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Photoluminescence and Cathodoluminescence Characterization of InGaAs Ridge Quantum Wires Formed by Selective Molecular Beam Epitaxy

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Arrays of new type InGaAs ridge quantum wires were grown on patterned InP (001) substrates by selective molecular beam epitaxy (MBE), and were characterized by photoluminescence (PL) and cathodoluminescence (CL) methods. Both in the PL and CL measurements, the InGaAs wires showed strong emission peaks with narrow peak widths, indicating that the wires possess excellent crystal and interface qualities as well as good spatial uniformity. The PL peak from the InGaAs ridge quantum wire was dominant within a temperature range from 20 to 290K and had a strong intensity even at 290K.

1. INTRODUCTION

Judging from recent trends of device miniaturization in LSI technology, quantum wires and dots may become basic building blocks of next generation quantum LSIs. For realization of such quantum LSIs, it is necessary to establish a suitable fabrication method of damage-free quantum structures that allow realization of quantum devices operating at room temperatures.

Among the various approaches of fabricating quantum wires and quantum dots, selective and self-organized growth appear to be promising because of absence of process-induced damage.[1)-5)] Particularly, growth on high index facets formed on patterned substrates is interesting since growth rate modification and related material transfer may take place so as to enhance selectivity and self-organized growth kinetics. Additional advantage of such a method is that it provides a good controllability of the positioning of quantum structures.

From such a point of view, we have recently been studying selective molecular beam epitaxial (MBE) growth characteristics of InGaAs/InAlAs material system and succeeded in realizing a new type of InGaAs/InAlAs ridge quantum wire on a nonplanar substrate, utilizing the selective growth mechanism.[6)] This material system seems to be attractive for constructing high performance quantum devices operating at high temperatures because of its small effective mass and large conduction band discontinuity.

The purpose of this paper is to discuss the optical properties of the InGaAs ridge quantum wire formed by our novel approach. Photoluminescence (PL) and cathodoluminescence (CL) measurements were made to characterize the wires.

2. EXPERIMENTAL

Array of new type InGaAs ridge quantum wires was formed by selective MBE growth on a mesa patterned (001) InP substrate. Figures 1 shows the structure of the selectively grown InGaAs quantum wire together with an example of cross-sectional SEM image. The mesa pattern on (001) InP surface was prepared using photolithography and wet chemical etching. The orientation of mesa stripe was <$\bar{1}$10> direction and the pitch was 4μm. Each mesa consisted of a terrace with a width of 1μm and two (111)A sidewall facets. On the InP mesa stripes, ridge structures having smooth InGaAs (311)A facets could be formed by MBE growth of InGaAs buffer layer.[6),7)] Following the buffer InGaAs layer, InAlAs/InGaAs(wire)/ InAlAs layers were grown. During the growth of bottom InAlAs barrier layer, (411)A facets appeared and developed at the top of ridge. The InGaAs wire layer could be grown selectively at the (411)A facet region, resulting in the formation of InGaAs ridge quantum wires. As seen in Fig.1, the InGaAs ridge quantum wire with a lateral width of 100nm was successfully fabricated on the top of ridge. Presence of very thin quantum wells on (311)A sidewall facets can also be recognized in this figure. The amount of InGaAs supplied to realize this wire was equivalent to form a planar InGaAs layer with a thickness of 2.5nm, hereafter denoted t_{planar}=2.5nm. Other wires with thicker t_{planar} (=5nm) were also fabricated in this study.

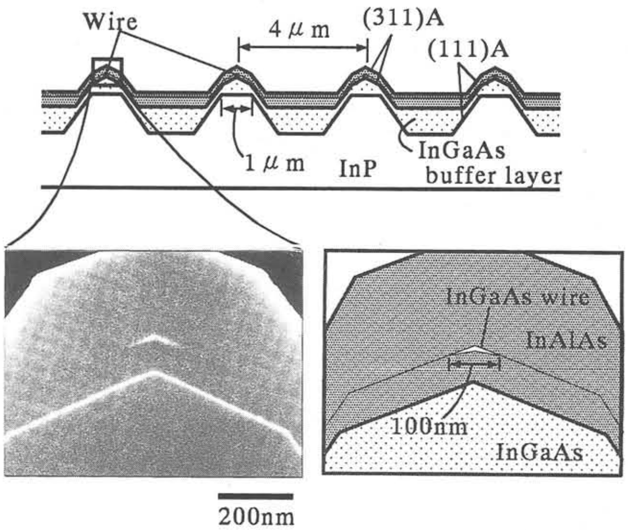


Fig.1 Structure of the new InGaAs quantum wire and its cross-sectional SEM image (t_{planar}=2.5nm).

