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Controlled Formation of Narrow and Uniform InGaAs Ridge Quantum Wire Arrays on Patterned InP Substrates by Selective Molecular Beam Epitaxy

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1.Introduction

Since the quantum wire is one of the basic components of various quantum devices, formation of arrays of narrow and uniform quantum wires in a controlled fashion is a key issue to realize advanced optoelectronic devices and future quantum LSIs.

The purpose of this paper is to investigate the feasibility of forming precisely size controlled, narrow and highly uniform $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ ridge quantum wires by selective MBE method on patterned InP substrates. A minimum wire width of 35nm and a minimum PL FWHM value of 32meV have been achieved in a controlled fashion by growth optimization. They seem to be the best values obtained so far on this material system and future improvements seem to be possible.

2. Method and Principle of Wire Formation

The sequence and the basic principle for wire formation is shown in **Fig.1**. An InP substrate having <$\bar{1}$10>-oriented mesa-stripe pattern is prepared by photolithography and wet chemical etching. Growth of the InGaAs buffer layer at T_{g1} and InAlAs layer at T_{g2} realizes (311)A ridge.

The principle of the ridge wire formation is based on our finding that the (311) ridge of InAlAs becomes unstable at a higher growth temperature, T_{g3}, and gradually changes into (411) ridge with a width W after the passage of time, t. Then, subsequent growth of InGaAs leads to selective formation of InGaAs wires with a width W surrounded by (311)A and (411)A facets. Finally, the wires are covered by a thick InAlAs barrier layers grown at T_{g4}.

3. Wire Width Control and PL Study

Figure 2(a) shows an example of cross-sectional SEM image of the InGaAs ridge quantum wire ($T_{g1}=T_{g2}=500°C$, $T_{g3}=580°C$, $T_{g4}=550°C$, t=10min). An arrow-head shaped InGaAs wire with an width of 90 nm was clearly seen. More specifically, the growth of bottom InAlAs layers at $T_{g3}=580$ °C for t=3, 5 and 10 min resulted in formation of the wire with widths, W, of 35, 46 and 90 nm, respectively. **Figure 2(b)** shows the measured dependence of the wire width, W, on the growth time, t, of bottom InAlAs layer at $T_{g3}=580°C$. As shown here, the wire width was found to be proportional to t with a slope of 0.15nm/sec, indicating that the quite simple and precise control of the wire size can be made in this method. Moreover, the wire width W and the total thickness of the bottom barrier layer can be adjusted independently as one likes by adjusting the thickness of the first InAlAs layer grown at T_{g2} properly.

PL spectra of the wire with W of 90, 46 and 35nm and with the InGaAs buffer layer grown at $T_{g1}=500°C$ are shown in **Fig.3**. All the spectra were found to posses essentially the same components and can be deconovluted into Gaussian peaks corresponding to the emissions from various parts which were previously assigned by a detailed spatially resolved cathodoluminescence study[1]. The major three parts are the emission from the wire, that from the parasitic quantum well (QW) on the (311)A facets and that from QW

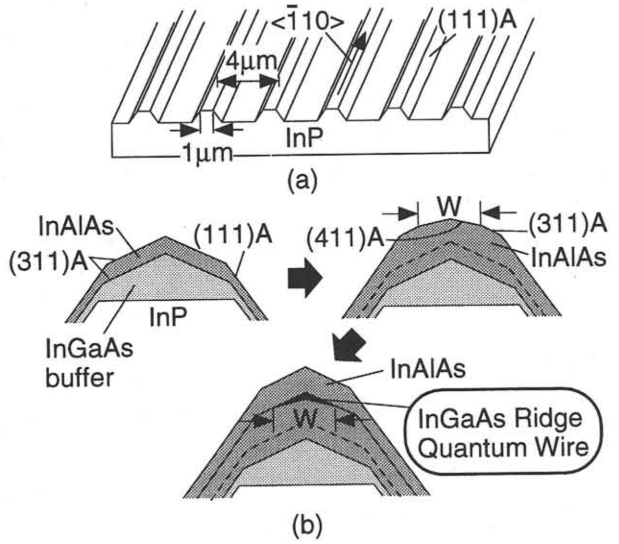


Fig.1 (a) Patterned Substrate used in this study and (b) Sample preparation sequence.

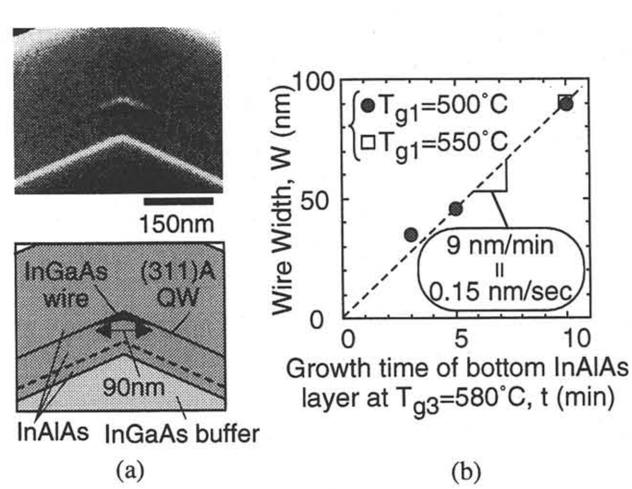


Fig.2 (a) Cross-sectional SEM image of the wire (t=10 min). (b) Dependence of the wire width on the growth time of the bottom InAlAs layer at 580°C.

