Comparison of InAlAs/InP Hetero-interface Properties -MBE vs. MOCVD-

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Abstract

InAlAs/InP hetero-interface grown by MBE was compared with that grown by MOCVD from the viewpoints of structural and electrical properties by using Grazing Incidence X-ray reflectometer and C-V method. The etching experiments on a thin InP layer were also made to examine the influence of the interface properties on the etching selectivity. It was revealed that the abruptness of InAlAs/InP interface grown by MBE was better than that grown by MOCVD if the special interface formation process was not employed. In the case of MOCVD epitaxial layer, it was suggested that the transition layer was formed at InAlAs to InP interface and this layer might affect not only electrical properties but also etching process of InP etch-stop layer.

Keywords: MBE, MOCVD, InP, hetero-interface

INTRODUCTION

InP based high electron mobility transistor (HEMT) is a very promising device for high-speed optical fiber communications or millimeter-wave applications [1]. For realizing good device performance, precise fabrication of the epitaxial layer structure is crucial. Especially, properties of a hetero-interface between InAlAs and InP, which is used as an etch-stop layer, are very important because they directly influence device reliability and process repeatability [2].

In most cases, epitaxial wafers for HEMT are grown by MBE or MOCVD and both methods are considered to have sufficient controllability for making HEMT structure. In the case of mass production type machines, however, there have been little report on the difference of the interface properties between these two methods.

In this paper, the structural and electrical properties of InAlAs/InP hetero-interface were studied on the epitaxial wafers grown by multi-wafer MBE and MOCVD. The influence of the interface properties on the etching selectivity of InP etch-stop layer was also examined.

EXPERIMENTAL PROCEDURE

MBE growth was carried out in VG Semicon's V100 system utilizing high-purity elemental Ga, In, As and GaP chunks. The P_2 beam was generated by decomposing GaP source from Compound Cell [3].
MOCVD growth was carried out in a conventional horizontal gas-flow reactor which is configured with a 5x4" planetary and face-down susceptor [4]. 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.
The epitaxial layer stacking structures shown in Table 1 were grown on in-house 3" semi-insulating InP (100) wafers. Growth was carried out continuously even at the hetero-interfaces, by simply switching the molecular beams or the gas flows without using any special technique such as growth interruption.

Table1 The epitaxial layer structures for structural analysis (a) and electrical analysis (b)

(a)

No.	Layer	Thickness (nm)
3	InAlAs	10
2	InP	20
1	InAlAs	210
3 inch Fe doped S.I. InP substrate		

(b)

No.	Layer	Thickness (nm)	Carrier conc.(/cm3)
4	InAlAs	12	2.0E+17
3	InP	96	2.0E+17
2	InAlAs	120	8.0E+16
1	InP	96	undoped
3 inch Fe doped S.I. InP substrate			

The epitaxial layers of the structure (a) in Table 1 were analyzed by Grazing Incidence X-ray reflectometer (Rigaku GXR2)[5]. In this method, thickness and roughness of each epitaxial layer are derived from the measured X-ray reflection spectrum as follows. The X-ray reflection spectrum contains the information of the layer thickness,

refractive index and hetero-interface roughness and Fourier Transformation of the spectrum gives a rough sketch of the structure such as the number of layers and the thickness of each layer. By starting from this rough sketch, X-ray reflection spectrum is simulated and fitted to the experimentally obtained spectrum by iterative calculation in which the epitaxial layer stacking structure is fixed and the thickness and the roughness of each layer are used as fitting parameters. The validity of the simulation results is evaluated by R-factor.
The epitaxial layers of the structure (b) in Table 1 were used for evaluating electrical properties of hetero-interfaces. C-V measurements were carried out to obtain carrier profile by using Hg probe, which had a double Schottky electrode configuration.
Etching experiments were made to examine the influence of the interface properties on the etching selectivity of InP etch-stop layer. Thin InP layer, about 3nm thick, on top of InAlAs buffer layer grown by MBE and MOCVD was etched by the phosphoric acid solution. The etched surface was observed by Normarsky microscope, SEM and AFM.

