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Fabrication of InGaAs Wires by Preferential MBE Growth on Corrugated InP Substrate

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InGaAs wire structures were successfully formed by preferential MBE on corrugated InP substrates having V-grooves with (211)A or (111)A facet produced by laser interference lithography. The effect of the growth conditions on structures and properties of the wires was examined by SEM and PL. The inner splitting phenomenon was observed in the wires formed on (211) facets and was explained by a growth kinetics related mechanism. Strong PL emission with a narrow peak width was observed, showing that the wire crystal and its interface are free from defects.

1. Introduction

Judging from recent trends of device miniaturization in LSI technology, it is certain that the device size will enter into the quantum mechanical region before long. Therefore, it is necessary to establish suitable fabrication methods of damage-free quantum structures that will become basic constituent elements of next generation quantum LSIs.

For realization of quantum structures, a variety of approaches have been used up to now[1)-3)]. Among them, the preferential growth techniques has attracted significant attention since it has a potential capability of producing damage-free quantum structures. So far, the preferential growth technique has been applied mostly to GaAs quantum structures and very few attempts have been made on semiconductor alloy materials. This is due to potential difficulties including achievement of composition control and uniformity[4)], danger of phase separation, generation of unwanted stress etc. expected in mixed alloys.

The purpose of this paper is to report on a preferential molecular beam epitaxy (MBE) growth process for fabrication of quantum wires using InGaAs/InAlAs material system. This system is particularly suited for quantum devices because of the high mobility and the large conduction band discontinuity. The preferential growth was made on the corrugated InP substrates formed by laser interference lithography[5)]. Relationships between the growth conditions, including the growth temperature and the arsenic pressure, and the structure and crystal quality of the wire were clarified using scanning electron microscope (SEM) observations and photoluminescence (PL) measurements. Understanding and overcoming the newly observed inner splitting phenomenon in the wire structure, the optimum processing conditions for formation of InGaAs wire structures with strong PL were established.

2. Selective MBE growth and structural characterization

The sample preparation sequence is shown in Fig.1. Surface corrugation on the InP substrate was prepared by the laser interference lithography technique[5)] using Ar ion laser (488nm) and wet chemical etching ($HCl:CH_3COOH:H_2O_2$). The period of corrugations was set to be 1um. The grating lines were parallel to the <110> direction.

Production of two kinds of V-groove facets was found to be possible simply by changing the surface treatment prior to photoresist coating for interference lithography. Namely, the ordinary treatment, consisting

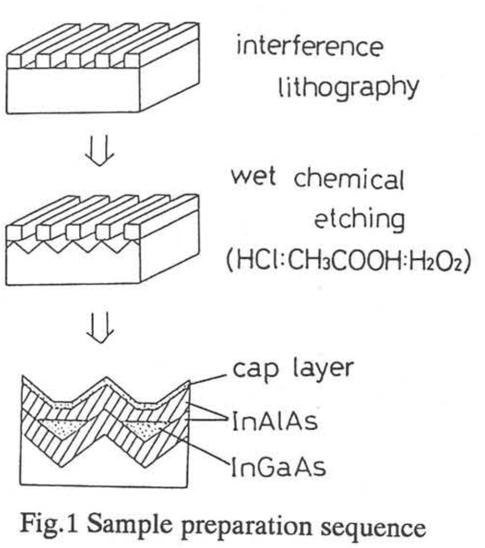


Fig.1 Sample preparation sequence

of cleaning using a series of organic solvents, deionized water rinsing and dry-up resulted in formation of (211) facets. On the other hand, an additional HF treatment after the ordinary treatment and before photoresist coating produced (111)A facets. The effect of HF treatment is attributed to increased adhesion between the substrates and photoresist by removal of surface oxides[6].

To establish selective growth conditions, InGaAs and InAlAs were grown on both (111) and (211) V-grooves at various substrate temperatures and As pressures. The results of SEM observations of cross-sectional structures are summarized in Fig.2. On the grooves with (211) facets, Structures A (both InGaAs and InAlAs follow the substrate), B (InAlAs follows the substrate and InGaAs gathers at the bottom of the groove) and C (both materials gather at the bottom) appeared at the growth temperatures, below 350°C, from 400°C to 430°C, and above 460°C, respectively. On the other hand, the Structures A, B and C appeared at the growth temperatures, below 350°C, at 400°C, and above 430°C, respectively, when growth was done on (111) V-grooves. As pressure was changed from $5x10^{-7}$ down to $1x10^{-5}$Torr, but no drastic change occurred in cross-sectional structures.

