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Fabrication and Control of GaAs/AlAs 10 nano-meter Scale Structure by MBE

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Quantum wires (QWR) have been successfully fabricated on the ridge of facet structures by means of molecular beam epitaxy (MBE) on a patterned (001) GaAs substrate. The structure studied by electron microscopes and by atomic force microscope (AFM) has shown that QWRs of 10 nm widths have been formed on the facet structures. Systematic studies enabled controling the QWR size by the growth temperature(Ts). Their optical properties indicate that one-dimensional electrons were confined on the QWR. The laser emission from ridge QWR structures was observed by optical pumping at temperatures 4.7 to 290 K. The spatially as well as spectrally resolved microscopic images of the emissions clearly showed the origin of the stimulated emission.
Key words: nano meter, MBE, quantum wire, laser and GaAs

1. Introduction

The semiconductor micro structure of nano-meter size has attracted a great attention because of anticipation of novel devices due to the peaked density of states of the low dimensional electrons [1]. It is clear that the size control of these nano structures with acceptable uniformity is necessary for appliing to the electronic devices. In addition, the control of its location and the formation of inter connections between the gates and the contacts, which have macro sizes (~ μm or mm), are important for the electronic device application. Furthermore these technics must be free of defect and of contamination which degrade the performance of the semiconductor nano structures. From this point of view, the epitaxy is one of the most promising technology as the mono-layer scale control in stacking on a one-dimension. Various efforts have been tried to introduce artificially controlled structures in the plane of growth. We have adopted the epitaxial growth on the patterned substrates, which the facet formation were reported. Facet formation by epitaxial growth on a patterned substrate has been explored with great interests as a promising method to organize the nano-meter size structures [2-6].

We have studied the ridge structure as well as its application for the ridge quantum wires (R-QWR) of nano-meter scale. We have succeeded to fabricate 10 nm scale R-QWRs on a variety of the ridge structures [7-18]. Their lifetime of photoluminescence has shown a unique temperature dependence which indicates one dimensional excitons are confined at the corner of the facet structures [12].

The good structural uniformity and the excellent width control of the wires are established by the UHV-AFM measurements [15, 16, 18]. Since the R-QWR structures have some advantages in making the large lateral confinement energy and the high crystal quality, they are promising to realize the room-temperature R-QWR lasers with the novel property of the 1D system. We fabricated a ridge laser containing R-QWR structure and its stimulated emission was observed by the optical excitation. We investigated the positions and the patterns of the stimulated emission by using the microscopic imaging measurements to examine the origins of the emissions [19, 20]. We here report the formation and the control of the facet structures for the QWR of nano-meter scale as a novel method for producing the artificial nano structures.

2. Formation of ridge structure

GaAs (001) wafers were patterned by photo lithography and were etched by a reactive ion etcher using $SiCl_4$. The mesa stripes are in the <110> direction and their widths and their depths were less than 2 μm and 2~3 μm, respectively. In order to form a base ridge structure, a 2.5 μm thick GaAs layer was grown. The growth rates of GaAs and AlAs were 0.25 μm/h and 0.10 μm/h, respectively. The As_4/Ga flux ratio on the (001) plane was about 4 measured on a flat (001) substrate. During this growth, the substrate holder was rotated so that As and Ga molecules were uniformly distributed.

The ridge shape and the morphology are strongly dependent on the T_s, the growth rate, the III-V ratio, the As flux, the growth interruption, the Al dose. The optical waveguide structure is a simple separately confined hetero-structure (SCH), which consist of the two cladding layers, A and E, sandwiching the active layer, C, between the two core layers: B and D. The active layer, the core layers and the cladding layers have different Al dose, hence we modify the growth conditions according to the each layer, so as to meet their different requirements, while keeping their good morphology. So far the AlGaAs alloy growth on a facet structure has been difficult, as it often leads to irregular facet structures and fluctuations in Al local contents. This is because of the different diffusion behaviors of Ga and Al ad-atoms. For the fabrication of laser structures, we adopted AlGaAs digital alloys which are short period super lattices (SLs), because the growth of GaAs as well as of thin AlAs