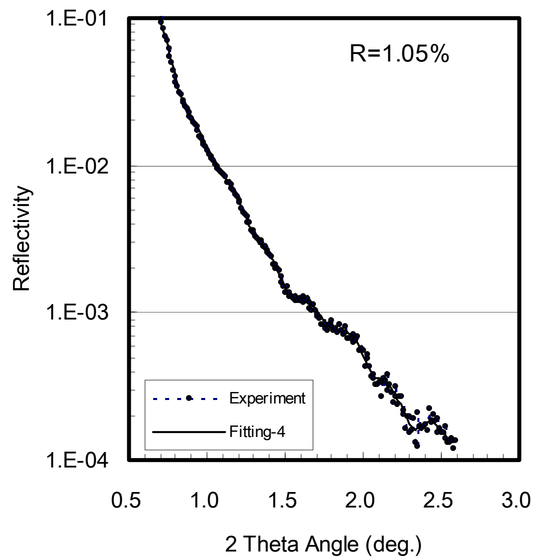

Fig.1 The x-ray reflection spectrum and simulation spectrum for MBE epitaxial layers

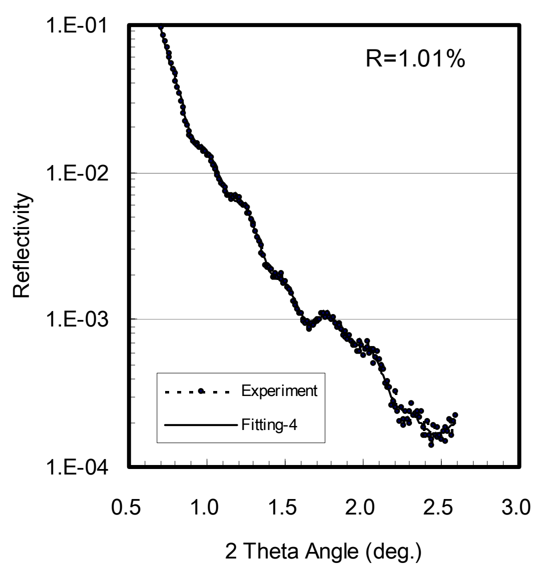

Fig.2 The x-ray reflection spectrum and simulation spectrum for MOCVD epitaxial layers

RESULTS AND DISCUSSION

Fig.1 and Fig.2 show the experimentally obtained X-ray reflection spectra with simulated curves for MBE wafer and MOCVD wafer, respectively.
At first, the simulation was carried out based on the designed epitaxial structures shown in Table 1(a). The resulting R-factor was 1.20% for the MBE epitaxial layer while that for the MOCVD epitaxial layer was 1.90%. This result indicates that the MOCVD epitaxial layer has a little different structure from the designed one.
Therefore, additional three kinds of simulation were carried out by assuming the transition layers at the interface of InP to InAlAs, InAlAs to InP and the both sides of InP. In these simulations 1.0nm and 0.4 nm were used as the initial values for the thickness and the roughness of the transition layer, respectively. All the simulation results are listed in Table 2.
In the case of MBE, the R-factor was slightly decreased to 1.05% from 1.20% by introducing the transition layers at the interfaces but the thickness of each transition layer was estimated to be less than 0.6 nm. On the other hand, in the case of MOCVD, introduction of transition layers at the both sides of the InP layer caused clear reduction of R-factor to 1.01 from 1.90%. The transition layer thickness at InAlAs to InP interface was estimated to be more than 2nm and that at InP to InAlAs interface was about 0.6 nm. The simulated curves in Fig.1 and 2 are both corresponding to Fitting-4 in Table 2.
Thus, it is suggested that the transition layers exist at the interfaces of the MOCVD epitaxial layers and the thickness of the transition layer at InAlAs to InP is thicker than that of the transition layer at InP to InAlAs. It is difficult, however, to judge from this experiment whether there is a transition layer at the interface of the MBE epitaxial layers.

Fig.3 shows the carrier profiles of the epitaxial layers (Table1 (b)) grown by MBE and MOCVD. The carrier accumulation at the interfaces on both sides of InAlAs layer was observed on the MBE wafer but not observed at InAlAs to InP interface on the MOCVD wafer.

Table 2 The fitting results for the epitaxial layers grown by MBE and MOCVD with assuming the transition layers