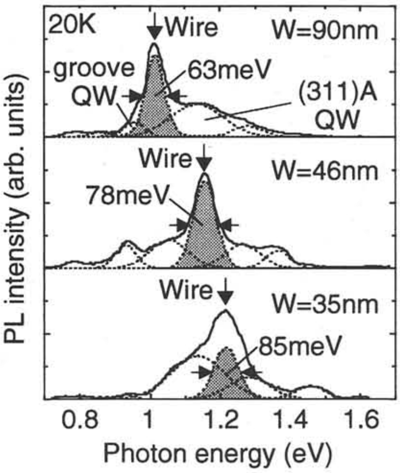


Fig.3 PL spectra of the wires (T_{g1}=500°C).

at the bottom grooves, respectively. In all the spectra, the peaks due to the wires showed the strongest intensity, indicating realization of the wires with high crystal qualities. The position of the PL peak of the wire shifts to a higher energy side with decreasing W. As shown in **Fig.4**, the dependence of energy positions of the peaks due to the wires on W agrees well with the theoretical curve obtained by numerically solving the Schrödinger equation using the observed wire shape and size and assuming a lattice-matching of the InGaAs wires to InP.

4. Size Uniformity and Its Improvement

The observed PL FWHM values are summarized in **Fig.5(a)** by filled circles where the FWHM value increases with decreasing W, indicating existence of fluctuation of wire size and/or alloy composition. In order to clarify the cause of fluctuation, a detailed SEM study was made. **Figure 5(b)** shows a typical plan-view SEM image of the wire having the InGaAs buffer layer grown at T_{g1}=500°C. As seen here, the growth at the (111)A sidewalls proceeded irregularly. Detailed SEM observation revealed that the irregular growth was due to an appearance of extra (122) facets on the (111)A sidewalls.

Then, such a irregular growth was found to be greatly suppressed by use of a high temperature for growth of the

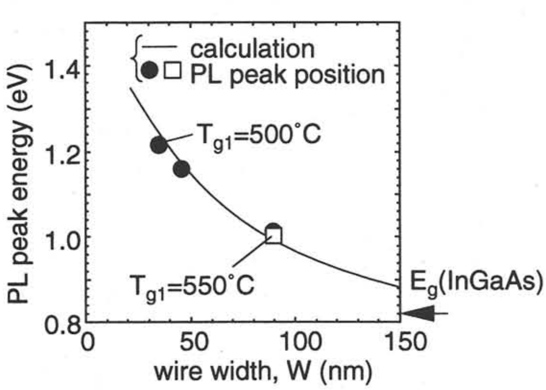
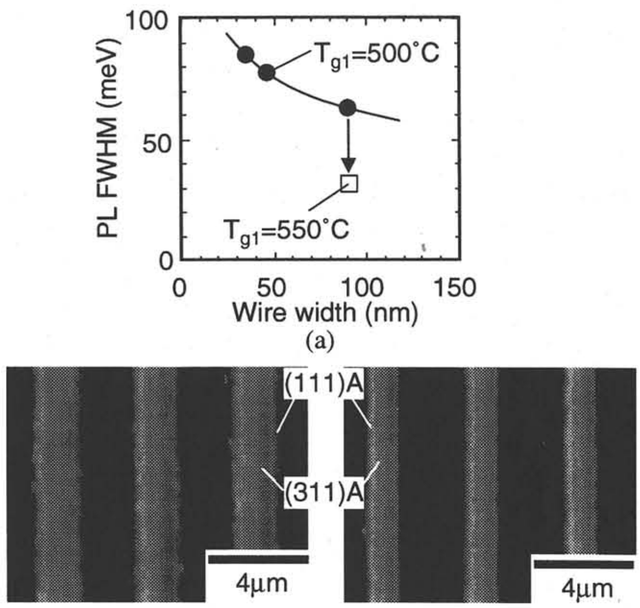


Fig.4 Dependence of the PL peak position on the wire width with theoretically expected curve.

InGaAs buffer layer (T_{g1}=550°C) as shown in **Fig.5(c)**. **Figure 6** shows a PL spectrum of the wire with the width W of 90nm and with the InGaAs buffer layers grown at T_{g1}=550°C. The energy position of the PL peak due to the wire again agrees well with the theoretical value as shown in Fig.4. On the other hand, quite narrow PL FWHM value of 32meV is achieved in this wire, which is the half of that of the previous wire (T_{g1}=500°C) as shown in Fig.5(a) by a white square, indicating drastic improvement of the uniformity of the wire by change of buffer layer growth condition. Thus, further improvement in uniformity seems to be possible by further optimization of the other MBE growth conditions.

Reference

1) H.Fujikura and H.Hasegawa: J. Electron. Mater., **25** 619 (1996).



(b) T_{g1}=500°C (c) T_{g1}=550°C

Fig.5 (a) Wire width dependence of PL FWHM values. (b), (c) Plan-view SEM images of the wires with T_{g1}=500 °C and 550°C, respectively.

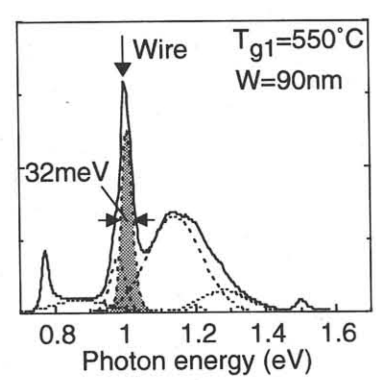


Fig.6 PL spectrum of the wire with high temperature grown InGaAs buffer layer (T_{g1}=550°C).