A standard solid-source MBE system was used in the present study. In all the growth runs, substrates were rotated during the growth to suppress the effect arising from the differences in the incident molecular beam directions with respect to the substrate structures. To monitor the surface reconstruction by the reflection high energy electron diffraction (RHEED), unpatterned planar (001) InP substrates were put beside the mesa-patterned substrates. The growth rate was set at 600nm/h on the planar substrate throughout this study. As_4 pressure was varied in a range from 1 to 3×10^{-6} Torr, where As stabilized surfaces were maintained during the growth.

To characterize the InGaAs ridge quantum wires, CL and PL measurements were performed. CL measurements were done at 4K, setting an acceleration voltage of electron beam at 10kV. PL measurements were made between 20K and 290K under excitation by Ar^+ laser light (514.5nm).

3. RESULTS AND DISCUSSION

The CL spectra of the wire (t_{planar}=2.5nm) measured at 4K are shown in Fig.2, together with the PL spectrum measured at 20K. The thicker and thinner broken curves in Fig.2 are CL spectra taken using spot excitation of the ridge region, including the quantum wire, and the bottom groove region, respectively. In the CL spectrum measured by exciting the ridge region, an intense peak was observed at 1.058eV. The peak exhibits a gradual tail at the higher energy side. On the other hand, a smaller and broader peak covering energy range from 0.9 to 1.2eV is seen in the CL spectrum of the bottom groove part. In the PL spectrum, a strong peak with a narrow width was observed at 1.017eV. In addition, two weaker peaks are seen at the higher and lower energy sides of the dominant peak in this spectrum. Another weak peak was also observed at around 0.8eV.

Both of the dominant peaks in the PL and CL spectra can be assigned to originate from the InGaAs ridge quantum wires. The difference in the positions of the dominant peaks in the CL and PL spectra is due to the band-filling effect caused by strong excitation in CL measurements. The weaker peak in the PL spectrum and the tail in the CL spectrum located at the higher energy side of the dominant peaks may be due to emission from thinner wells on (311)A sidewall facets whose presence was recognized in Fig.1. On the other hand, the weaker PL peak at the lower energy side of the dominant peak as well as the broader CL peak can be attributed to emission from the InGaAs well lying at the bottom groove part. The peak at around 0.8eV, which corresponds to the energy gap of InGaAs, can be assigned as the emission from the InGaAs buffer layer.

The CL image taken at the peak energy position of 1.058eV is shown in Fig.3. The positions of the bright spots exactly coincide with those of the ridge wires in SEM image, further confirming the above assignment.

Remarkably strong intensities of the emission from the ridge quantum wires in spite of their small volume indicate that the rate of carrier transfer into the wire and the efficiency of radiative recombination process with the wire are both high. In addition, uniform brightness of CL image at 1.058eV in Fig.3 indicates high uniformity of the wires.

A PL spectrum of the wire with thicker t_{planar} of 5nm and that of a simultaneously grown quantum well sample are compared in Fig.4. As seen in this figure, the spectrum of the wire have a dominant peak at 0.854eV with strong intensity and narrow FWHM of 39meV, comparable to that of the planar sample. Similarly to the previous case, the dominant peak in this spectrum was found to originate from the ridge quantum wire itself. This value of FWHM of the wire is close to the best value of 35meV reported[8] for unstrained InGaAs quantum wires prepared by selective epitaxy.

Figure 5 shows PL spectra of the wire (t_{planar}=2.5nm) measured within a temperature range from 20K to 290K. As seen in Fig.5, the peak from the InGaAs wire was dominant within the whole temperature range and had a strong intensity even at 290K. Figure 6 summarizes the measurement temperature (T_m) dependence of the position and intensity of the dominant PL peak of the wire (t_{planar}=2.5nm), together with those of the simultaneously grown InGaAs quantum well. As seen in Fig.6, the peak

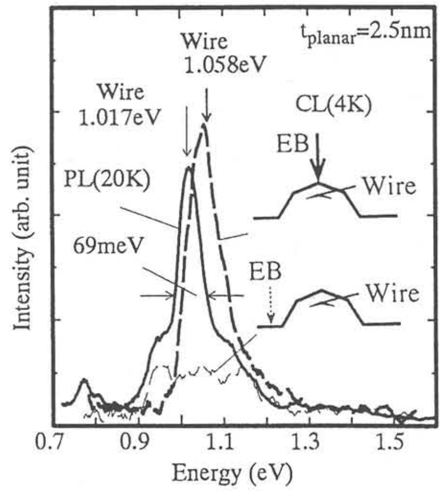
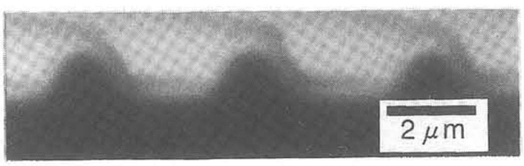
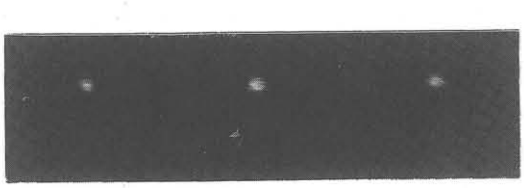


Fig.2 PL and CL spectra of the InGaAs ridge quantum wire (t_{planar}=2.5nm).