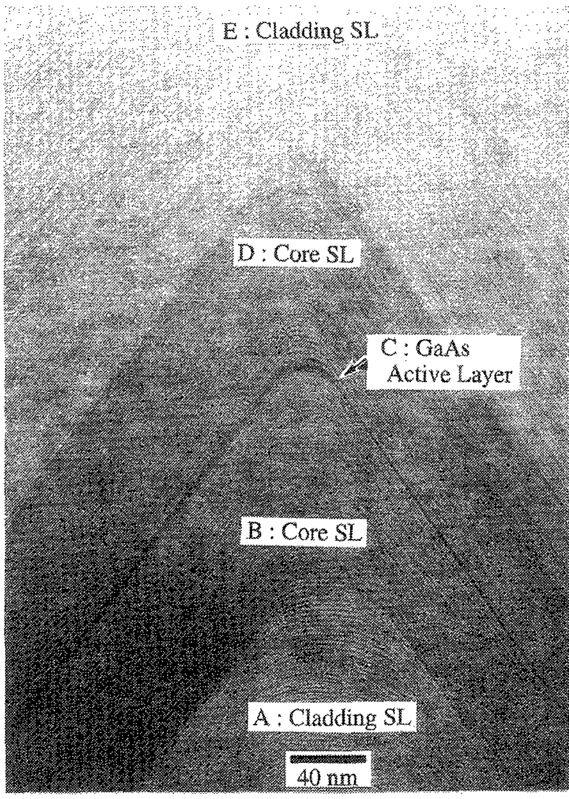

Figure 1. cross-sectional TEM image of the ridge quantum wire laser. Characters A, B, C, D, and E are representative lower cladding SL layer, lower core SL layer, active layer, upper core SL layer, and upper cladding SL layer, respectively.

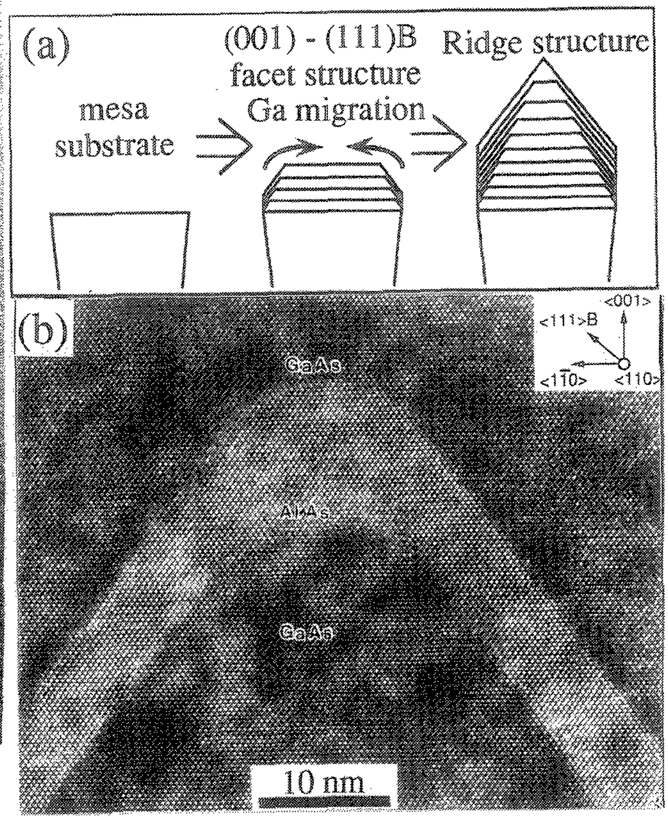

Figure 2. (a) is a schematics of the ridge structure formation. (b) is a TEM cross-sectional lattice image of the ridge structure.

layers of good uniformity had already been established. It also enables a rapid change of the Al content (x) between x=0.2 for core layers and x=0.4 for cladding layers during the growth.

Figure 1 shows a cross-sectional TEM micrograph of a R-QWR laser structure. In this picture, the GaAs active layer is clearly seen as a dark thin layer, where the width is about 20 nm. The clear TEM image which does not contain any dislocations nor stacking faults, verify the high crystalline quality of the MBE grown ridge wave guide structures. We can also see the individual period of SL layers. We can thus trace the time evolution of the ridge shape during the MBE growth.

3. Structural studies

As the growth proceeds, the width of the (001) top surface decreases, resulting in the facet structure consisting of a (001) top surface and two (111)B side surfaces. This facet growth is due to the migration of Ga atoms from the (111)B faces to the (001) top surface and eventually leads to the formation of a sharp ridge consisting of two (111)B facet as shown schematically in Fig. 2(a).

The characterization of the ridge structure requires the nano meter resolution and it also requires a wide range of measurements especially when the application for electronic devices are considered. We used various methods such as SEM, TEM, AFM and *in-situ* AFM.

