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Formation and Characterization of AlGaAs Quantum Wires on Vicinal (110) Surfaces

H. Nakashima, M. Takeuchi, K. Kimura, M. Iwane, H. K. Huang, K. Inoue, J. Christen*, M. Grundmann** and D. Bimberg**

The Institute of Scientific and Industrial Research, Osaka University, 8-1 Mihogaoka, Ibaraki, Osaka 567, Japan
**Fakultät für Naturwissenschaften, Otto-von-Guericke Universität Magdeburg, Universitätplatz 2, D-39016 Magdeburg, Germany*
***Institut für Festkörperphysik, Technische Universität Berlin, Hardenbergstrasse, 36, 1 Berlin 12, Germany*

AlGaAs quantum wires are naturally formed on vicinal GaAs (110) surfaces by molecular beam epitaxy. TEM, AFM and PL measurements consistently confirm this formation of quantum wires. The PL bands with narrow spectral width are observed for single quantum wires. The monochromatic CL images visualize the well resolved isolated single quantum wires.

1. Introduction

Recently, we have demonstrated that AlGaAs quantum wires were naturally formed on vicinal GaAs (110) surfaces using molecular beam epitaxy (MBE)[1]. These naturally formed quantum wires were induced by the formation of coherently aligned giant growth steps and remarkable compositional modulation of AlGaAs at the giant growth step edges. Using reflection high-energy election diffraction (RHEED), we have found that the step structures of AlGaAs during MBE growth depend on growth temperatures (diatomic steps above 600℃, giant steps below 600℃), while all the GaAs and AlAs surfaces consist of regular arrays of diatomic steps[2]. Energy dispersive X-ray spectroscopy (EDX) has clearly revealed the compositional modulation of AlGaAs at the giant step edges[3].

In this paper, we will review our results of transmission election microscopy (TEM), atomic force microscopy (AFM), photoluminescence (PL) and cathodoluminescence (CL) studies of these quantum wires.

2. Experimental

AlGaAs quantum wires were formed by following MBE growth procedures using AsH_3. First, GaAs (30nm)/ $Al_{0.5}Ga_{0.5}As$ (30nm) superlattices (SL) with 5 periods were grown on vicinal GaAs (110) surfaces misoriented 3°, 6° and 8° toward (111) A. Growth temperature and AsH_3 flow rate were 540° C and 1.5 sccm, respectively. During the SL growth, giant growth steps were formed and at the step edges the regions with low AlAs mole fraction (~0.41) were formed in $Al_{0.5}Ga_{0.5}As$ layers[3].

Next, an AlAs (30nm)/ $Al_{0.2}Ga_{0.8}As$(10nm)/ AlAs (30nm) single quantum well was grown on the surface with giant steps. AlGaAs quantum wires with AlAs mole fraction x_0 less than 0.14 which was estimated from PL peak position were naturally formed at the giant step edges due to compositional modulation, as schematically illustrated in Fig. 1[1,3,4]. For comparison, the above structure was grown on (100) substrates which were place side-by-side to the (110) samples.

3. TEM and AFM Observations

Figure 2 shows bright-field cross-sectional TEM images of the 6°-off (110) sample in the direction perpendicular to the wires. Dark layers are GaAs and bright layers are AlAs. In contrast to flat heterointerface on the GaAs buffer layer, multi-atomic steps are formed on the first $Al_{0.5}Ga_{0.5}As$ layer in the SL. The multi-atomic steps become larger as the SL grows. It is observed that the giant step structure, consisting of coherently aligned multi-atomic steps, is formed after the SL grows. Dark areas are observed at the step edges in the $Al_{0.5}Ga_{0.5}As$ layers, indicating that lateral compositional modulation occurs at the giant step edges. Although they are not clear in the $Al_{0.2}Ga_{0.8}As$ QW, the compositional modulation is confirmed from PL results[1]. The cross sections of the QWRs are about 10nm × 20nm. Examining TEM image in detail, we can explain the formation of the coherent giant step structures as follows. New multi-atomic steps are formed only in the $Al_{0.5}Ga_{0.5}As$ layers. This is consistent with the RHEED observations that the multi-atomic steps are formed only during AlGaAs growth at low growth temperatures, but not formed during GaAs and AlAs growth[2]. Moreover, during the GaAs growth, small multi-atomic steps are deformed and large multi-atomic steps remain selectively. Through these formation and deformation processes, the terrace width and the step height of the giant step structures are gradually regularized as the SL grows.

To clarify the roles of the SL, we also grew the samples without the SL. Figure 3 shows the surface morphologies of samples (a) with and (b) without the SL by AFM. Sample (b) has an $Al_{0.5}Ga_{0.5}As$ epitaxial layer instead of the SL, which is as thick as the SL. It is observed that the terrace width, the step height and the step length of sample (a) are larger and longer than those of sample (b). The SL plays an important role to from the coherent giant step structures. Suitably thick GaAs layers are necessary to coherently align multi-atomic steps. To know the effects of the off-angle, we studied the surface morphologies of the 8°-off, 6°-off and 3°-off samples using AFM. The 8°-off sample did not show the coherent step structure. The giant step structure was more coherent in the 3°-off sample than in the 6°-off sample.