(a) Cross-sectional SEM image.



(b) CL image at 1.058eV.

Fig.3 (a) Cross-sectional SEM and (b) CL images of the InGaAs ridge quantum wires (t_{planar}=2.5nm).

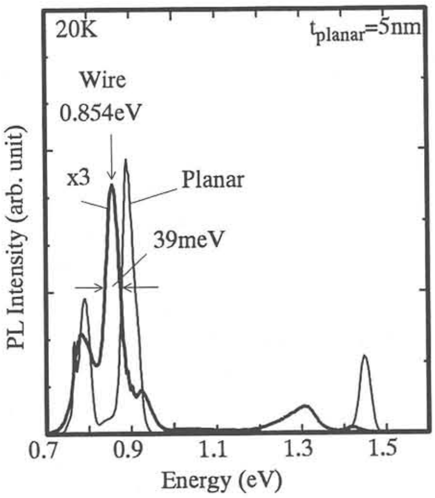


Fig.4 PL spectra of the ridge quantum wire (t_{planar}=5nm) and the corresponding quantum well.

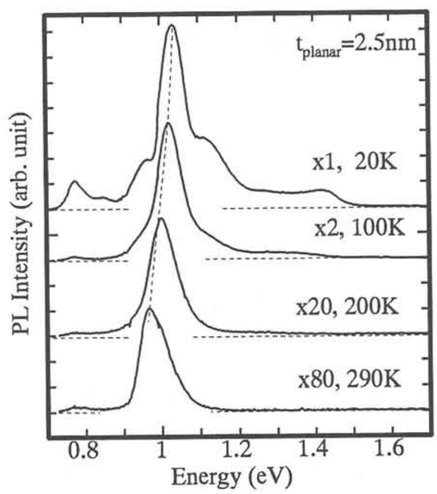


Fig.5 Temperature dependence of the PL spectra of the InGaAs ridge quantum wire (t_{planar}=2.5nm).

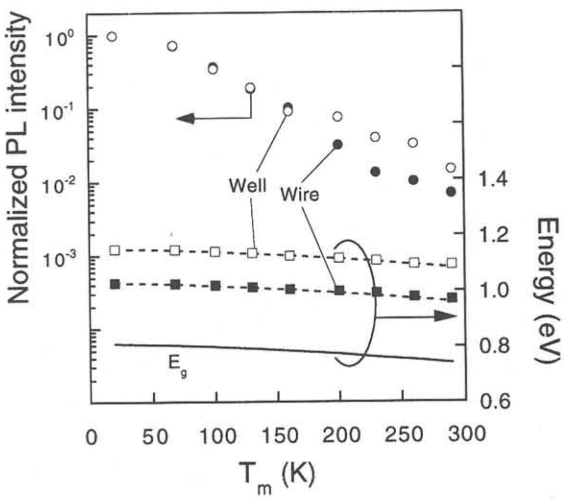


Fig.6 Summary of the measurement temperature (T_m) dependence of the PL peak position and intensity of the dominant peak of the wire (t_{planar}=2.5nm), together with those of the corresponding InGaAs quantum well.

positions of the quantum wire and well both follow the variation of the energy gap as expected. The PL intensity of the wire was almost constant up to 100K, beyond which it decreased. This behavior is same as that of the well as seen in Fig.6. This indicates that the crystal and interface quality of the selectively grown wires are comparable to those of the quantum well grown on planar (001) substrate.

4. CONCLUSION

To characterize the optical properties of the new type of InGaAs ridge quantum wires fabricated by selective MBE growth, detailed PL and CL measurements were made.

The results of PL and CL measurements indicated that the array of wires possess excellent crystal and interface qualities as well as good spatial uniformity. In addition, remarkably strong intensities of the emission from the ridge quantum wires in spite of their small volume indicates that the rate of carrier transfer into the wire and the efficiency of radiative recombination process with the wire are both high.

According to the measured temperature dependence of the PL spectra of InGaAs ridge quantum wire, the peak from the InGaAs ridge quantum wire was dominant within the whole temperature range of 20K–290K and had the strong intensity even at room temperature.

5. REFERENCES

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