Then, InAlAs/InGaAs/InAlAs and InAlAs/InGaAs/InP wire structures were grown on the (111) and (211) V-grooves using the above conditions. SEM micrographs of the cross-sections of the InAlAs/InGaAs/InAlAs wires grown on (211) and (111) V-grooves are shown in Figs.3(a) and (b), respectively, together with their schematic representation. Existence of a triangular shaped wires are clearly seen in each case.

Although the fabricated wire sizes are too large in Fig.3 to expect occurrence of quantum effects, reduction of wire size into mesoscopic regime can be done simply by reducing the amounts of Ga and In supply.

3. Inner Splitting Phenomenon in Wire Structure

The wires grown on (211) grooves having bottom InAlAs barrier layer showed an additional feature of inner splitting in the wire structure as seen in Fig.3(a). Since such inner splitting is obviously

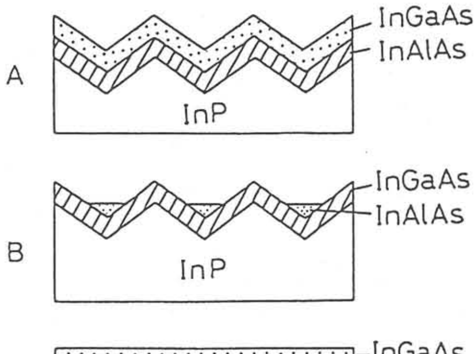
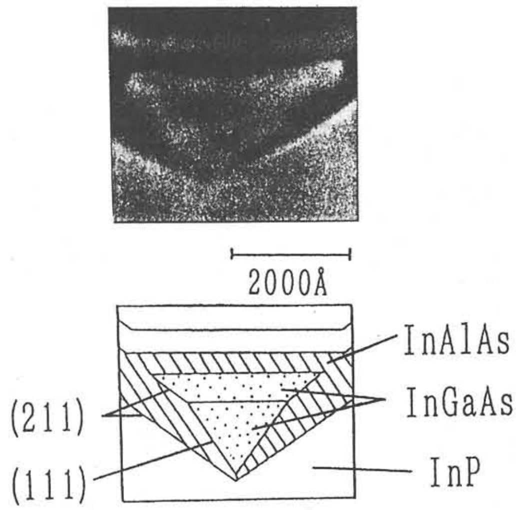
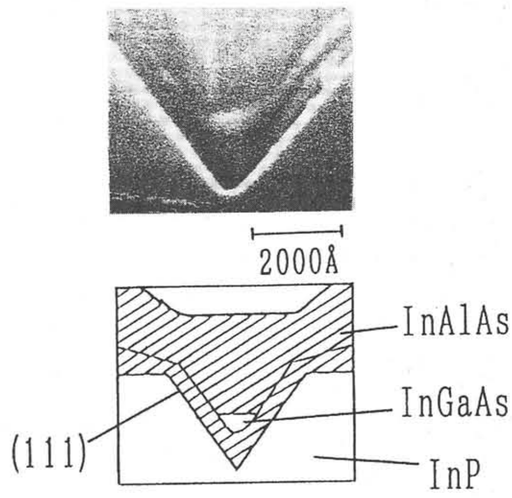


Fig.2 Temperature dependence of sample structures



(a) (211)V-groove



(b) (111)V-groove

Fig.3 SEM photograph and its schematic view

unfavorable for quantum wire realization, its formation mechanism was investigated.

It seems that there are two possible driving forces that may cause such a separation. One is the thermodynamically driven mechanism towards phase separation through spinodal decomposition which is known to occur in many alloy systems[7]. The other is the growth kinetics related mechanism including differences in the surface diffusion length, the incorporation characteristics etc. of various group III atoms on various facets.

To test the possibility of occurrence of spinodal decomposition, growth of InGaAs wire above the estimated critical temperature for spinodal decomposition of 470°C was attempted, but it did not remove splitting. Furthermore, it was noted that the wire splitting phenomenon took place only in the case of growth on (211) V-grooves having a bottom InAlAs barrier layer. Growth on (211) V-grooves without a bottom InAlAs did not lead to such splitting. Close SEM examination revealed that the (211) oriented

InAlAs bottom barrier layer grown using condition B actually include small (111) facet tip at the bottom part of V-grooves and the inner splitting is triggered at the boundary of (211) and (111) facets.