4. PL and CL Results.

The PL peaks of 3°-off and 6°-off samples are red-shifted from that of the (100) sample, showing the formation of quantum wires. The spectral width of the 3°-off sample is narrower than that of the 6°-off sample. This narrow spectral width indicates the more uniform quantum wire structures which is consistent with AFM observation of more coherent giant step structure of the 3°-off sample. The strong polarization of the PL is also observed for the 3°-off sample. as in the 6°-off samples[1]. The same large polarization degree (20%) of the 3°-off sample as of 6°-off sample confirms the heavy-hole confinement to the quantum wires[5].

In order to know the PL of the single quantum wires, an Al mask with a 0.3 μm wide slit was formed on the sample surface using direct electron beam writing and life-off techniques, as illustrated in Fig. 4. Figure 4 shows the PL spectra taken through this 0.3 μm wide slit and without mask. The spatially integrated PL band is broad and its FWHM (full width at half maximum) is about 23 meV. Two sharp PL bands are observed though the 0.3 μm wide slit and their FWHM's are about 5 meV. Since the separation between the wires in an AFM image is about 0.2 μm these two sharp PL bands are concluded to come from the two single quantum wires. This means that each quantum wire emits luminescence at different energy and the spatially integrated PL band is inhomogeneously broadened, reflecting the nonuniformity of the quantum wires in size and composition.

We have taken a set of CL spot spectra. The exciting e-beam of the scanning electron microscope (SEM) has been focused to 10 different random positions on the sample, with a small excitation area (~0.1 μm in diameter). This spot spectrum changes with the position and shows the fine stricture with several extremely sharp lines. In order to confirm that each sharp CL line originates from a specific single quantum wire, we took CL images at different wavelengths, as shown in Fig. 5. These monochromatic CL images clearly show that each quantum wire emits luminescence at a different wavelength. The longitudinal nonuniformity was observed in some quantum wires.

5. Conclusion

We have demonstrated that AlGaAs quantum wires were naturally formed on vicinal GaAs (110) surfaces using MBE. TEM, AFM and PL consistently confirmed the formation of quantum wires. The narrow PL band was observed for a single quantum wire. Monochromatic CL images visualize the well resolved isolated single quantum wires.

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References

1) Inoue, K. Kimura, K. Maehashi, S. Hasegawa, H. Nakashima, O. Matsuda and K. Murase, J. Crystal Growth 127 (1993) 1041.
2) Hasegawa, M. Sato, K. Maehashi, H. Asahi and H. Nakashima, J. Crystal Growth 111 (1991) 371.
3) Takeuchi, K. Shiba, H. K. Huang, K. Inoue, K. Maehashi and H. Nakashima, to be published in J. Crystal Growth.
4) Inoue, H. K. Huang, M. Takeuchi, K. Kimura, H. Nakashima, M. Iwane, O. Matsuda and K. Murase, Jpn. J. Appl. Phys. 34 (1995) 1342.
5) R. McIntyre and L. J. Sham, Phys. Rev. B45 (1992) 9443.

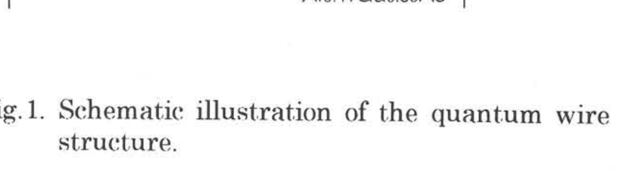

Fig. 1. Schematic illustration of the quantum wire structure.

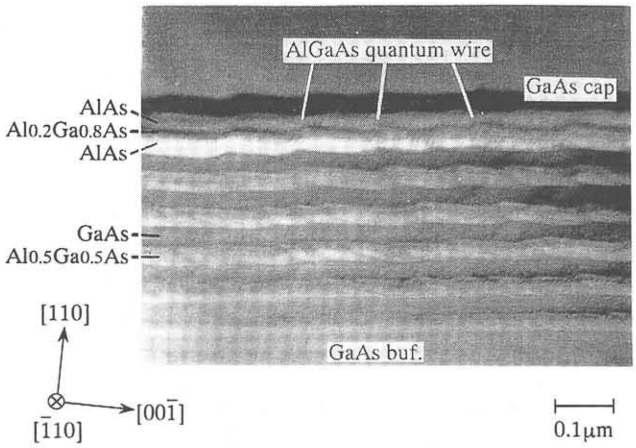

Fig.2. Cross-sectional TEM image of AlGaAs quantum wires.