Layer		Fitting-1				Fitting-2				Fitting-3				Fitting-4			
		MBE Epi		MOCVD Epi		MBE Epi		MOCVD Epi		MBE Epi		MOCVD Epi		MBE Epi		MOCVD Epi	
		Initial Value	Fitting Results	Initial Value	Fitting Results	Initial Value	Fitting Results	Initial Value	Fitting Results	Initial Value	Fitting Results	Initial Value	Fitting Results	Initial Value	Fitting Results	Initial Value	Fitting Results
InAlAs	Thickness (nm)	9.70	10.26	10.06	9.93	9.70	10.58	10.06	9.94	9.70	10.28	10.06	9.92	9.70	10.34	9.70	10.29
	Roughness (nm	0.40	0.40	0.40	0.32	0.40	0.39	0.40	0.23	0.40	0.40	0.40	0.32	0.40	0.38	0.40	0.25
Transition layer	Thickness (nm)					1.00	0.26	1.00	1.25					1.00	0.56	1.00	0.59
	Roughness (nm					0.40	0.39	0.40	0.40					0.40	0.40	0.40	0.40
InP	Thickness (nm)	22.18	21.63	19.95	19.46	22.18	21.30	19.95	19.65	22.18	21.75	19.95	19.97	22.18	21.55	19.95	19.08
	Roughness (nm	0.40	0.09	0.40	0.07	0.40	0.23	0.40	0.40	0.40	0.08	0.40	0.15	0.40	0.20	0.40	0.40
Transition layer	Thickness (nm)									1.00	0.09	1.00	2.67	1.00	0.22	1.00	2.96
	Roughness (nm									0.30	0.39	0.40	0.43	0.30	0.39	0.40	0.36
InAlAs	Thickness (nm)	206.20	209.16	210.44	208.59	206.20	209.20	210.44	204.88	206.20	209.03	210.44	209.56	206.20	209.16	210.44	205.92
	Roughness (nm	0.40	0.38	0.40	0.39	0.40	0.35	0.40	0.07	0.40	0.40	0.40	0.41	0.40	0.40	0.40	0.42
R-Factor (%)		1.20		1.90		1.10		1.10		1.19		1.83		1.05		1.01	

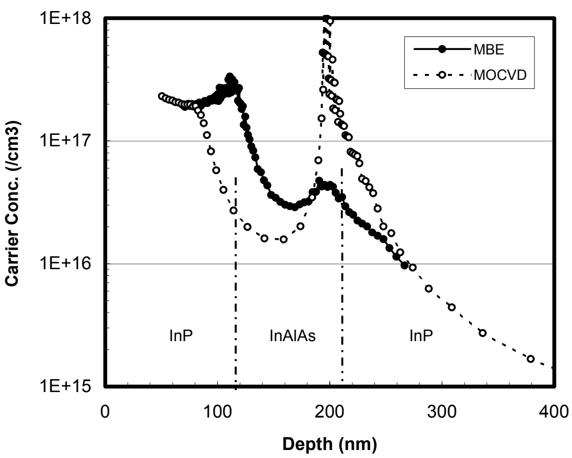

Fig.3 The carrier profiles of the epitaxial layers grown by MBE and MOCVD

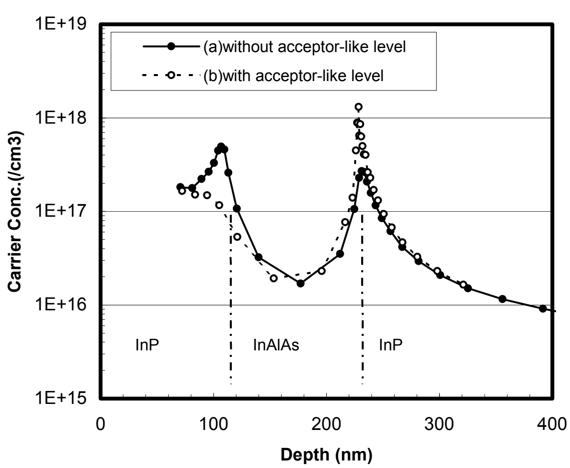

Fig.4 The calculated carrier profiles of the epitaxial layer (a) without and (b) with assuming an acceptor-like level at InAlAs to InP interface

In order to understand these phenomena, the carrier profiles were calculated by solving one-dimensional Poisson equation. The calculated results are shown in Fig.4. The line (a) was obtained by assuming the uniform distribution of dopant in each layer while the line (b) was obtained by assuming the additional acceptor-like level at InAlAs to InP interface.

By comparing Fig.3 and Fig.4, it is concluded that in the case of MOCVD wafer there is an acceptor-like level at InAlAs to InP interface, which may be related to the comparatively thick transition layer observed in the structural analysis.

In the etching experiments, the etched surface was observed after every ten seconds of etch step.

In the case of MBE wafers, the surface appearance was not changed up to 50 seconds of etching and after additional 10 seconds of etching, the surface suddenly became rough as shown in Fig. 5(a). The roughness of this surface was estimated to be about a few tens of nanometer by AFM observation. It is considered that the surface roughness appears when InP layer has just been etched out, because the etching rate of InAlAs is about a hundred times larger than that of InP.