From the these experiments, possibility of phase separation by spinodal decomposition was excluded and the splitting was concluded to be due to difference of migration lengths and incorporation characteristics of group III atoms on (211) and (111) facets.

4. PL measurements

PL measurements were done at 77K and 7K. No photoluminescence was observed from the wire structures without bottom InAlAs barrier layer both grown on (111) and (211) V-grooves. This may be due to poor interface quality or poor quality of wire crystals.

Measured PL spectra of wires having InAlAs top and bottom barrier layers are shown in Fig.4. The dash-dot curve is the 77K PL spectrum of the wire formed on (211) V-grooves. It has three peaks with the one at 1.05eV coming from a thin InGaAs cap layer. Other two peaks come from the two parts of the splitting wire. The solid and dashed curves in Fig.4 show the PL spectra of the wire formed on ($1\bar{1}1$) grooves at 7K and 77K, respectively. The peak around 0.8eV originates from the InGaAs wire. The observed sharp peak width (FWHM = 30meV at 7K) with a high intensity indicates that the quality of the InGaAs wire crystal is excellent. From the detailed analysis of the dependence of the PL peak position on temperature, it was concluded that the alloy composition of the InGaAs wire is almost equal to the one lattice matched to InP. Figure 5 shows the excitation power dependence of the peak intensity of 0.8eV peak at 7K. The observed unity slope also shows that the wire crystal and its interface are defect-free.

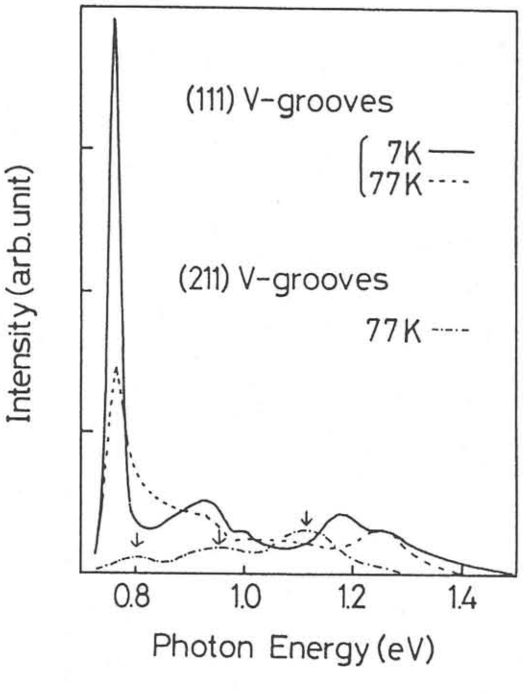


Fig.4 PL spectra of the wires

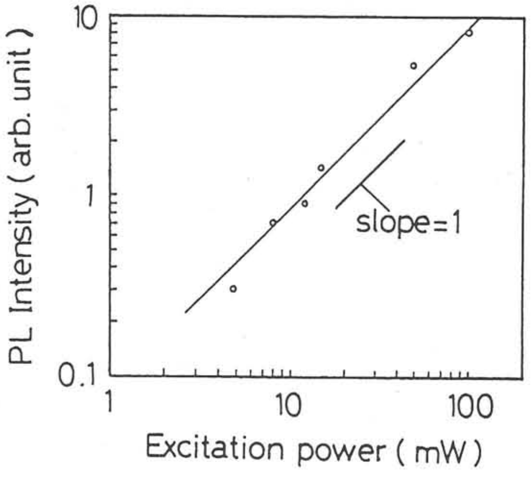


Fig.5 Excitation power dependence of the peak intensity of 0.8eV peak at 7K. (($1\bar{1}1$) V-grooves)

5. Summary

$In_{0.53}Ga_{0.47}As$ wires embedded in $In_{0.52}Al_{0.48}As$ barriers on ($1\bar{1}1$) or (211) V-grooved InP substrates were successfully grown for the first time using the preferential MBE growth technique. The growth conditions to form wire structures with strong PL intensity were established.

An inner splitting phenomenon of the wire structure was observed, and was shown to be not due to the spinodal decomposition but due to a growth kinetics related mechanism.

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