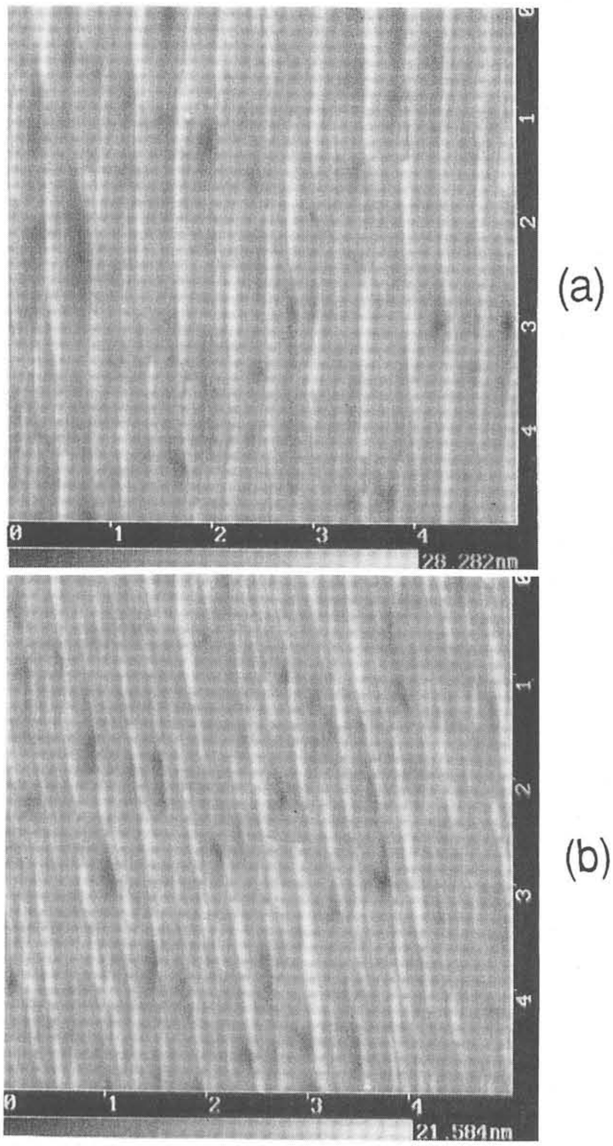

Fig.3. AFM images of surface morphologies (a) with and (b) without SL. (5μm × 5μm)

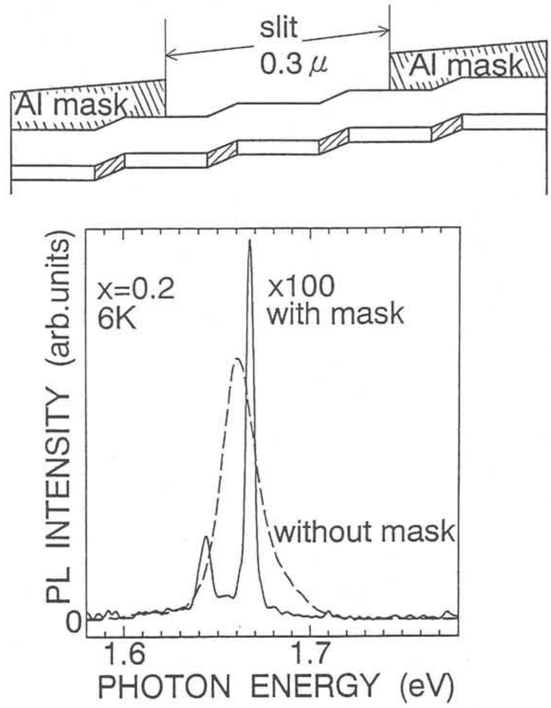

Fig.4. PL spectra through 0.3 μm slit of Al mask on the sample (solid line) and without mask (dashed line).

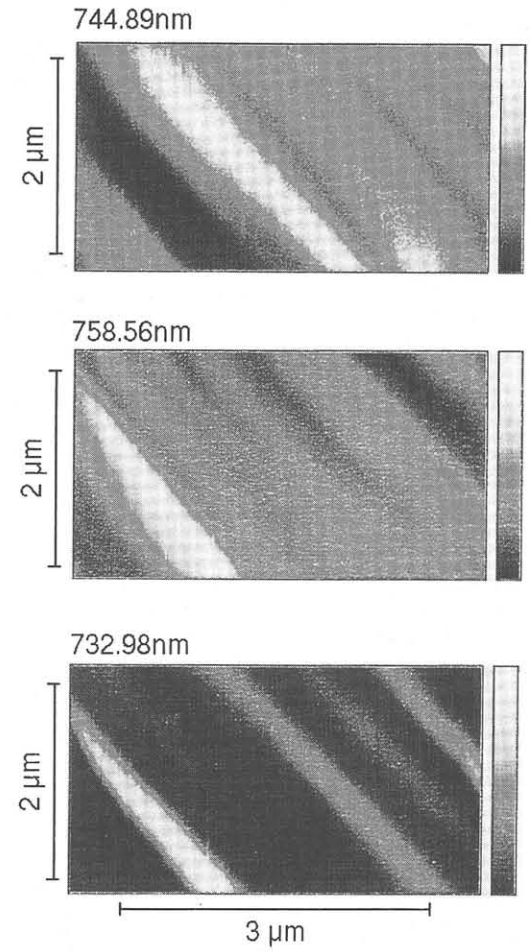

Fig.5. Monochromatic CL images showing the well resolved single quantum wires.