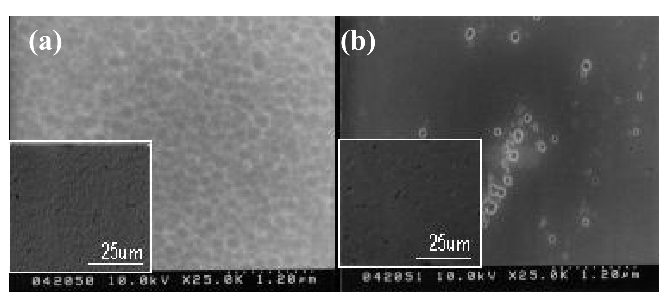

Fig.5 The Normarsky micrograph (insert) and SEM micrograph of etched surface of MBE (a) and MOCVD (b) epitaxial wafers.

In the case of MOCVD wafers, during the first 50 seconds of etching the surface appearance (roughness) was almost the same as MBE wafers with the exception of pits, which appeared after 20 seconds of etching and remained almost unchanged until InP layer completely disappeared. Fig. 5(b) shows the surface of MOCVD wafer after 50 second of etching. The depth of these pits was estimated to be more than 100nm but the accurate measurement was not possible by AFM. These pits are considered to correspond to As-rich regions in InP layer because it is widely accepted that the etching rate of As-contaminated InP is much faster than that of pure InP. This model was confirmed by etching rate measurement on MBE-grown InP layers as shown in Fig.6, in which As was intentionally doped to InP layers.

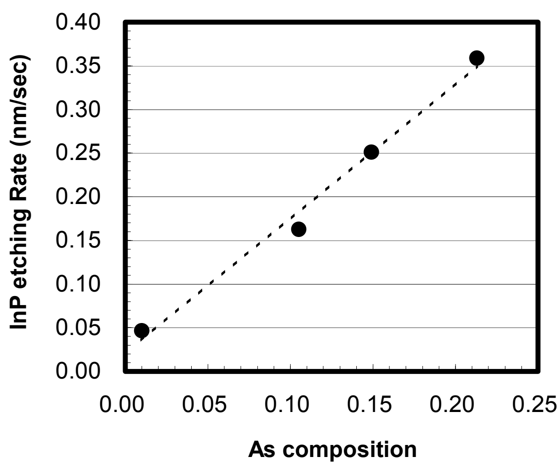

Fig.6 As composition dependence of the etching rate of InP:As layers

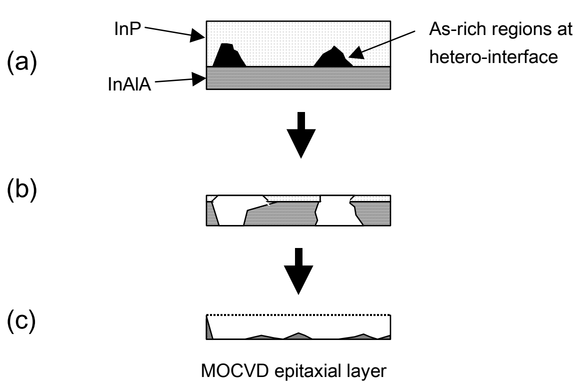

Fig.7 The model of etching process of InP etch-stop layers
(a) Initial stage, (b) pits formation stage corresponding to Fig.5 (b) micrograph, (c) after disappearance of InP layer

The etching process of InP etch-stop layer is explained as shown in Fig.7. At initial stage of etching (0-20 seconds) (a), InP etch-stop layer is etched slowly and uniformly. At second stage (20-50 seconds) (b), As-rich regions in InP layer are etched faster than other part of the layer and many pits are formed. At final stage (longer than 50 seconds) (c), pits disappear when the InP layer is completely etched.

SUMMARY

The interface properties of epitaxial wafers grown by MBE and MOCVD were evaluated by X-ray reflectometer and C-V method. Etching experiments were also made on InP etch-stop layer. It was revealed that the abruptness of InAlAs/InP interface grown by MBE was better than that grown by MOCVD if the special interface formation process was not employed. The result of structural analysis implies that there are nominally no transition layers when grown by MBE. In the case of MOCVD, it is suggested that scattered As-rich regions in InP layer are formed at InAlAs to InP interface and this configuration may be interpreted as a transition layer in structural and electrical analysis.
It is indicated that special attention has to be paid to the interface formation process when the InAlAs/InP system is grown by MOCVD.

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ACRONYMS

HEMT: High Electron Mobility Transistor
MBE: Moleculor Beam Epitaxy
MOCVD: Metal-Organic Chemical Vapor Deposition
SEM: Scanning Electron Microscope