The TEM measurements offer the detailed, but localized, information about the atomic arrangement of the nano structures. It also informs the existence or non-existence of defects such as dislocations and stacking faults. The TEM(fig. 2(b)) shows that the effective ridge width (*W*) is about 10 nm, and the shape is rounded. The *W* will never become zero, because of the frequent motion of atoms at the top of the ridge, and it gets wider at higherT_s. Hence, the *W* can be controlled by adjusting the T_s [18]. This mechanism is partially simulated by Monte Carlo simulation [13]. It should be also notable that the *W* of AlAs ridge is smaller than that of the GaAs, which indicates the stronger interaction of Al atoms.

The AFM measurements provide us with the three dimensional structural image which allows us to evaluate the facet structure of nano-meter scale. In the case of the facet structure, in which , the heights exceed 1μm and the shapes are very sharp, such as ridge structures, we have to make sure that the AFM tip shape is appropriate. This is bacause the tip shape, the scan direction and the scan speed have strong effects on the result of measurements [15]. Figure 3 shows the *ex-situ* AFM measurement of the ridge cross section. The AlAs layers are observed as the swollen layers due

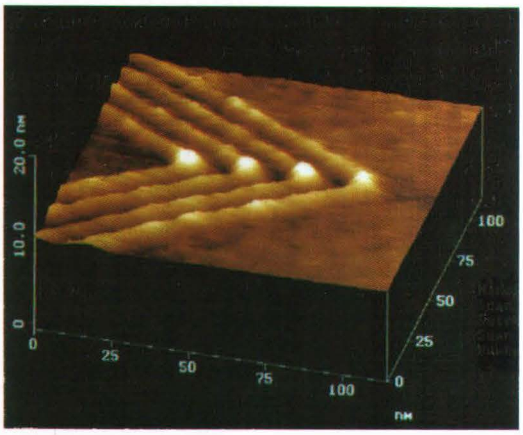

Figure 3. cross-sectional AFM of the ridge structure. The AlAs layers are shown as swollen layers due to oxidation.

to their oxidation. This fact enables to distinguish of the hetero interface of nano-meter scale. We have systematically investigated the effects of the T_s and the As flux on the W and the morphology of the ridge structure. The results show that a very sharp and uniform GaAs ridge structures ($W < 10$ nm) can be obtained. We also evaluated the shape of R-QWR by using the ultra-high-vacuum (UHV) AFM system which is connected to the MBE chamber. We used a commercially available UHV-AFM system (Auto Probe VP by Park Scientific Instruments) with minor modifications. This system allowed us to evaluate the size and the uniformity of the ridge structures at various phases of the growth. This is because the sample can be transferred between the chambers of MBE and AFM without being exposed to air. The sample can continue to grow after the measurements by this MBE-AFM system. We studied the time evolution of the ridge structures and found the self-smoothing phenomenon of the ridge structures during the MBE growth. Figure 4 shows two AFM images of a sample at different stages. The upper one shows a rough faceted structure observed near the end of the ridge formation. A large amount of atomic migration during the formation of the ridge structure is thought to introduce the instability of the surfaces. The lower is a AFM image of the same sample observed after the another MBE growth at 535 ℃, which shows a very sharp and uniform ridge of 10 nm width. The ridge structure is stable and can be formed even on the rough faceted structure[15, 16, 18].

4. Optical properties

The samples of the previous chapter were cleaved to form optical cavities of various lengths; L = 0.3-1 mm in wire direction. The photoluminescence (PL) spectra were measured for various excitation intensities. The Ti sapphire pulsed laser with the energy of 1.766 eV was used. The pulse duration and repetition rate are 150 fs and 76 MHz, respectively. The PL peak from the R-QWR was observed at 1.609 eV for weak excitation. This peak shifts to a higher energy for a higher excitation

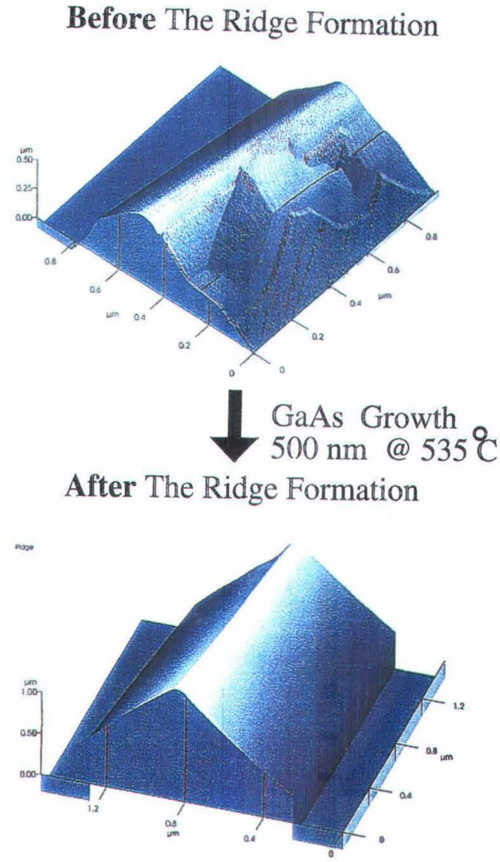

Figure 4. in-situ AFM mesuments of the ridge structure and its self-smoothing process.

