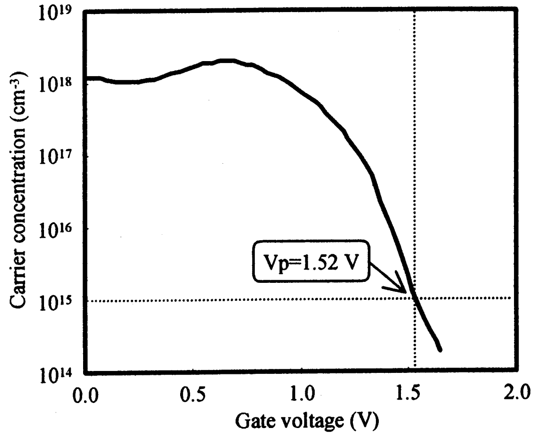


FIG. 6. Carrier concentration as a function of gate voltage in MOVPE-grown M-HEMT wafer measured by C-V method. We define that the HEMT is pinched-off when the carrier concentration becomes $<10^{15}$ cm^{-3}. Thus Vp=1.52 (V) in this case.

Fig. 3 could be the reason for such high electron mobilities [3]. The maximum value of mobility in the $In_{0.36}Ga_{0.64}As$ channel was 8,300 cm^2/Vs, overtaking that of the P-HEMT by more than 1,500 cm^2/Vs.

Figure 5 shows the carrier profile in the MOVPE-grown M-HEMT as determined by C-V measurement. It is apparent that carriers were accumulated correctly in the channel layer, and that no impurity carrier exists in the metamorphic buffer layer. The relationship between the carrier concentration and applied gate voltages in C-V measurement is also shown in Fig. 6. We define the applied voltage at which the carrier concentration becomes $10^{15}cm^{-3}$ as the pinch-off voltage (Vp), where the depletion layer extended to about 200 nm beneath the channel layer in this case. The Vp of 1.52 V in the MOVPE-grown M-HEMT was almost the same as the designed value, thus the drain conductance seemed to be well suppressed. The MOVPE-grown metamorphic $In_{0.35}Al_{0.65}As$ showed perfect pinch off performance, and no obstacles to the practical use of MOVPE-grown M-HEMT wafers were observed.

CONCLUSION

In this study, we have investigated the feasibility of the growth of M-HEMT structures by MOVPE. Both the surface morphology and electrical properties are satisfactory, and almost identical to those of MBE material. This result clearly indicates that MOVPE-grown M-HEMT epitaxial wafers are of sufficient quality for practical use, and that it is a promising material for the coming upsurge in microwave frequency device applications.

REFERENCES

[1] T. Suemitsu, H. Yokoyama, Y. Umeda, T. Enoki, and Y. Ishii, Jpn. J. Appl. Phys.**38**, 1174 (1999)

[2] K. van der Zanden, M. Behet, and G. Borghs, *Comparison of Metamorphic InGaAs/InAlAs HEMT's on GaAs with InP based LM HEMT's*, 1999 GaAs MANTECH Technical Digest

[3] M. Haupt, K. Köhler, P. Ganser, S. Müller, and W. Rothemund, J. Crystal Growth, **175/176**, 1028 (1997)

[4] M. Zaknoune, Y. Cordier, S. Bollaert, D. Ferre, D. Théron, and Y. Crosnier, ELECTRONICS LETTERS, **35**, 1670 (1999)

[5] M. Behet, K. van der Zanden, G. Borghs, and A. Behres, Appl. Phys. Lett., **73**, 2760 (1998)