power. This blue shift indicates the saturation of carriers in the ground state and in the lower excited states, of the R-QWRs resulting to the occupation of higher excited states. At the pumping power of 20 mW, the stimulated emission was observed at 1.662 eV. This lasing energy is higher by 53 meV than the ground-state PL energy of R-QWR. The energy difference between the ground state of the R-QWR and that of the side quantum well (Side-QW) was 90-100 meV. These Side-QWs were formed on (111)B next to the R-QWR. The lasing was observed at all the temperatures between 4.7 K and 290 K. When the optical cavity length was increased to 1 mm and the mirror loss at the end of cavity was decreased, the lasing occurred between lower-order excited states with a slightly lower gain [19].

The identification of the origins of these PL peaks was done by the spatially resolved PL measurements at 4.7 K. The sample in a cryostat was optically excited by pulsed a YLF laser. The PL light from the cleaved edge of the R-QWR laser was collected by a lens and was detected by a CCD camera. In front of the camera, an interference filter (2 nm band width) was placed to resolve the images spectrally. The spatial resolution of this system is 1 μm at 1.59 eV. The filtered intensity mappings of the R-QWR laser at 4.7 K were shown in Figs. 5(a) to (d). Figure 5(a) is a schematics of the ridge laser structure. The center of the circle is the location of the R-QWR. Fig. 5 (b) is an intensity

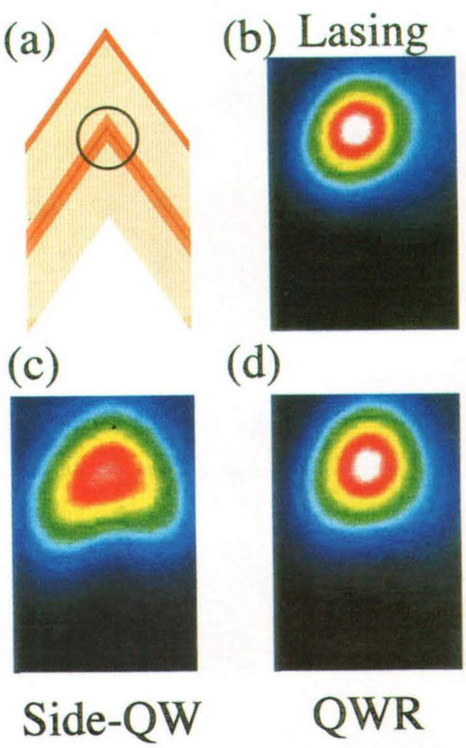

Figure 5. schematics (a) and filtered cross-sectional PL contour-plot images of ridge quantum wire laser. (b) is an image of the stimulated emission at 1.687 eV indicated as 'Lasing'. (c) and (d) show that the PL images at 1.610 eV and 1.699 eV are identified as QWR and Side-QWs, respectively. Note that the Lasing' image is centered at the top of the ridge structure, similar to the PL image of the QWR.

mapping of lasing emission from R-QWRs at the high excitation power of 143 mW. Figure 5 (c) shows the peak at 1.71 eV is emission from Side-QWs for the weak excitation power of 0.43 mW. Figure 5 (d) shows that the peak at 1.589 eV is the emission from the R-QWR. Fig. 5 (b) is similar to Fig. 5 (d), implying that the R-QWR is lasing. The observed emission pattern supports our assignment that the origin of the stimulated emission is the optical transition between the excited states of the R-QWRs. More detailed discussions about the mechanisms and dynamics of the stimulated emission are given at elsewhere [19].

5. Conclusions

The TEM, and AFM, observations revealed a plentiful information of the unique nature of the MBE ridge growth mechanisms. They also revealed the necessity for further improvements on the uniformity of the ridge structure.

The stimulated emission was observed in the R-QWR laser structures up to 290 K. The origin of the stimulated emission was found tobe the transitions between the higher excited states of R-QWRs.

In summery, the R-QWR showed the potential of the facet structure.

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